Cross-Modal Action Control

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vorgelegt von
Aleksandra Pieczykolan
aus Wrocław

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Erstgutachter: Prof Dr. Lynn Huestegge

Zweitgutachter: Prof. Dr. Iring Koch

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Zusammenfassung

Multitasking als allgegenwärtiges Phänomen wird heutzutage in verschiedenen wissenschaftlichen Disziplinen diskutiert. In der vorliegenden Arbeit wird Multitasking aus der Perspektive der kognitiven Verhaltenswissenschaften beleuchtet mit dem Fokus auf der Rolle von Konfliktlösungsprozessen bei der Verarbeitung von Mehrfachtätigkeiten. Insbesondere liegt der Fokus auf kognitiven Mechanismen der *crossmodalen Handlungskontrolle*, d.h. der Kontrolle von zwei Handlungen in verschiedenen Effektorsystemen. Mit dem Ziel, den bisherigen Umfang derjenigen Handlungsmodalitäten zu erweitern, die üblicherweise in Studien eingesetzt wurden, wurden okulomotorische Reaktionen (d.h. Sakkaden), die bisher als Handlungsmodalität in der Forschung vernachlässigt wurden, in Kombination mit Reaktionen in anderen Efffektorsystemen untersucht (d.h. mit manuellen und vokalen Reaktionen). Weiterhin wurde beabsichtigt, Mechanismen von *Crosstalk* zu spezifizieren, welches ein Erklärungskonzept darstellt, das sich auf den Aufgabeninhalt bezieht. Crosstalk erscheint besonders relevant für crossmodale Handlungen, da sich Handlungsmodalitäten vor allem bezüglich ihrer Reaktionsmerkmale unterscheiden. In der vorliegenden Arbeit werden vier Studien berichtet, die auf jeweils zwei oder drei Experimenten beruhen.

In Studie A wurden crossmodale Doppelreaktionen auf einen einzelnen Stimulus untersucht mit der Fragestellung, wie sich das Zusammenspiel des Vorhandenseins von Reaktionsalternativen und der Kompatibilität zwischen Reaktionen (also dem Crosstalkpotential) auswirkt. In drei Experimenten zeigte sich, dass Crosstalk in mehrere Komponenten dissoziiert werden kann, nämlich eine Komponente, die auf der aktuellen Konfliktstärke (Online-Crosstalk) basiert, und eine gedächtnisbasierte Komponente, die entweder durch Restaktivität vergangener Handlungsanforderungen bestimmt wird (retrospektiver Crosstalk), oder durch Vorbereitung auf zukünftige Handlungsanforderungen (prospektiver Crosstalk).

Studie B lieferte Evidenz dafür, dass okulomotorische Reaktionen sowohl struktureller als auch inhaltsbasierte Interferenz unterliegen. In drei Experimenten wurde das Paradigma zeitlich überlappender Aufgaben verwendet, bei dem zwei Stimuli mit zeitlichem Versatz präsentiert wurden, auf die jeweils mit einer okulomotorischen und einer manuellen Handlung reagiert werden musste. Dabei wurden sowohl Hinweise auf einen seriellen als auch auf einen parallelen Verarbeitungsmodus gefunden. Weiterhin deuteten die Ergebnisse darauf hin, dass abhängig von

der Aufgabenkompatibilität zwischen diesen Verarbeitungsmodi gewechselt wurde, d.h. zu eher paralleler Verarbeitung bei kompatiblen Aufgabenanforderungen und zu eher serieller Verarbeitung bei inkompatiblen Aufgabenanforderungen.

In Studie C wurden Verarbeitungsprioritäten zwischen Effektorsystemen untersucht. In zwei Experimenten zeigte sich, dass das zuvor berichtete Verarbeitungsdominanzmuster repliziert werden konnte, bei der okulomotorische Reaktionen vokale Reaktionen dominieren und diese wiederum manuelle Reaktionen dominieren. Die relative Stärke der Dominanz konnte allerdings bei vorhandenem Reaktionskonflikt angepasst werden. Die Verarbeitungsprioritäten wurden hierbei zum Teil in Richtung derjenigen Reaktion verschoben, in der bereits ein Konflikt im Bezug auf die Kompatibilität zwischen Stimulus und Reaktion gelöst werden musste. Dieses Ergebnis zeigt, dass Verarbeitungsprioritäten flexibel an die spezifischen Handlungsanforderungen angepasst werden können.

Studie D beschäftigte sich mit einem bisher weitgehend vernachlässigten Bereich innerhalb der Doppelaufgabenforschung, nämlich der Kontrolle der zeitlichen Reaktionsreihenfolge. In einer drei Experimente umfassenden Untersuchung wurden mehrere Faktoren variiert, die sich in früheren Studien bereits als relevant für Mechanismen der Doppelaufgabeninterferenz gezeigt haben. In der vorliegenden Studie wurde gezeigt, dass die finale Reaktionsreihenfolge in einem Handlungsdurchgang das Ergebnis eines kontinuierlichen Anpassungsprozesses ist, welcher auf dem Zusammenspiel mehrerer top-down-Faktoren, z.B. der Antizipation von Reaktionsmerkmalen, und mehrerer bottom-up-Faktoren, wie z.B. der Stimulusreihenfolge oder der Aufgabenkompatibilität, basiert.

Die vorliegende Arbeit liefert somit einen wichtigen Beitrag zum Fortschritt des Verständnisses der Verarbeitung komplexer Handlungsanforderungen aus der Perspektive crossmodaler Handlungen. Insbesondere wurden Spezifikationen für Mechanismen der Effektorpriorisierung und der Kontrolle der Reaktionsreihenfolge als auch eine neuartige Taxonomie von Crosstalk vorgestellt, welche als umfassende Rahmenvorstellung zur Erklärung von Interferenzmechanismen bei Kontrollprozessen von Mehrfachanforderungen dienlich sein kann.

Abstract

Nowadays, multitasking is ubiquitously discussed within many different scientific disciplines. The present work addressed multitasking from the perspective of cognitive behavioural sciences by investigating the role of conflict resolution processes that arise during the requirements of multiple-action control. More specifically, the present work focuses on cognitive mechanisms in the case of *cross-modal action control*, which involves the performance of two actions in different effector systems. One aim was to broaden the scope of action modalities typically considered in the literature by studying oculomotor responses (i.e. saccades) – an action modality that has been largely neglected in previous research – in combination with responses in other effector systems (i.e. manual and vocal responses). A further aim was to specify the mechanisms of *crosstalk* as an explanatory concept referring to the action content, which is particularly relevant since cross-modal actions usually differ regarding their response characteristics. The present work comprises four studies (each involving two or three experiments).

In Study A, cross-modal response compounds based on a single stimulus were studied with respect to the interplay of the presence of response alternatives and between-response compatibility (i.e. crosstalk potential). In three experiments, this study showed that crosstalk can be dissociated into a component that determines the amount of current conflict (i.e. online crosstalk) and a memory-based component that originates either from residual activation of previous action demands (retrospective crosstalk) or from preparation for future demands (prospective crosstalk).

Study B provided first evidence that oculomotor responses are subject to interference based on both structural and content-based origins. In three experiments, an overlapping tasks paradigm was employed in which the onsets between two stimuli that triggered oculomotor and manual responses were varied. Evidence for both serial and parallel processing of the two tasks was found. The results further indicated that based on the between-task compatibility participants shifted between these processing modes, i.e. to more parallel processing during compatible task demands and to more serial processing during incompatible task demands.

Study C examined processing priorities among effector systems and demonstrated in two experiments that the previously reported prioritisation scheme, in which the oculomotor system is prioritised over the vocal and manual effector system, can be replicated, but is also adjusted in its strength by the presence of response conflict. Specifically, processing priorities were shifted towards the response that already is involved in conflict resolution (in terms of stimulus-response compatibility), suggesting that processing priorities can be flexibly adapted to particular task demands.

Study D addressed response order control in dual tasks, an issue that has been widely neglected in previous research. In a comprehensive study of three experiments including several factors that are known to be relevant for dual-task interference mechanisms, it was shown that the final response order in a given trial is the result of a continuous adjustment process based on the interplay of several top-down factors, such as the anticipation of response characteristics, and bottom-up factors, such as stimulus order and between-task compatibility.

In summary, the present work advances the theoretical understanding of complex action control by providing a cross-modal action perspective, by proposing mechanisms for effector-system prioritisation and response order control, and by proposing a novel taxonomy of crosstalk as an overarching framework for interference mechanisms in multiple-response control.

Contents

1 | General Introduction

1.1 The cognitive approach to multitasking

Cognitive psychology as a fundamental field of research aims at understanding the human cognitive architecture and its functional principles. For this purpose, one of the established methods for studying cognition is to drive the cognitive system to its limits (e.g. analogously to analysing substance properties under extreme tension in material sciences) and to observe resulting behavioural or neurophysiological consequences. Such straining of the cognitive system can be achieved by introducing difficult behavioural requirements, for example, by applying time pressure or unfamiliar task settings in order to study conflict resolution processes and conflict monitoring (e.g. Botvinick, Nystrom, Fissell, Carter, & Cohen, 1999). The present work focuses on conflict resolution processes that arise during the requirement of multiple-task control (i.e. *multitasking*), and particularly, I will address mechanisms that are associated with conflict based on response characteristics (as opposed to stimulus characteristics).

First, it is necessary to define the term ‘multitasking’ and to outline briefly how multitasking is operationalised in the area of cognitive sciences. In everyday language, the term multitasking might be associated with the scenario, for example, of riding a bike while talking on the phone or solving crossword puzzles while working out on a treadmill, of which both represent the simultaneous performance of complex real-life tasks. However, although it is certainly important to know what kind of conflict such complex dual tasks pose on human cognition, for instance regarding safety and legal issues during road traffic or at a gym (for examples of studies utilising complex tasks see Solomons & Stein, 1896; Spelke, Hirst, & Neisser, 1976; Strayer & Johnston, 2001), studying this kind of tasks can be problematic in that the low level of experimental control over timing of cognitive processes does not allow a clear interpretation of underlying temporal dynamics and mechanisms.

Therefore, in a highly controlled laboratory environment human behaviour is divided into ‘elementary particles’ of action units, for example simple button pressing or uttering monosyllabic words. Such an environment provides the basis for a high control of the duration of both stimulation and reaction, so that eventually the only unknown variable in the equation remains the duration of the cognitive process of interest.

A ‘task’ is then defined as consisting of a stimulus (S), an associated response (R), and the cognitive (at first rather abstract) association between stimulus and response, called the S-R *mapping*. The latter can have been learned in the past (and as such is familiar in the present, e.g. pressing the ‘open door’ button on the microwave after hearing the ‘ping’ sound), but in experimental settings it is typically induced by instructing (arbitrary) rules (e.g. pressing the ‘y’ key in response to a tone on the left ear). A task is normally defined as completed once the response has been executed. While much research effort has been directed to explore effects of different S-R associations in individual tasks (e.g. in terms of S-R compatibility, see Proctor & Reeve, 1990; Hommel, 1998b; Kornblum, Hasbroucq, & Osman, 1990), multitasking research takes its interest in the coordination of several S-R mappings around the same time. Therefore, the experimental multitasking approach involves studying performance of two or more tasks in close temporal proximity. Importantly, the amount of temporal overlap between tasks is subject to variation and as such determines the specific cognitive requirements for task coordination. For example, a situation in which a new stimulus (requiring a new response) appears *after* the execution of a previous response is considered as requiring a complete switch from Task 1 to Task 2 (i.e. without any temporal overlap, see *task switching*, e.g. Allport, Styles, & Hsieh, 1994; Kiesel et al., 2010; Monsell, 2003). Meanwhile, a scenario that involves actual temporal overlap in that two stimuli are present *before* the first response has been executed is defined as *dual-task* situation.

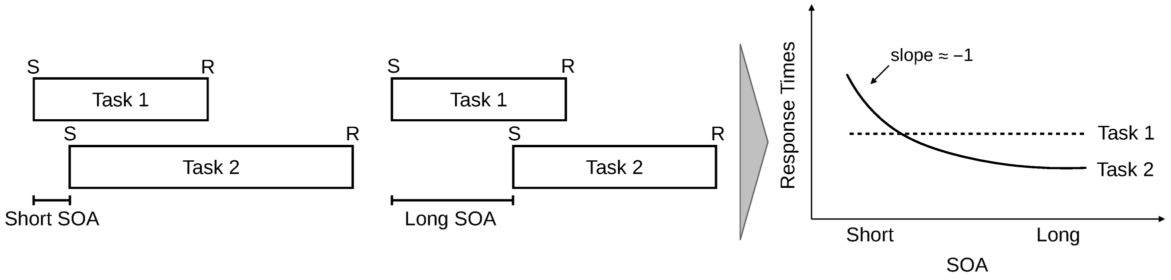
It must be noted that in the literature the term ‘dual task’ is also used in a broader sense, for example for situations, in which tasks do not necessarily require an immediate, speeded response to a stimulus (for instance in purely perceptual tasks with delayed report or memory maintenance tasks, e.g. Jolicœur & Dell’Acqua, 1998). Furthermore, this term covers situations, in which one component task involves more than just one single, distinct response (but a sequence of responses, e.g. Bratzke et al., 2008; Keele, 1968), or when there is not even a dedicated stimulus triggering the response (e.g. continuous finger tapping, see Kee, Bathurst, & Hellige, 1983; Neys, 2006; or performing the so called *n-back task*, e.g. Jaeggi et al., 2003, in which participants count backwards by n). In the present work, I will focus on mechanisms underlying *dual-response* control, which can be regarded as a variant within the broad field of multitasking – one that particularly involves the execution of two distinct, speeded responses (i.e. in the sense of a *dual action*). Specifically, the focus will be on *cross-modal* action control, that is the execution of two responses in different effector systems. The present definition of cross-modal action is not restricted to the definition of a dual-task situation requiring separate stimuli (or different aspects of the same stimulus) to trigger each of the two responses (see the following Section 1.1.1). Instead, cross-modal action includes any setup, in which two distinct responses in different response modalities are executed, which also might be based on a common (aspect of a) stimulus. Therefore, cross-modal action can be regarded as a specific case within the scope of multiple-response control. Most importantly, the theories of cross-modal action processing are nevertheless based on experiments utilising typical dual-task paradigms and on mechanisms discussed in dual-task frameworks. Therefore, in the next section I will describe typical dual-task paradigms, and later in Section 1.2, I will outline dual-task frameworks that are relevant for discussing cross-modal action.

1.1.1 Dual-task paradigms

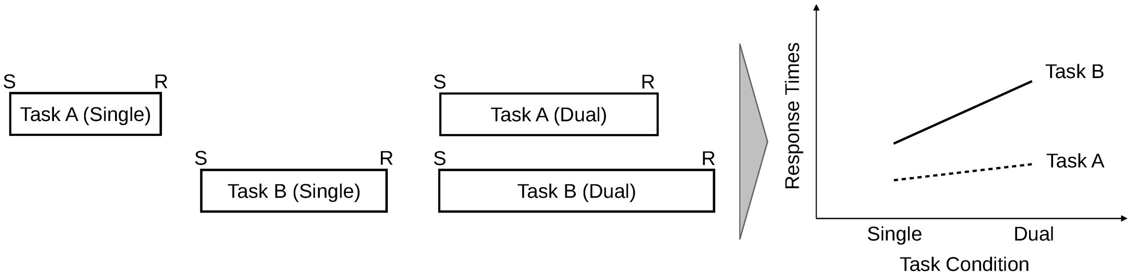
Performance deterioration in dual-task conditions compared to single-task conditions (i.e. performance costs as reflected in longer response times or larger error rates) has been a hallmark of multitasking research, and explanations for such impairments have been proposed within several theoretical frameworks (which will be outlined in detail in Section 1.2). In principle, these frameworks are based on the fundamental question if (or under which circumstances) the mind is capable of processing two tasks at the same time and if performance costs might be the result of limitations in mental capacity. This issue seems particularly intriguing, since the brain is obviously able to operate in parallel (e.g. Alexander & Crutcher, 1990), that is several brain regions are oxygenated at the same time and the neurones in those regions independently produce electrical fields (e.g. Belliveau et al., 1991; Hämäläinen, Hari, Ilmoniemi, Knuutila, & Lounasmaa, 1993; see also Bayliss, 1916). However, one should note that the concept of parallel processing in cognition should not be directly equated to the idea of multiple processors that necessarily cause an eradication of any dual-task interference when each task is processed independently by different processing modules. Instead, parallel processing shall be understood as the structural opposite of serial processing. Parallel processing, therefore, might still yield dual-task interference when either the cognitive capacity is limited and hence shared between tasks or (without the assumption of a structural limitation) the task content of both tasks interferes because each task is not processed in an encapsulated manner (see Section 1.2.4 for a discussion on encapsulated task processing).

It has been shown repeatedly that performing two simple manual reactions (pressing keys) in response to two stimuli in close temporal distance results in dual-task costs (i.e. longer response times compared to performing one key press in isolation, e.g. Telford, 1931; Welford, 1967) for the second reaction. Interestingly, the observation that response times for Task 2 increased with shorter inter-stimulus intervals has been interpreted in the first half of the 20th century in terms of a ‘psychological refractory period’ (PRP), in that the cognitive system is assumed to require a certain amount of ‘charging’ time in order to be able to work or ‘think’ again after performing the mental operation of responding to a stimulus (Telford, 1931; Welford, 1967). In later research, this term was adopted, but applied to a more specific observation during overlapping dual-task situations, that is when Response 1 (R_1) was not executed before Stimulus 2 (S_2) appeared. The result – which has widely been replicated ever since – was that response times (RTs) for the second response were longer at short inter-stimulus intervals, which are commonly referred to as stimulus onset asynchrony (SOA), and decreased with longer SOAs. Meanwhile, RT_1 remained largely unaffected by the SOA manipulation. Today, the characteristic dependence of RT_2 on SOA (with a nearly linear slope of -1 at short SOAs, see Figure 1.1A) is commonly known as the *PRP effect* (Herman & Kantowitz, 1970; Pashler, 1984, 1994), and the associated PRP paradigm involving a variable SOA has become the cornerstone of dual-task research.

Instead of sequential stimulus presentation as in the PRP paradigm, another successful method to study dual-task processing is to prompt for two responses by presenting two stimuli with an SOA of 0 ms (simultaneous-onset paradigm, e.g. Fagot & Pashler, 1992; Navon & Miller, 1987; see Figure 1.1B). A variant of the simultaneous-onset paradigm is the single-onset paradigm, in which only one common single stimulus is presented, and the two responses are either directed to different aspects of the stimulus (e.g. a letter with a colour and meaning Hommel, 1998a) or to the same aspect of the stimulus. Fagot and Pashler (1992) suggested that two responses to the same aspect of a stimulus (e.g. uttering ‘A’ and pressing a key associated with the letter ‘A’ in response to an ‘A’ on a monitor screen, see Holender, 1980) share one common response selection process, thus rather represent a single task than a dual task (see also the notion of ‘redundant responses’ in Fagot & Pashler, 1992; Holender, 1980). In the simultaneous- or single-onset paradigm, dual-task costs for



A. Schematic illustration of the PRP paradigm consisting of two sequentially presented stimuli S requiring two associated responses R. The crucial manipulation is the variation of the stimulus onset asynchrony (SOA) across trials resulting in longer response times for Task 2 at short SOAs than at long SOAs.



B. Schematic illustration of the simultaneous-onset paradigm, in which a stimulus S triggers either one single response R in Task A or Task B (single task), or the simultaneous presentation of two stimuli requires two responses (dual task). Dual-task costs for each response are defined as the response time difference between single-task conditions and dual-task conditions.

Figure 1.1. Experimental paradigms typically utilised in dual-task research.

each component task are obtained by subtracting response times in trials, in which only one response is required in isolation (single-task conditions), from the respective response times in trials, in which both responses are required (dual-task conditions). Importantly, each paradigm is especially suited for specific research question applications and therefore closely linked (or even restricted) to specific theoretical interpretations (see Section on dual-task frameworks). While the SOA manipulation in the PRP paradigm entails the advantage of experimental control over the amount of task overlap thus allowing for an examination of the time course of dual-task interference, the simultaneous- (and single-)onset paradigm provides the possibility of comparing dual-task costs between both responses under similar stimulus processing conditions (see Figure 1.1B). However, it has been shown that this supposedly direct comparison of a singe and dual-task situation might not be unproblematic, since in a block-wise manipulation the preparatory states before single- and dual-task blocks appear to differ (e.g. Gottsdanker, 1980; Gottsdanker, Broadbent, & Sant, 1963; see also Schubert, 1999). Nevertheless, each paradigm has its merits if interpreted within its limits.

Interestingly, although these experimental paradigms allow for varying the properties of the stimulus, of the response, and of the stimulus-response mapping within and between tasks, most studies on dual-task control mechanisms utilised the manual effector system as response modality for both tasks (e.g. Pashler, 1994). However, when considering actual behaviour in daily life, it becomes apparent that it often involves simultaneous actions across different effector systems, for example oculomotor, vocal, or pedal responses, in addition to manual responses.

Therefore, the aim of the present work is to explore control mechanisms in situations involving two responses executed in different effector systems – that is *cross-modal action*. The emphasis will be on processes that are particularly relevant for cross-modal action (in addition to – or instead of – dual-response control within one effector system). In the next section of the introduction, I will elaborate in more detail on the relevance of studying cross-modal response situations (Section 1.1.2). Afterwards I will discuss current theoretical frameworks of dual-task processing (Section 1.2) that are relevant in discussion cross-modal action, and I will go into the details of the results of recent studies in cross-modal action research which form the basis of the studies of this work (Section 1.2.4). Finally, I will derive the overall research questions of the present work (Section 1.3) and give an overview of the specific theoretical issues tackled as four separate studies.

1.1.2 Relevance of cross-modal action research

An important fact is that the majority of dual-task studies employed experimental paradigms in which responses in each task were executed within the same action modality (typically manual responses, e.g. see Pashler, 1994). Considerably fewer studies involved cross-modal response demands, for example, concurrent manual and vocal action (e.g. Hazeltine, Ruthruff, & Remington, 2006), and only very little attention has been paid to the study of other response modalities (see Huestegge & Hazeltine, 2011, for a review). However, research findings from the last decades have accrued in favour of an ‘embodied cognition’ view (see Wilson, 2002, for a critical review), thus rendering it plausible to assume that peripheral bodily systems – that is the effectors in which actions are executed – and their characteristics play an important role for cognition.

The relative lack of empirical evidence for modality influences in dual-task control may be due to several reasons. In current dual-task frameworks, the specific response modalities in terms of *effector* *systems* in dual tasks are often regarded as irrelevant for central cognitive operations due to their peripheral nature (e.g. Meyer & Kieras, 1997a). Especially, eye movements in psychological sciences were studied more as an indicator of visual attention (i.e. as a precondition for perceptual processes) than in terms of an action modality of its own (i.e. as oculomotor responses). Particularly, this holds for studies that explicitly focused on the coordination of eye and hand movements in the context of reaching and grasping (e.g. Issen & Knill, 2012), where eye movements are supposed to provide visual feedback for optimised manual movement control (see Huestegge, 2011, for a review). It must be noted that situations typically researched in the field of eye-hand coordination should not be regarded as dual-task situations, since both actions are directed to a common goal, namely the object that is grasped, while for a dual task the targets of an eye and manual movement represent distinct entities. In addition, for a long time it has been assumed that saccades are special in that they are able to bypass any central response processing operations and thus are not subject to cross-response interference even when directed towards different objects (Bekkering, Adam, Kingma, Huson, & Whiting, 1994; Pashler, Carrier, & Hoffman, 1993). However, recent studies suggest that substantial interference can indeed occur when saccades need to be coordinated with concurrent response demands in other effector domains (e.g. in combination with manual or vocal responses, see Huestegge & Koch, 2009, 2010).

The role of eye movements in dual tasks is of particular interest, since we permanently move our eyes (intentionally) while performing an action in another effector system that is not associated in any manner with the particular eye movement, for instance when a car driver makes a saccade towards the navigation system while talking to the passenger about lunch. However, the underlying processing mechanisms of cross-modal response coordination involving oculomotor control have largely remained unclear. Thus, the present work especially addressed the role of oculomotor control in cross-modal action by studying the oculomotor effector system (i.e. saccades) in combination with other effector systems (i.e. manual and vocal responses).

1.2 Theoretical accounts of dual-task interference

In this section, I will outline frameworks accounting for dual-task interference based mainly on structural assumptions of the mental architecture (Section 1.2.1), or focussing on the task content (Section 1.2.2), or consisting of both of the former types (Section 1.2.3). Finally, in Section 1.2.4 I will discuss the current state of research regarding the specific role of task content for cross-modal action control.

1.2.1 Structural accounts of dual-task costs

Structural accounts of dual-task costs predominantly explain performance limits by referring to inevitable limitations based on the layout of the mental architecture.

In the last decades, one of the most prominent advocates of a structural account has been Pashler (1994), who explained dual-task costs by assuming a response selection bottleneck (RSB). According to RSB theory, cognitive information processing consists of three stages for each task, namely a perceptual stage, a central response selection (RS) stage, in which a response is selected in accordance with task rules, and a response execution stage. Crucially, RSB theory assumes that the central response selection stage can only be occupied by one task at a time (similar to a single CPU core in a computer), so that the second task needs to wait for clearance of the bottleneck. The RSB framework was mainly derived from experiments utilising the PRP procedure that typically yielded a PRP effect (see Figure 1.1A), that is a decrease of response times (RTs) for the second task with increasing SOA (e.g. De Jong, 1993; Kamienkowski, Pashler, Dehaene, & Sigman, 2011; Pashler, 1984; Pashler & Johnston, 1989; Ruthruff, Pashler, & Hazeltine, 2003b). The idea that the response selection stage constitutes the serial bottleneck instead of the stimulus or response processing stage stems from the *locus of slack* logic. According to this method, a prolongation of stage durations before or at the bottleneck stage in Task 1 yields additive effects for RT_2 because of a forward propagation of RT_1 effects onto RT_2. However, a prolongation of the stage duration before the bottleneck stage in Task 2 results in under-additive effects for RT_2. In this case, the prolongation of the pre-bottleneck stage is absorbed during the cognitive *slack* time imposed by Task 1 due to parallel processing of the pre-bottleneck stage of Task 2 and the bottleneck stage of Task 1. According to the same logic, varying the duration of the bottleneck stage in both tasks should yield additive effects for Task 2 performance. Thus, the observation of under-additive effects on RT_2 in the majority of dual-task studies that manipulated the stimulus identification stage of Task 2 (e.g. by degrading the stimulus quality) was regarded as strong evidence that response selection of two tasks cannot be processed in parallel whereas this is possible for other stages (e.g. Broadbent & Gregory, 1967; Duncan, 1980; Karlin & Kestenbaum, 1968; Smith, 1969, for examples of manipulations of response selection and stimulus identification; however, see review by Meyer & Kieras, 1997a, for a discussion on studies demonstrating bottlenecks at other stages of processing).

Due to its structural nature, the RSB account is essentially content-blind in that its predictions are solely derived from the chronology of the particular tasks. Due to the same reason, the RSB can also be regarded as *a-modal*, in that response characteristics such as response modalities are irrelevant for central processing, because they do not come into play until *after* central processing has occurred.

A competing structural explanation of dual-task interference refers to the notion of a limited single resource (Kahneman, 1973; Navon & Gopher, 1979). In contrast to bottleneck theory, where central processing is only available for one task at a time (i.e. serial central processing), the central resource (or capacity) can principally be accessed by two tasks in parallel. Typically, dual-task costs in resource theory are assumed to arise due to resource limitations, so that capacity needs to be shared between both tasks. This view was originally supported by empirical evidence showing that subjects are able to prioritise one task over another based on specific instructions (e.g. Norman & Bobrow, 1975). Importantly, the performance of one task could be improved in dual-task situations, but only at the cost of the concurrent task, demonstrating that there appears to be an upper limit for dual-task resources (which can be depicted by *performance operating characteristics (POC)* introduced by Norman & Bobrow, 1975, describing the function how resources are exchanged between two tasks; see also Navon & Gopher, 1979). The general idea of capacity sharing between tasks along with parallel central processing is still prevalent in recent theories of dual-task control (e.g. Navon & Miller, 2002; Tombu & Jolicœur, 2003). Notably, RSB accounts can be reconciled with single resource theory by conceptualising the former as an all-or-nothing variant of the latter. Note that the single resource account also proposes a structural limitation of cognition, and it is also content-blind in that performance costs solely depend on the proportional resource allocation between tasks.

Despite their overall success, some empirical observations posed serious challenges to structural accounts. For example, PRP studies showed that the interrelation between the specific response identities of the two tasks affects performance. For example, combining two ‘left’ (i.e. spatially compatible) responses across tasks yields better performance (even in the first task) than combining ‘left’ and ‘right’ (i.e. incompatible) responses (e.g. Ellenbogen & Meiran, 2010; Hommel, 1998a), suggesting that the specific content relation between responses (or between stimuli and responses) can play an important role. Similarly, single resource theory ran into difficulties explaining why, for example, it is harder to perform two tasks at the same time when both involve visual stimulus processing than when both involve different stimulus modalities (e.g. visual and auditory content; e.g. Wickens, 2008). Furthermore, it is easier to simultaneously perform a task with visual input and manual output (VM task) and a task with auditory input and vocal output (AV task) than to perform two tasks with reversed modality mappings (i.e. combining a VV task and an AM task; input-output modality compatibility effect; see Hazeltine et al., 2006; Stephan & Koch, 2010). Taken together, these observations clearly demonstrate that content matters in dual-task control.

1.2.2 Content-based accounts of dual-task costs

A direct successor to the single resource theory that was able to account for some of the modality effects referred to above was the multiple resource theory (Navon & Gopher, 1979; Wickens, 2002; see also Salvucci & Taatgen, 2008, for the assumption of multiple resources within a computational framework). By assuming separate limited resource pools for different input channels or different response modalities (i.e. effector systems), multiple resource models partially acknowledged the importance of the processed content and explained why tasks involving different modalities were easier to combine than tasks involving the same modality. However, multiple resource theory still does not explain two of the phenomena reported above, namely spatial compatibility effects across responses and input-output modality compatibility effects. For example, the manipulation of spatial response compatibility does not affect the structure of resource pools involved in a dual-task situation (since, e.g. both left and right manual key presses are instances of manual responses), but nevertheless yields substantial effects on performance (e.g. Hommel, 1998a). Finally, multiple resource models (along with the concept of resources in general) have been criticised with respect to the circular nature of defining resources and thus their explanatory value in general (e.g. Allport, 1987).

An important theoretical alternative explaining content-based interference in multitasking is the notion of information crosstalk. At this point, I will define crosstalk as the emergence of interference originating from the relatedness of the contents of two tasks or processing streams.

The term crosstalk was derived from engineering, where it usually describes undesired effects of a current-carrying conductor cable (e.g. a telephone wire) on signals of adjacent wires, eventually leading to signal degradation, and was originally introduced to the cognitive sciences by Kinsbourne (1981). Some years later, Navon and Miller (1987) studied crosstalk in terms of an outcome conflict (Navon, 1985) that may occur during the simultaneous processing of two tasks. Specifically, they hypothesised that the outcome of processing one task (or channel) can cause harmful side effects on processing the other task (or channel), based on the degree of semantic inter-relatedness of the tasks. While some researchers also referred to the term ‘crosstalk’ as an explanatory concept in single-task situations, for example, when a target stimulus contains distracting information or is accompanied by distractor stimuli (Stroop, 1935; Eriksen & Eriksen, 1974), or when stimulus features are in conflict with response demands (Simon, 1969; Proctor, 2011), I will focus here on crosstalk in dual-task situations involving two responses.

The classic three-stage model of crosstalk

In a seminal study, Navon and Miller (1987) combined two simultaneous search tasks, both involving visual input (words, letters, and digits) and two manual key press responses (one hand for each task). Participants indicated if a member of a specific item category was present or absent in each task in both single-task and dual-task conditions. Crucially, in dual-task conditions, the relation between responses associated with non-target words and the target category was manipulated within and across tasks (see also Hirst & Kalmar, 1987). As a result, Navon and Miller (1987) essentially proposed a three-stage model of crosstalk in order to explain effects that could not be accounted for by any type of resource theory. According to their model, crosstalk can occur on each stage of information processing, that is in the form of perceptual conflict, conflict on the S-R mapping level (also referred to as S-R translation), and cross-response conflict.

Perceptual conflict was evident in performance impairment when response-channel targets occurred in the other channel, whereas S-R mapping level conflict was reflected in adverse effects on performance when other-channel targets occurred in the response channel. Finally, they found that divergent (i.e. incompatible) response demands across tasks increased dual-task costs, and attributed these costs to cross-response conflict. Subsequent research on crosstalk in dual-task control can easily be classified within this three-stage model of crosstalk (Figure 1.2).

Some studies addressed the boundary conditions for the occurrence of perceptual crosstalk. For example, Logan and Schulkind (2000) found no evidence for crosstalk when two concurrent tasks involved different task sets, even though the stimulus category of the two tasks overlapped (i.e. both stimuli were digits). This finding implies that cross-stimulus relatedness per se is not sufficient for crosstalk phenomena to occur. On the other hand, Hommel (1998a) reported empirical evidence for crosstalk without any overlap in stimulus properties between tasks, suggesting that overlap on the perceptual stage is not necessary to produce crosstalk.

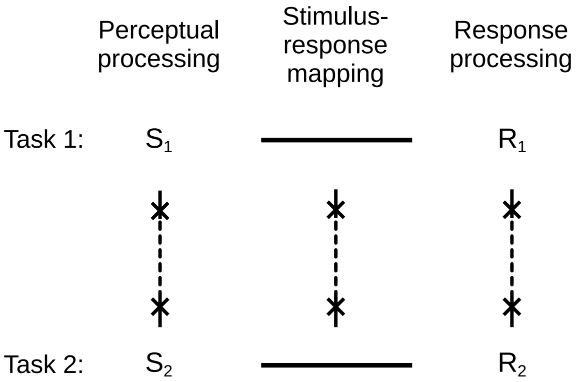


Figure 1.2. Schematic illustration of Navon & Miller's (1987) three-stage taxonomy of crosstalk. Crosstalk (represented by dotted lines) can occur at the level of perceptual processing, S-R mapping, and response processing.

Crosstalk on the level of S-R mappings was further studied under the name of 'category-based crosstalk' by Logan and Gordon (2001). In line with Navon and Miller (1987), they hypothesised that categorisations (i.e. the mapping of stimuli to the relevant response categories) of competing stimuli can affect processing of a currently prioritised stimulus. Another special case of crosstalk on the level of S-R mappings was proposed by Stephan and Koch (2010) in their explanation of the input-output modality compatibility effect (see end of previous Section). According to their view, crosstalk on the level of S-R mappings can also be based on modality aspects of S-R mappings (i.e. specific S-R modality pairings), instead of, for example, spatial characteristics.

However, most of the empirical research on crosstalk has focused on response-based conflict by utilising spatial response compatibility manipulations (see Lien & Proctor, 2002), for example, within the PRP paradigm (e.g. Duncan, 1979). Recent research yielded evidence for a phenomenon labelled 'backward crosstalk', a term referring to the finding that a content-related relationship between responses (i.e. response compatibility) of two overlapping tasks in the PRP paradigm was found to not only affect RT_2, but also RT_1 (e.g. Ellenbogen & Meiran, 2010; Hommel, 1998a; Hommel & Eglau, 2002; Janczyk, 2016; Janczyk, Pfister, Hommel, & Kunde, 2014; Logan & Delheimer, 2001; Logan & Schulkind, 2000; Miller, 2006; Miller & Alderton, 2006; Schubert, Fischer, & Stelzel, 2008; Thomson, Watter, & Finkelshtein, 2010). This finding is difficult to explain within a basic serial RSB model, which would only predict feed-forward effects on RT_2. Note that such response-related crosstalk can principally occur on both the S-R mapping stage (e.g.

Hommel & Eglau, 2002) and the response processing stage (e.g. Miller & Alderton, 2006). However, backward crosstalk can be incorporated within the RSB model with one additional assumption: If the central processing stage consisted of two substages, response activation and response selection, of which response selection still represented a serial bottleneck but response activation occurred in parallel, then crosstalk could arise during response activation, thus affecting also RT_1 (Hommel, 1998a; Schubert et al., 2008; Watter & Logan, 2006). In contrast to basic RSB models, such mutual cross-task interference can be explained within parallel processing accounts (e.g. Navon & Miller, 2002; Tombu & Jolicœur, 2003) without additional assumptions.

It is to note that crosstalk manipulations typically involve dual-task sets that share dimensional overlap (for a taxonomy of dimensional overlap, see Kornblum et al., 1990), in that both responses are related in terms of a relevant (e.g. spatial) dimension (e.g. left/right), so that an increase of dual-task costs for incompatible task demands compared to compatible task demands is regarded as an empirical marker for the occurrence of crosstalk. However, for example, Koch (2009; see also Koch & Rumiati, 2006) showed that dimensional overlap between response sets per se can give rise to dual-task costs even when responses are spatially compatible rather than when they are unrelated indicating that unrelated responses might facilitate performance. On the other hand, Huestegge, Pieczykolan, and Koch (2014) reported that unrelated responses yielded no facilitation for the faster response (i.e. R_1) and even performance costs for R_2 compared to related responses. Notably, these studies were comparably different in terms of their experimental procedure. Huestegge et al. (2014) utilised two speeded responses triggered by one common stimulus, which might have yielded response code priming in the case of compatible responses (see Fagot & Pashler, 1992). In the study by Koch (2009) the dual-task situation consisted of the presentation of two distinct stimuli and a delayed response (R_2) in one of the two tasks, thus inhibitory processes due to response delay might have played a role in processing tasks with dimensional overlap (Kleinsorge, 1999; Schuch & Koch, 2004). Therefore, results and interpretations of these studies might be difficult to compare directly. Until now, the role of dimensional overlap in dual-task control is under debate, and more empirical research is needed concerning this issue.

Regarding the extent of semantic relatedness necessary for the occurrence of crosstalk, Miller (2006) found that RTs in Task 1 were faster when there was an active response in Task 2 (i.e. a *go* task), than when Task 2 involved withholding a response (i.e. a *no-go* task), suggesting that crosstalk might have bearing also on abstract task representations than only on specific task features that characterise the task content. Occasionally, the term crosstalk has also been used to describe interference in terms of the ‘transmission of noise rather than of specific stimulus or response features’ (Hazeltine et al., 2006, p. 338). However, for the sake of conceptual cleanliness, I will here use a more strict definition of crosstalk as content-based interference.

Lack of theoretical development of crosstalk

Interestingly, while current multitasking researchers agree that crosstalk is an important and irreducible explanatory concept along with bottlenecks, capacity/resource sharing (e.g. see Feng, Schwemmer, Gershman, & Cohen, 2014; Logan & Gordon, 2001; Navon & Miller, 2002; Pashler, 1994; Tombu & Jolicœur, 2003), empirical research on crosstalk has been surprisingly scarce, and the theoretical concept has essentially remained unchanged and relatively vague almost 30 years after Navon and Miller (1987). According to a literature survey covering the last 30 years (using the *Web Of Knowledge* database), 15 journal articles (six of those in the last five years) on dual-task research in the field of cognitive psychology contained the term ‘crosstalk’ in their title (‘resource’: 30 x, ‘bottleneck’: 58 x), which clearly calls for more empirical and theoretical attention.

1.2.3 Composite accounts of dual-task control

It is important to note that each of the theoretical frameworks outlined above is based on a single specific underlying mechanism, in that dual-task interference is assumed to originate either from a bottleneck, or from sharing of a limited capacity, or from crosstalk. However, in the literature it has been suggested that human processing might rely on more than just one single principle.

A prominent example is the attempt to preserve the idea of a serial response selection bottleneck while integrating the possibility for the occurrence of crosstalk during response activation (see previous Section on content-based accounts). This resulted in the proposition of a *hybrid* processing account that integrates both serial and parallel processing (e.g. Hommel, 1998a; Schubert et al., 2008; Watter & Logan, 2006). Another proposition – following the idea of a flexible task-specific processing – comes from Logan and Gordon (2001), who suggested that serial processing might represent a strategy that is explicitly employed when parallel processing is not efficient enough (e.g. during the problem of binding the correct responses to the respective stimuli, i.e. the *dual-task binding problem*). Hence, serial processing would be the result of the endeavour to avoid crosstalk (Lehle & Hübner, 2009; Paucke, Oppermann, Koch, & Jescheniak, 2015), but not the result of a generic ‘hard-wired’ bottleneck. In line with strategy-based processing modes, Meyer and Kieras

(1997a, 1997b) proposed a framework that in general assumes serial processing because of the same reasons, that is to avoid conflict between tasks. However, Meyer and Kieras (1997a) specified this mechanism by assuming that a supervising executive process strategically defers the execution of the response in Task 2 although it was selected during the processing of Task 1 to ensure that Task 1 received sufficient processing priorities.

Finally, it has been suggested that bottlenecks might not (only) occur at the response selection but also at response execution stage (e.g. Bratzke, Rolke, & Ulrich, 2009; De Jong, 1993; Sommer, Leuthold, & Schubert, 2001; Ulrich et al., 2006). However, the nature of these account is still based on the assumption of generic serial processing within the respective stages.

1.2.4 Crosstalk in cross-modal action: Evidence against encapsulation of effector sytems

As outlined in the previous section, it appears that the notion of crosstalk is especially qualified for explaining modality influences in dual-response processing. From another point of view, utilising cross-modal response demands is especially suited in order to study crosstalk.

Basically, the concept of crosstalk is equivalent to the idea that task processing does not occur in an encapsulated manner (Huestegge et al., 2014). This means that whenever a manipulation in a Task A not only affects the task itself, but also a concurrent Task B, Task B is not immune to interference from other concurrent action demands. Thus, Task B processing is not encapsulated or shielded from crosstalk by Task A (for further details on the idea of task shielding in dual tasks see Fischer, Gottschalk, & Dreisbach, 2014). For example, regarding the question of the encapsulation of effector system representations during cross-modal action, Huestegge et al. (2014) studied if the oculomotor and the vocal system represent encapsulated cognitive modules, and thus are not prone to the occurrence of crosstalk. This effector system combination is particularly interesting, since oculomotor and vocal responses are distinct in terms of physiological properties in that they are controlled by different brain areas (Horn & Leigh, 2011; Simonyan & Horwitz, 2011) and consist of non overlapping motor actions (ocular movements and movements of the vocal tract). However, it was found that oculomotor and vocal responses were not shielded against each other in that both exhibited dual-response costs. Interestingly, this was not even the case when responses did not share any *dimensional overlap* in terms of response content (e.g. looking to the *left* while uttering ‘*Maus*’, i.e. German for mouse).

In line with this idea, results by Huestegge and Koch (2009) can be interpreted as evidence against the encapsulation of the oculomotor and the manual effector system. More specifically, they conducted a series of four experiments involving saccades and manual responses in a single-onset paradigm with the focus on examining response-based crosstalk with dimensional overlap. Utilising a single auditory stimulus presented to the left or right ear, they avoided unbalanced S-R pairings across responses (see Hazeltine et al., 2006), in that the stimulus required a translation of the spatial dimension of the tone (left/right) into a saccade to a left or right target on the monitor as well as the translation into a manual key press with the left or right index finger. Interestingly, in their first experiment under compatible S-R mapping conditions for both responses they found dual-response costs for manual responses, suggesting that saccades are not bypassing central processing as previously assumed, but indeed interfere with the concurrent processing of another response (see Section 1.1.2). Crucially, across three experiments the type of response code conflict was varied in order to determine the specific source of response-based crosstalk.

In their second experiment, they introduced a stimulus-effector incompatibility into the manual response by having participants cross their hands with the requirement of responding to a left tone with the right index finger, which was associated with the left key. Meanwhile, the saccades remained S-R compatible. This configuration led to an incompatibility between effector-based response codes of the manual response and the spatial response codes of the saccade response while spatial (i.e. location-based) response codes still remained compatible between responses. In a third experiment, the crossed-hands manipulation was introduced again but this time participants were required to respond with the effector that spatially corresponded to the location of the stimulus in the manual response (S-R location incompatibility) which led to incompatible spatial response codes between response locations across effectors. The observation that in these two experiments saccades, which were always executed prior to the manual response, also exhibited dual-response costs provides evidence for backward crosstalk and demonstrates that both responses were processed (at least partially) in parallel. A comparison across the first two experiments revealed that the stimulus-effector incompatibility alone had a rather small influence compared to the compatible S-R mapping setting. Interestingly, the introduction of an incompatibility between the response locations across responses (i.e. a saccade to the left target and pressing the key on the right) significantly increased dual-response cost for both responses, suggesting that confusability of response (location) codes instead of effector-based codes was mainly responsible for between-response crosstalk.

Furthermore, the amount of dual-response costs for saccades despite being always S-R compatible was dependent on the compatibility manipulation in the manual response, yielding further evidence against separated encapsulated processing. When finally introducing an incompatible S-R mapping for both responses while maintaining R-R compatibility (i.e. a tone on the left required a saccade to the right target and a key press on the right), dual-response costs decreased again, thus corroborating the previous assumption that incompatible response location codes are the driving force behind response-based crosstalk and led to confusion during the mapping of spatial codes to response modality codes.

In a subsequent work Huestegge and Koch (2010) aimed at specifying the mechanisms of response-related crosstalk with respect to the influence of temporal response distance. Again utilising saccades and manual responses in a single stimulus setup, they contrasted the dual-response costs in a condition with S-R compatible saccades and S-R incompatible manual responses to the dual-response costs in a condition with S-R incompatible saccades and S-R compatible manual responses. Interestingly, while in the former condition responses were executed with a larger response distance than in the latter, overall dual-response costs remained unchanged. This result suggests that the crosstalk that emerged in the presence of response conflict (i.e. R-R incompatibility) in both conditions is independent of the temporal response distance, and Huestegge and Koch (2010) proposed that responses are not selected in two separate response selection processes for each response but in a conjoint *mapping selection* in which response codes (i.e. spatial codes and modality codes) need to be bound together based on task instructions (see Figure 1.3). Specifically, they formulated a framework of cross-modal action control in which crosstalk is assumed to be the result of competing mapping selections, in that the mapping in the current trial competes with persisting activation of an alternative mapping from a previous trial. Interestingly, the assumption of competing mapping selections between successive trials still awaits empirical testing.

Another recent study by Huestegge and Koch (2013) can also be interpreted as evidence against encapsulation, and, in particular, it demonstrates the context specificity of crosstalk between two responses. In this study, they examined pairwise (S-R and R-R compatible) combinations of oculomotor, manual and vocal response modalities triggered by a common auditory stimulus. Not only that they found dual-response costs for any combination of response modalities despite compatible response demands, but they also observed that the amount of dual-response costs varied between modalities (cost asymmetry). Most interestingly, dual-response costs for the same, that is

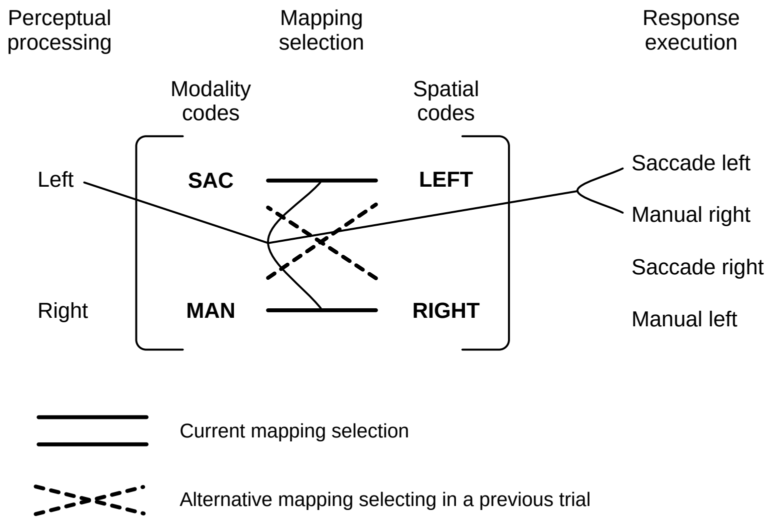


Figure 1.3. A framework of crosstalk in cross-modal action according to Huestegge and Koch (2010). Crosstalk in a current trial is the result of competition between the current mapping selection and alternative mapping selection from previous trials. Mapping selection is assumed to be a conjoint process of binding spatial codes to modality codes.

vocal, response were larger in the context of oculomotor responses than in the context of manual responses. This suggests that the extent of susceptibility for crosstalk for a specific effector system is dependent on the particular context effector system. Likewise, one could say that a specific effector system exhibits a certain extent of permeability for crosstalk on the context effector system dependent on the identity of the context effector system. According to Huestegge and Koch (2013), the cost asymmetry represents evidence for a processing hierarchy based on a (top-down) effector system weighting, in that oculomotor responses are prioritised over vocal responses, and vocal responses over manual responses (according to the relative amount of dual-response costs). While this pattern was obtained under spatially compatible response demands, it is still unclear how the processing hierarchy would be affected if a conflict between responses had to be resolved (as in Huestegge & Koch, 2010). According to the framework outline above (Huestegge & Koch, 2010), crosstalk should affect both responses more or less evenly in terms of dual-response costs relative to the level of prioritisation based on effector system weighting, since the mapping selection occurs conjointly with no bias towards one effector system. While this prediction indeed could be verified for oculomotor and manual responses (Huestegge & Koch, 2010) – the combination that exhibits the largest prioritisation gradient – it is still to show if this also holds for other response modality combinations.

1.3 Overview of the present work: Open research questions and summaries of the present studies

In the previous sections, certain open questions regarding cross-modal dual-action control became apparent and will thus be addressed in four individual studies (A, B, C, and D), each in one chapter, based on eight experiments in total. Three of those experiments provided two distinct variable sets regarding different theoretical questions, which were addressed in two separate studies. In this section, I will briefly present the main questions underlying each study, while the following sections comprise summaries of each individual study.

Despite a growing body of evidence in favour of content-based interference mechanisms, the theoretical notion of crosstalk is still underdeveloped. This problem is particularly relevant, since influences due to the usage of specific response modalities (i.e. task content) can be well explained within crosstalk-related frameworks (e.g. as proposed by Huestegge & Koch, 2010). In this framework, it is assumed that response-based crosstalk emerges during the mapping of modalities to response features (e.g. spatial dimension) and that during these mappings conflict arises either within the demands of a current response, but – more importantly – also between the demands of the current and previous or future response. In Study A of the present work, I will address the question of contextual interference in cross-modal action.

A further question that shall be addressed in the present work is the extent of generalisability of the previous results regarding the role of crosstalk in cross-modal task demands. Although it was shown that oculomotor and manual responses are subject to dual-response costs that are dependent on the between-task compatibility, it might be that this was the result of the specific paradigm utilised in these studies. The fact that both responses were always triggered by a common stimulus might have enforced a single conjoint response selection thus eliminating any possibility for structural interference stemming from a bottleneck. Therefore, in order to establish a data base that is comparable to previous dual-task studies, it is necessary to examine oculomotor and manual responses in a more conventional dual-task paradigm, that is the PRP paradigm, in which both responses are triggered by distinct respective stimuli. If crosstalk plays a crucial role in cross-modal action control, this should become evident irrespective of the particular paradigm utilised, and, in the case of the PRP paradigm, in the form of backward crosstalk effects on Task 1. This question will be addressed in Study B.

Study C will follow up on the idea of generalisability based on the concern of the reproducibility of previous results with other combinations of effector systems, since previous results were obtained employing solely the combination of the oculomotor and manual effector system. In particular, this issue will be tied in with the question raised in the previous section of how the processing hierarchy between effector systems is affected during conflicting response demands within a trial. Note that the chapter reporting Study C represents a modified version of a previously published work (Pieczykolan & Huestegge, 2014).

Finally, in Study D I will address a relatively novel research line in dual-task control, which has received very little attention to date, namely the mechanisms of temporal response order scheduling. While the PRP paradigm allows for assessing the temporal evolvement of dual-task interference by varying the temporal task overlap utilising different stimulus onset asynchronies, any interpretation of such interference effects is based on the premise that tasks are processed in the order in which their corresponding stimuli are presented. However, there have been indications that for the combination of the oculomotor and manual effector system this is not necessarily the case. Specifically, it was observed that oculomotor responses are temporally prioritised in that they are executed first although the respective stimulus was presented second (Pashler et al., 1993). However, this study was not aimed particularly at studying response order control in (cross-modal) dual tasks. Therefore, we systematically examined mechanisms determining temporal response order scheduling in the PRP paradigm for oculomotor and manual responses. Importantly, we included between-task crosstalk as a potential factor because it is known to cause backward crosstalk effects on Task 1 performance. A compatibility effect would suggest that task content is processed prior to the determination of response order, and thus would be informative regarding (temporal) processing dynamics in general.

Importantly, these four studies (or chapters) can be read in any order, because the relevant theoretical background will be covered in each chapter. The remainder of the present section contains a summary for each of the four studies including a brief overview of the hypotheses, methods, and results. Therefore, in the General Discussion – instead of giving summaries of the individual studies – I will sum up the theoretical contribution of the present work and discuss the interrelation among the present studies as well as the theoretical progress within theories on multiple-action control. Finally, I will discuss some issues which emerged during the present studies, that could be addressed in future work.

1.3.1 Summary of Study A: Interference in Cross-Modal Action – Response Selection, Crosstalk, and General Dual-Execution Costs

Synopsis: In Study A, cross-modal response compounds based on a single stimulus were studied with respect to the interplay of the number of response alternatives and between-response compatibility (i.e. crosstalk potential). In sum, this study shows that crosstalk can be dissociated into a component that determines the amount of current conflict (i.e. *online crosstalk*) and a memory-based component that originates from residual activation of previous action demands (*retrospective crosstalk*) and from the preparation for future demands (*prospective crosstalk*).

Content: Performing several actions simultaneously usually yields interference phenomena, which are commonly explained by referring to theoretical concepts such as structural limitations associated with action selection or crosstalk based on task content. In this context, temporal task structure has always been a main focus of interest in many research paradigms. For example, temporal task overlap is manipulated in the PRP paradigm, and inter-response intervals are analysed in various dual-task paradigms (e.g. Ulrich & Miller, 2008). On the other hand, however, corresponding theoretical frameworks usually focus on explaining interference within individual experimental trials, while largely neglecting contextual effects (i.e. between trials, see Fischer, Plessow, Kunde, & Kiesel, 2010; Jentzsch & Leuthold, 2005, for rare examples regarding this question). Since a substantial body of literature on another instance of multitasking (i.e. task switching, see introductory section on multitasking) suggests that performance in a current task or trial is strongly affected by characteristics of the previous task or trial (Allport et al., 1994; Rogers & Monsell, 1995; Kiesel et al., 2010), an studying the effects of sequential modulation in dual-task settings appears quite promising. However, up to now there has been no systematic research on the interaction of within-trial and between-trial conflict. While most corresponding research focuses on dual-task scenarios involving two independent tasks, in Study A we examined the role of response selection for the control of cross-modal response compounds (saccades and manual responses) triggered by one single stimulus.

In Experiments 1A and 1B, we studied single- and dual-response performance for spatially compatible and incompatible responses (within-trial crosstalk manipulation) in conditions with or without response selection requirements (i.e. responses either changed randomly between trials or were constantly repeated within a block). Experiment 2 further explored trial-by-trial processing dynamics by manipulating the number of response (compound) repetitions in a row (run length effects). The results showed that response-based crosstalk effects increased when response compound selection demands were present, suggesting that response-based crosstalk mainly operates at the selection stage. Trial-by-trial analyses regarding context effects revealed evidence for competition between representations of action demands in terms of interference between current, previous, and expected response requirements. Additionally, even when neither incompatibility nor response selection requirements were present we still observed substantial residual dual-execution costs.

1.3.2 Summary of Study B:

Oculomotor Control and Dual-Task Interference – Evidence from the PRP paradigm

Synopsis: Study B provided first evidence that oculomotor responses are subject to interference based on both structural and content-based origins. An overlapping tasks paradigm utilising oculomotor and manual responses was employed, in which the onsets between two stimuli were varied. Evidence for both serial and parallel processing of the two tasks was found. The results further indicated that participants shifted between these processing modes based on between-task compatibility, i.e. to more parallel processing during compatible task demands and to more serial processing during incompatible task demands.

Content: For a long time the oculomotor system has been regarded as a special case in multiple-action control because the first dual-task study that has investigated saccades in dual tasks (Pashler et al., 1993) concluded that the oculomotor system is special in that it does not occupy central processing resources in the same way as other effector systems do. While this previous study was solely discussed on the basis of a basic response selection bottleneck (RSB) account, the present study reconsidered this issue by discussing dual-task interference between concurrent oculomotor and manual responses on the background of other current explanatory frameworks, such as capacity sharing (as an alternative to the RSB allowing for parallel processing) and crosstalk (content-based interference).

In three PRP experiments, participants performed a saccade to a left or right target and a manual left or right key press in response to two respective auditory stimuli with a variable SOA, thus allowing for an examination of between-task compatibility effects based on crosstalk. Two experiments involved a variable task order under unrestricted instructions (Experiment 1) and explicit instructions to respond according to stimulus order (Experiment 2). By utilising both task orders, we studied oculomotor control in an active role (as Task 1) and in a passive role (as Task 2), hence extending the study by Pashler et al. (1993). In Experiment 3, the stimulus for the manual task was always presented prior to the stimulus for the oculomotor task (fixed task order) under unrestricted instructions. We found PRP effects for (both the oculomotor and manual) Task 2 in both task orders suggesting that oculomotor processing is not an exception to typical dual-task interference mechanisms. Additionally we observed interference for Task 1, which can be explained by considering the possibility of parallel processing. Importantly, the present study demonstrates that processing modes during oculomotor control can be flexibly adjusted by shifting between more serial and more parallel processing, depending on the amount of potential crosstalk and the predictability of task order, while instructions regarding response order do not play a major role for the choice of the particular processing mode.

1.3.3 Summary of Study C: Oculomotor Dominance in Multitasking – Mechanisms of Conflict Resolution in Cross-Modal Action

Synopsis: Study C examined processing priorities among effector systems and demonstrated that the previously reported prioritisation scheme, in which the oculomotor system is prioritised over the vocal and manual effector system, can be replicated, but is also adjusted in its strength by the presence of response conflict. Specifically, processing priorities were shifted towards the response that already is involved in conflict resolution (in terms of stimulus-response compatibility), suggesting that processing priorities can be flexibly adapted to particular task demands.

Content: In daily life, eye movement control usually occurs in the context of concurrent action demands in other effector domains. However, little research has focused on understanding how such cross-modal action demands are coordinated, especially when conflicting information needs to be processed conjunctly in different action modalities.

In two experiments, we address this issue by studying vocal responses in the context of spatially conflicting eye movements (Experiment 1) and in the context of spatially conflicting manual actions (Experiment 2, under controlled eye fixation conditions). Importantly, response conflict was achieved by introducing a spatially compatible S-R mapping for one response and a spatially incompatible S-R mapping for the context response in one group while introducing reversed S-R mappings in a second group. While maintaining comparable between-response conflict in each mapping group (i.e. responses were incompatible to each other), this manipulation simultaneously caused a variation of the temporal response distance. Crucially, a comparison across experiments allows us to assess resource scheduling priorities among the three effector systems by comparing the same (vocal) response demands in the context of eye movements in contrast to manual responses. The results indicate that in situations involving response conflict, eye movements are prioritised over concurrent action demands in another effector systems. This oculomotor dominance effect corroborates previous observations in the context of multiple-action demands without spatial response conflict. Furthermore, and in line with recent theoretical accounts of parallel multiple-action control, resource scheduling patterns appear to be flexibly adjustable based on the temporal proximity of the two actions that need to be performed with the tendency to prioritise the more difficult action, that is the response in which an S-R mapping conflict needs to be already resolved.

1.3.4 Summary of Study D: Action Scheduling in Multitasking – A Multi-Phase Framework of Response Order Control

Synopsis: Study D addressed response order control in dual tasks, an issue that has been widely neglected in previous research. In a comprehensive study including several factors that are known to be relevant for dual-task interference mechanisms, it was shown that the final response order in a given trial is the result of a continuous adjustment process based on the interplay of several top-down factors, such as the anticipation of response characteristics, and bottom-up factors, such as stimulus order and between-task compatibility. Based on the present findings, a multi-phase framework of temporal response order control is proposed.

Content: Temporal organisation of human behaviour is particularly important when several action requirements must be processed around the same time. A crucial challenge in such multitasking situations is to control temporal response order. However, multitasking studies usually focus on temporal processing dynamics after a specific response order – which is usually triggered by stimulus sequence and instructions – has been determined, whereas a comprehensive study of response order scheduling mechanisms is still lacking.

Across three psychological refractory period (PRP) experiments, we examined the impact of response characteristics, stimulus order, temporal stimulus distance, between-task compatibility, instructions, and predictability of stimulus order on response order decisions. Crucially, we utilised a combination of effector systems (oculomotor and manual) that is known to ensure reasonable response order variability in the first place. Note that this study and Study B are based on the same data set, however, both address distinct underlying theoretical concepts and report results based on different dependent variables. Therefore, they are reported in two separate studies. While in Study B, interference effects on RTs and errors for each response modality dependent on a certain response order were analysed, in Study D we focused on the amount of reversed responses regarding the question of temporal response order control. The results suggest that – contrary to previous assumptions – bottom-up factors alone (e.g. stimulus order) are not necessarily the primary determinant of temporal action scheduling. Instead, we found a major influence of effector-based characteristics (i.e. oculomotor task prioritisation) which could be attenuated by both instructions and changes of the task environment (providing temporally predictable input). Importantly, substantial effects of between-task compatibility suggest that a dedicated stimulus code comparison precedes (and affects) response order decisions. Based on the present results and previous findings, we propose a multi-phase framework of temporal response order control which emphasises the extent to which cognitive control of action scheduling is dynamically adaptive to particular task characteristics.

2 | Study A

Interference in Cross-Modal Action – Response Selection, Crosstalk, and General Dual-Execution Costs

2.1 Introduction

While the cognitive approach to the study of human behaviour is typically characterised by controlled experiments involving basic, isolated actions such as manual key press responses (see Baumeister, Vohs, & Funder, 2007), actual human behaviour is more complex in that it usually involves multiple actions at a time – often across several effector systems. Usually, the execution of multiple (vs. single, isolated) actions is associated with performance costs in terms of increased response times (RTs) and error rates. Such costs are mostly studied in the context of dual-task research, where two responses are required that each are part of a distinct task. Thus, each response is triggered by a separate stimulus (or discernible stimulus dimension), and correct performance can only be achieved by attending to both stimuli and by applying the stimulus-response (S-R) translation rules associated with each task (e.g. Pashler, 1994). However, multiple-action control can also be studied in a situation where one single stimulus (aspect) defines two responses (single onset paradigm) – a situation that has been described as rather resembling a single-task situation requiring response compounds (Fagot & Pashler, 1992). With the present study we intend to add to this underrepresented line of research by studying the simultaneous execution of manual and oculomotor actions with the aim to shed more light on basic mechanisms underlying the control of cross-modal response compounds. Specifically, we focus on the role of two well-known sources of interference in action control, namely response selection and crosstalk.

The concept of *response selection* can be traced back to a pioneer of the study of ‘mental mechanics’, F. C. Donders (1969), and was initially developed in the context of single-task processing. The crucial assumption is that whenever more than one response is task-relevant, a time-consuming decision process becomes necessary to select the appropriate response (among alternatives) based on stimulus-response (S-R) rules, eventually prolonging the overall response time (RT). Note that this idea of response selection as a time-consuming mental processing stage is essentially a structural account and does not inherently depend on the particular task content (e.g. the specific response characteristics) that needs to be processed. Long after Donders (1969), the notion of response selection was revitalised by Pashler (1994), who suggested that this particular mental process (unlike other mental processes such as stimulus identification or response execution) cannot occur for two tasks at the same time (i.e. two response selection processes must be carried out serially), thus constituting a central limitation of the human mind.

In contrast to this content-blind, structural account of action control, the concept of *crosstalk* has been proposed in order to account for interference effects that are specifically related to the task content. While the term ‘crosstalk’ has infrequently been utilised to explain interference effects in single tasks (e.g. in the Stroop paradigm, see Eidels, Townsend, & Algom, 2010), it is more commonly referred to in dual-task research (Navon & Miller, 1987; Miller, 2006). After being introduced to the cognitive sciences by Kinsbourne (1981), Navon and Miller (1987) studied crosstalk in terms of outcome conflicts in dual-task processing (see also Navon, 1985). Specifically, they investigated how processing in one task affect the other task during parallel processing, based on the degree of semantic inter-relatedness of the tasks. For example, combining two ‘left’ (i.e. spatially compatible) responses across tasks typically yields better performance (in both tasks) than combining incompatible ‘left’ and ‘right’ responses (e.g. Hommel, 1998a), a finding that was explained in terms of beneficial (Koch & Prinz, 2002) or adverse (Hommel, 1998a) crosstalk effects. Thus, the semantic interrelation of *task content* (in terms of cognitive codes or representations) can be an important source of interference in action control in addition to response selection.

Differential effects of both sources of interference (i.e. response selection and crosstalk) were mainly demonstrated in the field of dual-task research, mostly within the psychological refractory period (PRP) paradigm (Lien & Proctor, 2002; Duncan, 1979). Although our present study does not involve such a typical dual-task setup (because we are focussing on dual-response compounds triggered by a single stimulus), we will briefly summarise relevant results and theoretical implications. The PRP paradigm was designed to vary the temporal overlap between two tasks by manipulating the stimulus onset asynchrony (SOA) and has been used to show that the response selection stages of two tasks cannot occur at the same time (Pashler, 1994). On the other hand, the PRP paradigm has also been utilised to study crosstalk effects by manipulating between-task compatibility. A typical result is that spatial incompatibility between (manual and vocal, or two manual) responses causes increased RTs not only in the second, but also in the first of the two overlapping tasks – a phenomenon usually referred to as *backward crosstalk* (e.g. Ellenbogen & Meiran, 2010; Hommel, 1998a; Janczyk, Pfister, Hommel, & Kunde, 2014; Logan & Schulkind, 2000; Miller, 2006; Miller & Alderton, 2006). Note that these previous studies examined crosstalk in the presence of two (potentially) conflicting response selection processes, since one of several response alternatives needed to be selected in each of the two tasks. Here, we manipulated crosstalk (in terms of spatial response compatibility) within cross-modal response compounds triggered by a single stimulus, which allows us to investigate corresponding crosstalk effects in the presence and absence of response (compound) selection. With such a manipulation we are able to assess the extent to which crosstalk affects action control in the absence of selection requirements.

Few previous studies addressed the issue of response compound control within the single onset paradigm. For example, Holender (1980) asked participants to respond to visual letters with either a button press response, a vocal naming response, or both. A comparison of single- and dual-response times revealed dual-response costs for vocal responses, but not for manual responses. This result pattern has been replicated by Fagot and Pashler (1992), who additionally manipulated S-R compatibility of the manual response across several experiments. Based on their pattern of results, they concluded that the single onset paradigm yields a single compound response selection process underlying the execution of both responses. Note that these previous studies did neither manipulate response-response compatibility to study cross-response crosstalk, nor did they study performance in the absence of response selection requirements.

The issue of cross-response crosstalk in the single onset paradigm was investigated by Huestegge and Koch in previous research (2009, 2010). Participants had to respond to auditory stimuli with spatially compatible or incompatible oculomotor and manual responses. For example, participants in one block in the incompatible condition were instructed to respond to a left auditory stimulus with a left saccade and a right key press, and to a right auditory stimulus with a right saccade and a left key press (or vice versa). Thus, a block of trials involved a random alternation of two stimuli, each indicating a predefined response compound. The results suggested evidence for cross-response crosstalk in this paradigm. Specifically, dual-response costs increased (across both effector systems) when responses were spatially incompatible (vs. compatible) to each other. However, based on these results we cannot finally determine whether these cross-response crosstalk effects occur on the level of response (compound) selection, or response execution. Furthermore, it is still unclear whether the observed dual-response costs would still emerge in the absence of both response selection demands and conflict based on spatially incompatible responses. In the present study, we followed up on a research tradition in our lab (see Huestegge, 2011, for a review) by having participants respond to lateralised auditory stimuli to the left or right ear with either a saccade (to the left or right), or a manual key press (operated by the left vs. right index finger), or both. Recent theoretical development in the field of embodied cognition suggests that cognition is less abstract (i.e. less independent from the associated input and output systems) than previously believed (e.g. Fodor, 1983), and that peripheral bodily systems and their characteristics essentially determine cognition (see Wilson, 2002, for a critical review). As a response to these insights, researchers started to focus on the underlying mechanisms of cross-modal action control, that is the control of simultaneous actions across different response modalities. Given that the focus of the present study is on the presence/absence of response selection requirements, we considered it especially informative to focus on compounds of manual and oculomotor responses. Specifically, while manual response control is known to be quite sensitive to response selection demands (Hick, 1952), saccades are reported to be much less sensitive in this regard (e.g. Kveraga, Boucher, & Hughes, 2002). Furthermore, this effector combination is especially suited to study spatial crosstalk effects because both responses are inherently spatial at the fundamental motor level (e.g. unlike vocal utterances such as ‘left’ and ‘right’).

Response selection was manipulated by introducing two conditions. In one condition, we minimised selection demands by requiring participants to perform the same response (or response compound) throughout a block of trials (similar to a simple RT task without response selection requirements), whereas in the other condition the specific response (compound) varied randomly from trial to trial (analogous to a two-choice RT task involving response selection). Note that the manipulation of the presence or absence of response selection has not yet been examined for cross-modal response compound demands.

Crosstalk was manipulated in a standard way (see above) by requiring participants to either respond with spatially compatible responses (e.g. combining a left saccade with a left manual response) or with spatially incompatible responses (e.g. combining a left saccade with a right manual response). In line with previous studies, we interpret differences in dual-response costs between compatible and incompatible conditions as evidence for dual-response interference based on crosstalk. While in Experiment 1A, response-response (R-R) incompatibility was operationalised by combining S-R compatible saccades with S-R incompatible manual responses, Experiment 1B served as a control condition involving the reversed mapping (i.e. S-R incompatible saccades combined with S-R compatible manual responses).

Importantly, in the present research design – unlike previous studies (e.g. Fagot & Pashler, 1992; Holender, 1980; Huestegge & Koch, 2009, 2013) – we introduced a crucial novel condition, namely the execution of response compounds without the necessity for response selection. Thus – unlike numerous previous studies on crosstalk – we are able to examine the role of between-response crosstalk in the *absence* of any within-task response selection processes, and hence whether cross-response crosstalk in cross-modal response compounds operates mainly on the level of response selection or response execution. Finally, the design allows us to test whether dual-response costs still occur under conditions without any response selection requirements and without adverse effects of crosstalk (i.e. mere dual-execution costs on the stage of response execution).

The response selection absence condition differs from the presence condition in terms of the content of the surrounding trials (i.e. the context): Specifically, in response selection presence conditions participants need to be prepared for two potential response alternatives throughout a block of trials. Response requirements in a given trial will thus be preceded either by the same or by the alternative response (compound), allowing for trial-by-trial analyses to get a more fine-grained picture of the underlying interference mechanisms. Specifically, we test whether the execution of a different (vs. same) response compound in the previous trial affects performance in a current trial (we will refer to this as retrospective interference), and whether repeating the same response compound in the context of uncertainty (mixed blocks) differs from performance in response selection absence blocks (as a marker of preparatory processes, which we refer to as prospective interference). Based on the results from Experiment 1, Experiment 2 systematically further explored trial-by-trial effects associated with response (compound) selection by examining performance as a function of response run length (i.e. as a function of the number of consecutive trials requiring the same response).

2.2 Experiment 1A

2.2.1 Method

Participants

Forty-eight participants with normal or corrected-to-normal vision were randomly assigned to two compatibility (spatially compatible/incompatible) groups (17 women and 7 men in each group). The mean age was 23 years (*SD* = 3.7, range = 19–36). They gave informed consent and received course credits or monetary reimbursement for participation.

Stimuli and Apparatus

Participants were seated 65 cm in front of a 21 inch cathode ray tube (temporal resolution: 100 Hz; spatial resolution: 1024 px × 768 px) with a keyboard in front of them. Saccades were registered using a head-mounted Eyelink II infrared reflection system (SR Research, Osgoode, Ontario, Canada) by measuring the position of the right pupil with a temporal resolution of 500 Hz (Eyelink II *pupil only mode*)[1]. We used the SR Research Experiment Builder software (SR Research, Osgoode, Ontario, Canada) for programming and analysing purposes. A chin rest was installed to minimise head movements.

A green fixation cross was presented at the centre of a black screen. Two green rectangular squares (8.3° to the left and right of the fixation cross) served as saccade targets and remained present throughout. The size of the fixation cross and the saccade targets was 0.33° each. On the keyboard, two keys (*left Ctrl* and *right arrow*) were chosen from the bottom key row as response keys. Participants responded with their left and right index fingers. Thus – unlike in research on eye-hand coordination – both types of movements (saccades and manual responses) did not share a common target. The imperative auditory stimulus consisted of an easily audible 1000 Hz pure tone (with a duration of 50 ms) that was presented to the left or right ear via supra-aural headphones.

Procedure

In each trial, participants responded to the unilateral (left or right) auditory stimulus. Participants in the *compatible responses group* were instructed to respond by pressing the spatially compatible

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[1] In the present work, these settings apply to any setup in which the Eyelink II system was utilised. Saccade latencies (regardless of the eye tracking system) were defined as the interval between stimulus onset and the initiation of the saccade utilising the Eyelink's build-in saccade parser (velocity threshold = 30°; acceleration threshold = $8000°s^{-2}$).

key (manual response in single-response blocks), by moving their gaze to the spatially compatible square on the screen (saccade response in single-response blocks), or both (dual-response blocks). They were instructed to respond as fast and accurately as possible. The *incompatible responses group* received the same instructions for the saccades, whereas manual responses had to be executed spatially incompatible to the stimulus (e.g. a left tone was mapped to a right key press; see Huestegge & Koch, 2010, for a similar manipulation) to elicit adverse crosstalk effects. While in *response selection presence* conditions stimuli were randomly presented to the left vs. right ear (two-alternative forced choice blocks), the *response selection absence* conditions involved the presentation of the same stimulus throughout a block of trials (similar to a simple-RT task), resulting in response (compound) repetitions only. Note that the two response selection conditions differ with respect to both the number of response demands and the number of stimuli (e.g. it would also be possible to use two stimuli in a go/no-go design to keep the number of stimuli constant). However, we deliberately decided to implement a most basic condition with minimised demands regarding response selection. Further note that it cannot be ruled out that a go/no-go design still involves response selection, namely between go and no-go responses.

To avoid anticipatory responses (especially in response selection absence conditions), we introduced a variable inter-stimulus interval (1500 ms, 2000 ms, 2500 ms, equally distributed). In single-saccade blocks and dual-response blocks participants were instructed to return their gaze to the central fixation cross after each response. In single-manual blocks participants were required to remain fixated on the central fixation cross throughout the block.

Participants accomplished 12 blocks of 30 trials presented in four sequences of three blocks each (e.g. single saccade, single manual response, dual response). A calibration routine was administered at the beginning of each block.

Design

We utilised four independent variables. Response modality (saccade vs. manual), response condition (single response vs. dual response), and response selection (RS presence vs. RS absence) were manipulated block-wise within participants. Compatibility (compatible vs. incompatible) was manipulated between participants. The order of the three response condition blocks (saccade, manual, and dual) and the order of response selection conditions were counterbalanced across participants. RTs and errors for saccades and manual responses were recorded as dependent variables.

2.2.2 Results

Response times

In single-manual blocks, we excluded 4.7 % of trials in the compatible group and 6.5 % of trials in the incompatible group due to erroneous saccade responses. Figure 2.1 shows the mean RTs for saccades and manual responses as a function of response modality, response condition, response selection, and compatibility. A mixed four-way ANOVA revealed a significant effect of response modality, $F(1{,}46) = 315.71$, $p < .001$, $\eta_p^2 = .87$, indicating the typical finding that saccades (223 ms) are initiated faster than manual responses (399 ms). The main effect of response condition was significant, too, $F(1{,}46) = 102.48$, $p < .001$, $\eta_p^2 = .69$, indicating longer RTs in dual-response conditions (351 ms) than in single-response conditions (270 ms), reflecting overall dual-response costs of 81 ms. Furthermore, there was a significant main effect of response selection, $F(1{,}46) = 200.49$, $p < .001$, $\eta_p^2 = .81$, with longer RTs in blocks involving response selection (358 ms) than in blocks without response selection (264 ms). The group comparison revealed a significant main effect of compatibility (336 ms in the incompatible group vs. 286 ms in the compatible group), $F(1{,}46) = 11.24$, $p = .002$, $\eta_p^2 = .20$.

Additionally, all two-way interactions were statistically significant. The interaction of response selection and response condition, $F(1{,}46) = 10.70$, $p = .002$, $\eta_p^2 = .19$, indicates that dual-response costs were greater when response selection was present (96 ms) than when it was absent (64 ms). The interaction of response selection and compatibility, $F(1{,}46) = 60.07$, $p < .001$, $\eta_p^2 = .57$, indicated a more substantial effect of response selection in incompatible conditions (145 ms) than in compatible conditions (42 ms). The interaction of response selection and modality, $F(1{,}46) = 200.87$, $p < .001$, $\eta_p^2 = .81$, indicates a larger impact of response selection on manual responses (142 ms) than on saccades (45 ms). The interaction of response condition and compatibility showed that dual-response costs were almost twice as high when responses were incompatible vs. compatible (106 ms vs. 55 ms), $F(1{,}46) = 10.04$, $p = .003$, $\eta_p^2 = .18$, while the interaction of response condition and modality indicates that dual-response costs were substantially greater for manual responses (139 ms) than for saccades (23 ms), $F(1{,}46) = 60.36$, $p < .001$, $\eta_p^2 = .57$. The interaction of compatibility and modality, $F(1{,}46) = 12.95$, $p = .001$, $\eta_p^2 = .22$, indicates a smaller compatibility effect for saccades (13 ms) than for manual responses (85 ms).

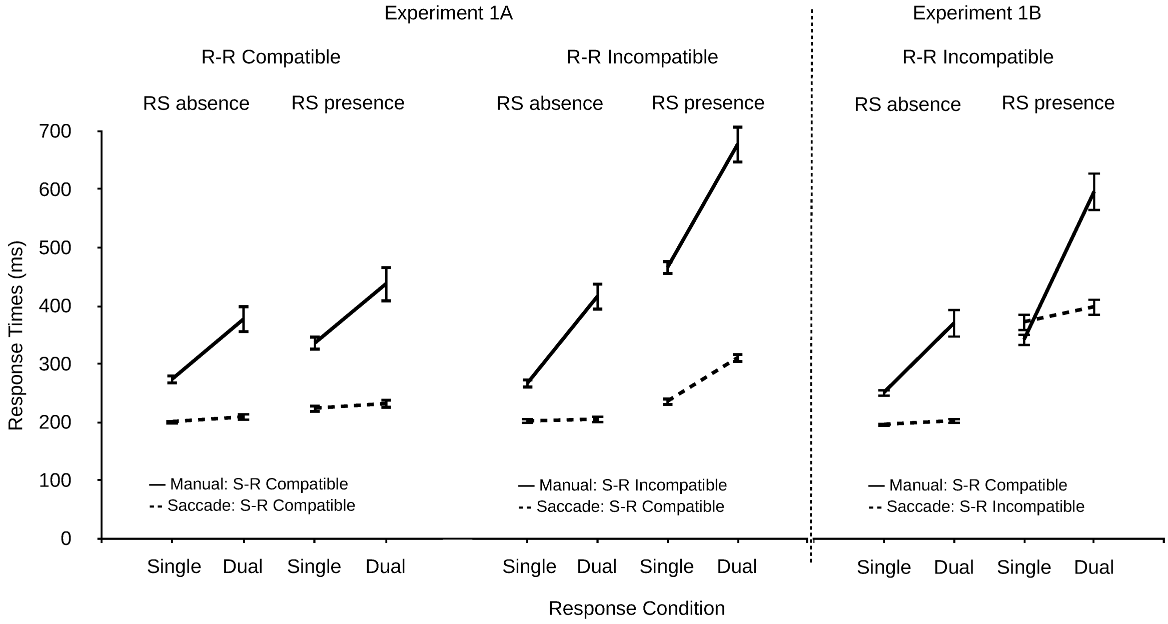

Figure 2.1. Mean RTs for saccades and manual responses in Experiment 1A and 1B as a function of response condition (single and dual) and response selection (RS absence and RS presence) for conditions involving (R-R) compatible and incompatible responses. In Experiment 1A, response incompatibility was introduced by utilising an incompatible S-R mapping for manual responses, while in Experiment 1B the S-R mapping for saccades was incompatible. Error bars represent standard errors.

Importantly, the three-way interaction of response condition, response selection, and compatibility was significant, $F(1{,}46) = 10.64$, $p = .002$, $\eta_p^2 = .19$, revealing that dual-response costs were smaller when response selection was absent (74 ms) than when it was present (138 ms) in the incompatible group but were virtually the same (55 ms vs. 55 ms) in the compatible group. This result demonstrates that response selection only affects dual-response costs when spatial conflict has to be resolved, or conversely that crosstalk affects dual-response costs mainly in the presence of response selection demands. The interaction of response selection, compatibility, and modality was significant, too, $F(1{,}46) = 72.14$, $p < .001$, $\eta_p^2 = .61$, but neither the interaction of modality, response condition and compatibility, $F(1{,}46) = 2.02$, $p > .15$, nor the interaction of modality, response condition and response selection, $F < 1$, were significant. Thus, there was no statistical evidence for differences in dual-response costs between modalities dependent on the specific R-R compatibility or response selection demands. Finally, there was no significant four-way interaction, $F < 1$, indicating that the important three-way interaction of response condition, response selection, and compatibility did not significantly differ between (S-R incompatible) manual responses and (S-R compatible) saccades.

A post hoc analysis of dual-response costs for each modality in all experimental conditions (i.e. for each line in Figure 2.1) showed that saccades exhibited significant dual-response costs only in blocks involving response selection (72 ms in the incompatible responses group, $t(23) = 8.3$, $p < .001$; 8 ms in the compatible group, $t(23) = 2.5$, $p = .021$), while no significant dual-response costs for saccades occurred in blocks without response selection requirements ($<$ 8 ms, all ps $> .15$). In contrast, manual dual-response costs were significant throughout all conditions, all ps $< .05$, including the condition involving compatible responses without response selection requirements.

Interestingly, a post hoc analysis of manual RTs in conditions without response selection revealed no significant interaction between compatibility and response condition, $F(1,46) = 1.88$, $p > .10$, whereas the same analysis for conditions involving response selection resulted in a significant interaction, $F(1,46) = 7.08$, $p = .011$, $\eta_p^2 = .13$. This suggests that without a certain amount of response ambivalence generated by the availability of response alternatives, compatibility (in terms of crosstalk) does not have a substantial impact on performance. This finding further underlines the (previously neglected) importance of taking the behavioural context into account – that is the presence/absence of alternative response options in surroundings trials within a block – when discussing crosstalk effects.

Contextual effects related to response selection

The results reported above clearly indicate that the context of available response alternatives, namely the presence of mixed or constant response alternatives (i.e. with or without response selection), affected overall RTs and dual-response costs under certain conditions. However, the underlying mechanisms of this influence still remain an open issue. To differentiate between potentially different sources, we computed further analyses. Specifically, we tested whether dual-response performance for trials with response repetitions in response selection blocks is worse than dual-response performance in blocks without response selection (*response alternative mixing costs*). Since both conditions are comparable in that they require a repetition of the same response, we reasoned that such costs could be interpreted as an empirical marker for interference based on a global preparedness for potentially upcoming response alternatives within a block of trials (*prospective interference*). Second, we tested for local transition effects (trial-by-trial effects) in blocks involving response selection, that is if there are significant differences in dual-response performance between response switches and repetitions. If the response from the previous trial interfered with that in the current trial (or if repeated responses led to priming), we would expect worse dual-response performance for response switches (*local modulation of interference*). Since a modulation of dual-response performance by the presence/absence of response selection was only observed in the incompatible group, we restricted our analysis to those data.

As a result, response alternative mixing costs amounted to 65 ms for saccades, thus differing significantly from zero, $t(23) = 5.91$, $p < .001$, and to 53 ms for manual responses, $t(23) = 1.78$, $p = .044$ (one-tailed). This is clear evidence for the occurrence of response alternative mixing costs, indicating prospective interference. In contrast, dual-response switching costs did not significantly differ from zero (12 ms for saccades and 9 ms for manual responses, both ps $> .18$). Thus, there was no clear evidence for impaired performance in response switch trials compared to repetition trials (in blocks involving response selection), and thus no clear evidence for the occurrence of local (trial-by-trial) modulation of interference.

Error rates (overall mean $= 2.2\,\%$) were too low to conduct meaningful statistical analyses. Note that there was no numerical trend in the data that would support the presence of speed-accuracy trade-offs.

2.2.3 Discussion

We observed dual-response costs for manual responses in all experimental conditions, even in the compatible group without response selection requirements. This finding suggests that the execution of multiple responses per se leads to *general dual-execution costs*, that is costs that occur in the absence of any of the two traditionally cited sources of interference (response selection and crosstalk). This novel finding demonstrates that a substantial portion of dual-response costs previously reported in research on cross-modal action control (e.g. Huestegge & Koch, 2009, 2013) occurs due to such unspecific response coordination costs at a late processing stage related to response execution. The fact that the effect of response selection was greater for manual than for oculomotor responses is in line with previous observations that saccades are less sensitive to response selection manipulations (Kveraga et al., 2002) than manual responses (e.g. Hick, 1952).

Beside these general dual-execution costs, our results clearly suggest a strong effect of cross-response crosstalk (Navon & Miller, 1987) as reflected in worse performance in spatially incompatible (compared to compatible) conditions, which is in line with previous research on simultaneously executed saccades and manual responses (Huestegge & Koch, 2009). Importantly, the presence of a significant three-way interaction of response condition, compatibility, and response selection demonstrated that crosstalk affects dual-response costs if and only if response selection demands are present in the first place. Thus, cross-response crosstalk effects operates on the level of response selection, not (or to a much lesser extent) on the level of response execution. If we assume that the presence of response selection is necessarily associated with active representations of all relevant response alternatives throughout a block of trials, this finding suggests that conflicting information based on memory content negatively affects performance only when there is an additional need for conflict resolution in the current trial (i.e. a trial involving incompatible responses).

Given that the present dual-response task does not consist of two logically independent responses, one could argue that it is difficult to interpret the present results within classic dual-task frameworks, for example, the traditional response selection bottleneck (Pashler, 1994). More specifically, Fagot and Pashler (1992) convincingly demonstrated that triggering two responses with a single aspect of a common stimulus involves only one common response selection process, similar to a single task. However, they only referred to situations involving two compatible responses, thus it is still unclear whether two *incompatible* responses might also be initiated based on of a single selection process. If we now assume two independent response selection processes for the two incompatible responses in our design, it could explain the particularly large dual-response costs for the second (manual) response in conditions involving both response selection and crosstalk. Specifically, saccade response selection may have caused a postponement of the second (manual) response. However, such a basic bottleneck account cannot readily explain the emergence of strong dual-response costs for the saccades in these conditions, which are executed first and should thus not be postponed (see Hommel, 1998a, for necessary extensions of the bottleneck framework to account for such data). In sum, due to the specific setup of the present experiment one should be careful in interpreting the findings within traditional dual-task frameworks that typically assume two response selection processes. An alternative to the assumption of separate response selections would be that the presence of response selection and adverse crosstalk conditions rather increased the difficulty of a unitary (but more complex) selection process comprinsing both responses (see General Discussion for details).

The observed costs related to the mixing of dual-response alternatives suggest that a large portion of dual-response costs is based on *prospective interference*, that is interference due to being prepared for all potential response alternatives. More specifically, an underlying mechanism of this preparation could be that cognitive representations for all potential response alternatives exhibit a stronger baseline activation in response selection blocks than in blocks without response selection. This would then lead to relatively more conflict when one of the potential response alternatives eventually needs to be selected, because the currently irrelevant alternative is never completely ‘inactive’.

Surprisingly, the data revealed no evidence for the occurrence of a *local modulation of dual-response performance*, although studies on basic single-task performance usually report beneficial priming effects for response repetitions as opposed to switches (e.g. Remington, 1969). Specifically, the absence of significant costs of switching between response alternatives at first sight suggests that there was no persisting activation of the execution of a different response compound in the previous trial impairing performance in the current trial. One potential explanation could be that in our experimental design response repetitions were nearly as likely to occur as response switches. Thus, the cognitive system may have been well prepared for the occurrence of a response alternative switch in the majority of actual switch trials, and this preparation may have counteracted potential effects of conflict based on persisting activation from previous trials, an issue we further addressed in Experiment 2.

Since the spatial incompatibility between responses was introduced through a spatially incompatible S-R-mapping for manual responses, one might argue that the important three-way interaction described above may have been caused by the introduction of S-R (instead of or in addition to R-R incompatibility). However, we did not find evidence for a significant four-way interaction, that is the effects on dual-response costs caused by response selection and crosstalk did not significantly differ between manual responses and saccades, the latter being S-R compatible throughout all experimental conditions. Therefore, it appears unlikely that S-R incompatibility (instead of R-R incompatibility) has played a major role here (see also Huestegge & Koch, 2009, for a similar conclusion). Additionally, previous research utilising the same single stimulus paradigm (Huestegge & Koch, 2009) suggested that the introduction of S-R incompatibility for both manual and saccade responses (resulting in R-R compatibility despite an even greater ‘amount’ of overall S-R incompatibility) substantially reduced dual-response costs (when compared to a mixed S-R compatibility condition similar to our crosstalk present condition). Nevertheless, in order to rule out that the (eventually arbitrary) decision to introduce S-R incompatibility for manual responses in

Experiment 1A was a driving force behind the observed data pattern, we conducted Experiment 1B in which we collected data in an alternative ‘between-response incompatibility condition’ with compatible S-R mappings for manual responses and incompatible S-R mappings for saccades.

2.3 Experiment 1B

2.3.1 Method

Participants

A new group of 24 students (16 woman and 8 men) participated in Experiment 1B with a mean age of 23 years (*SD* $=$ 2.1, range $=$ 20–30).

Apparatus, stimuli, procedure, and design

Apparatus and stimuli were the same as in Experiment 1A. The overall procedure was also the same except for the instruction to respond with S-R incompatible saccades and S-R compatible manual responses. Regarding the design, it is important to note that we tested only one (*incompatible responses*) group of participants in order to compare the results with those from the corresponding incompatible responses group of Experiment 1A.

2.3.2 Results

In order to ensure that our main conclusions from Experiment 1A did not depend on the particular S-R mapping implementation, we analysed the data of the incompatible responses group of Experiment 1B by directly comparing them to the incompatible responses group from Experiment 1A. We applied a mixed four-way ANOVA with the independent variables response modality, response condition, response selection, and S-R mapping (A: S-R incompatible manual responses and S-R compatible saccades, B: S-R compatible manual responses and S-R incompatible saccades). If the specific S-R mapping implementation mattered, this would become apparent in any significant interaction involving S-R mapping and response condition.

We excluded 1.6 % of the data due to anticipative responses ($<$ 150 ms for manual responses and $<$ 70 ms for saccades) and due to erroneous saccades in manual-single trials. As in Experiment 1A, there were significant main effects (see Figure 2.1) of modality, $F(1{,}46) = 242.37$, $p < .001$, $\eta_p^2 = .84$, response condition, $F(1{,}46) = 109.05$, $p < .001$, $\eta_p^2 = .70$, and response selection, $F(1{,}46) = 271.26$,

$p < .001$, $\eta_p^2 = .86$. However, RTs did not significantly differ between both S-R mapping groups across experiments (336 ms vs. 330 ms), $F < 1$.

Modality and S-R mapping interacted significantly, $F(1,46) = 35.54$, $p = .001$, $\eta_p^2 = .44$, indicating that the typical compatibility effect (i.e. S-R compatible responses are faster than incompatible responses) resulted in a trade-off across modalities: S-R incompatible manual RTs were 64 ms slower than compatible ones, while S-R compatible saccades were 54 ms faster than incompatible saccades. As in Experiment 1A, the interaction of response selection and modality, $F(1,46) = 58.99$, $p < .001$, $\eta_p^2 = .56$, indicates a larger impact of response selection on manual responses (187 ms) than on saccades (124 ms). The interaction of response selection and response condition, $F(1,46) = 35.84$, $p < .001$, $\eta_p^2 = .44$, indicates larger dual-response costs when response selection was present (136 ms) compared to absent (67 ms). The interaction of response condition and modality indicates greater dual-response costs for manual responses (177 ms) than for saccades (26 ms), $F(1,46) = 67.25$, $p < .001$, $\eta_p^2 = .60$. There was no significant interaction of response selection and S-R mapping, $F = 1.24$, $p = .27$, nor of response condition and S-R mapping, $F < 1$, $p = .68$, suggesting that S-R mapping had no significant influence on both the impact of response selection and dual-response costs.

Importantly, the three-way interaction of response condition, response selection, and S-R mapping was not significant either, $F < 1$, suggesting that response selection affected dual-response costs in a comparable way regardless of the particular S-R mapping across experiments. Also, the interaction of response condition, modality, and S-R mapping was not significant, $F < 1$, thus there was no statistical evidence for a difference in dual-response costs between modalities dependent on S-R mapping. Interestingly, there was a significant interaction of modality, response selection, and S-R mapping, $F(1,46) = 121.79$, $p < .001$, $\eta_p^2 = .73$, showing that the effect of response selection was larger on S-R incompatible manual responses than on S-R compatible saccades (222 ms vs. 68 ms) in Experiment 1A while it was larger on S-R incompatible saccades than on S-R compatible manual responses in Experiment 1B (180 ms vs. 153 ms). This result can be regarded as supporting our previous observation that response selection and crosstalk (here: between the stimulus and each individual response) are interdependent, because the effect of response selection was larger on the respective S-R incompatible response. Additionally, the interaction between modality, response condition and response selection was significant, $F(1,46) = 8.53$, $p = .005$, $\eta_p^2 = .16$, indicating that the impact of response condition on dual-response costs was larger for manual responses than for saccades. Note that these results do not contradict any conclusion drawn in Experiment 1A, because they do not indicate any influence of the S-R mapping on the relevant interaction of response selection and dual-response costs.

Finally, there was a significant four-way interaction, $F(1{,}46) = 11.81$, $p = .001$, $\eta_p^2 = .20$, revealing that the previously reported non-significant three-way interaction between response condition, response selection, and S-R mapping was the result of averaging across modalities. Separate post hoc three-way ANOVAs for manual responses and saccades revealed a non-significant three-way interaction for manual responses, in that dual-response costs of S-R compatible manual responses in Experiment 1B were increased in a comparable way by the presence of response selection as were S-R incompatible manual responses in Experiment 1A, $F(1{,}46) = 3.47$, $p = .069$. For saccades, however, the respective three-way interaction was significant, $F(1{,}46) = 8.36$, $p = .006$, $\eta_p^2 = .15$, suggesting that the presence of response selection caused larger dual-response costs for S-R compatible saccades in Experiment 1A than for S-R incompatible saccades in Experiment 1B, while there were no dual-response costs in response selection absent conditions. One-sided t-tests comparing single- and dual-response RT for (S-R incompatible) saccades in the response selection present condition revealed significant dual-response costs of 25 ms (cf., 72 ms for S-R compatible saccades in Experiment 1A), $t(23) = 2.03$, $p = .027$, but no significant dual-response costs without response selection, $p = .19$, hence replicating the data pattern from Experiment 1A.

Taken together, our important conclusion drawn in Experiment 1A – that the process of selecting between alternative responses is a necessary precondition for observing strong crosstalk effects on dual-response costs – is not dependent on the specific S-R mapping implementation, and each response modality is affected in a comparable way regardless of its specific S-R compatibility. In particular, the choice of S-R incompatible saccades and S-R compatible manual responses results in reduced interference for saccades, which is compensated for by an increase of interference for manual responses. This is in line with previous observations of flexible resource scheduling in cross-modal dual-response control, where incompatible S-R mappings were shown to be prioritised over compatible S-R mappings (Pieczykolan & Huestegge, 2014). In sum, the data from Experiment 1B support the conclusions from Experiment 1A.

2.4 Experiment 2

As discussed at the end of Experiment 1A, a potentially important source of dual-response interference are contextual effects. However, if an equal distribution of switch and repetition trials might have prevented possible after-effects of persisting activation from previous trials, then in the present Experiment 2, which includes longer sequences of repeating response requirements, there should be a less stronger bias towards being prepared for response switches. This should allow us to observe potential local context effects. More specifically, we systematically varied the run length of trial sequences requiring the same response (compound) to be able to track the timeline of potential trial-by-trial effects in dual-response conditions. Such effects would provide further evidence that dual-response performance is at least partially based on fundamental phenomena such as residual interference or repetition priming (e.g. Remington, 1969). These specific mechanisms may eventually turn out to be at the core of previously observed effects on RTs that were explained through the rather unspecific assumption of the presence of a response selection stage in dual-response control. Specifically, based on corresponding findings in basic single-response control research we predicted that (under more ideal conditions in Experiment 2) response repetitions would indeed yield a performance increase. Such an observation would rule out an alternative explanation of the data from Experiment 1A, namely that the executive control of cross-modal response compounds has no memory (i.e. does not exhibit any trial-by-trial effects).

2.4.1 Method

Participants

A new group of 24 students (5 men and 19 woman) participated in Experiment 2 with a mean age of 25 years (*SD* = 7.9, range = 19–54). They gave informed consent and received either course credits or monetary reimbursement for participation.

Apparatus, stimuli, and procedure

Apparatus, stimuli, and instructions for participants were the same as in Experiment 1. However, given that Experiment 1 suggested that switching between response alternatives (in conditions involving response selection) only affected dual-response costs in the presence of crosstalk, we solely utilised the corresponding spatially incompatible conditions in Experiment 2 (specifically, the combination of S-R compatible saccades and S-R incompatible manual responses from Experiment 1A). Furthermore, there were no blocks without response selection requirements in Experiment 2. Instead, we systematically manipulated the number of repetitions of the same response (compound) in a row (in the following referred to as *run length*). We implemented four different run lengths (1, 2, 4, 8), which were presented in a random order in each block (e.g. 2, 4, 1, 2, 8, etc.). The frequency of each run length was kept constant. Note that this procedure yields different transition probabilities for each run length position (e.g. the switch probability after the 3rd, 5th, 6th, and 7th repetition in a row is zero, which is not the case after, e.g. the 2nd repetition). The inter-trial interval was varied between 1500 ms, 2000 ms, 2500 ms, and 3000 ms, and was equally distributed across run lengths. In total, participants completed two sequences of three blocks (single saccade, single manual, and dual condition) consisting of 60 trials each. The order of blocks within a sequence was counterbalanced across participants resulting in six different block sequences.

Design

Response modality (saccade and manual response), response condition (single and dual), and run length (1, 2, 4, and 8) were manipulated within participants. As dependent variables, we measured RTs and errors for saccades and manual responses.

2.4.2 Results

We excluded all trials of the first run of repetitions within each block of trials. Additionally, if a trial within a run length contained an error, this trial and the following trials of that run length were excluded. In single manual blocks, trials with erroneously executed saccades were excluded. This cleansing procedure yielded 73.7 % valid data (of 22 participants) that were further analysed (for two participants, this procedure yielded empty cells in some conditions and they were excluded from further analysis).

Table 2.1 displays mean RTs for all trial positions of the four run lengths. Pairwise (Bonferroni-corrected) t-tests revealed no significant differences between corresponding trial positions across run lengths (e.g. the second trial in each run length) in single- and dual-response conditions for both response modalities (except for one data point in the single saccade data, where Trial 1 of run length 8 significantly – but unsystematically – differed from the corresponding data points in run length 2, $p = .042$, and 4, $p = .024$). As a consequence, corresponding data points were merged across run lengths for the graphs in Figure 2.2. For statistical purposes, we implemented a three-way ANOVA with the independent variables response modality, response condition, and trial position in run. For the factor *trial position* we utilised the RT data from the *last* trial position of each run length (i.e. first trial of run length one, second trial of run length two, fourth trial of run length four, and eighth trial of run length eight) to capture the maximum repetition benefit associated with each run length condition.

The ANOVA revealed a significant main effect of trial position, $F(1,21) = 14.57$, $p < .001$, $\eta_p^2 = .41$, indicating overall decreasing RT with progressing trial position within a run (395 ms, 367 ms, 355 ms, and 339 ms for trial positions 1, 2, 4, and 8). We also observed a significant main effect of response condition, $F(1,21) = 35.39$, $p < .001$, $\eta_p^2 = .63$, indicating overall dual-response costs of 69 ms. As in Experiment 1, the main effect of response modality was significant, $F(1,21) = 194.79$, $p < .001$, $\eta_p^2 = .90$.

The interaction of trial position and response condition was significant, too, $F(3,63) = 4.1$, $p = .01$, $\eta_p^2 = .16$, revealing a steeper decrease in single-response RTs with progressing trial position, while dual-response RTs appeared to approach an asymptote after about four successive response repetitions (see Figure 2.2).

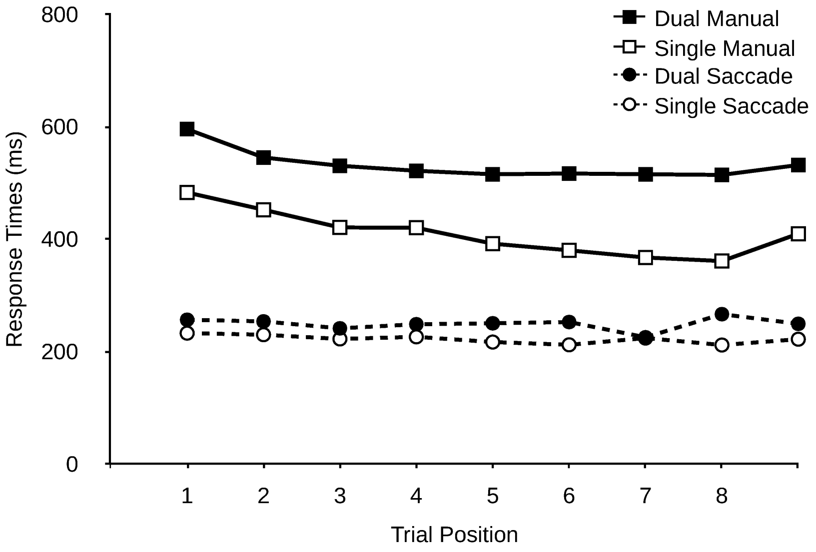

Figure 2.2. Mean response times (RT) for saccades and manual responses in Experiment 2 as a function of trial position in a run. Data points represent the arithmetic mean across all four run lengths (where applicable).

There was also an interaction of response modality and response condition, $F(1,21) = 6.8$, $p = .016$, $\eta_p^2 = .25$, signifying that dual-response costs were more pronounced for manual responses

Table 2.1

Mean response times (in ms) for saccades and manual responses in single and dual-response conditions as a function of trial position within four different run lengths in Experiment 2. Numbers in parentheses represent standard errors.

Response Modality	Response Condition	Run Length	Trial Position							
			1	2	3	4	5	6	7	8
Manual Response (S-R incompatible)	Dual	1	604 (38)							
		2	573 (31)	530 (34)						
		4	590 (34)	548 (33)	526 (31)	521 (32)				
		8	618 (32)	559 (31)	535 (28)	523 (29)	516 (29)	517 (25)	516 (26)	515 (31)
	Single	1	486 (19)							
		2	483 (21)	467 (24)						
		4	478 (16)	440 (20)	428 (17)	427 (19)				
		8	486 (20)	451 (16)	414 (14)	414 (20)	392 (17)	380 (13)	368 (15)	361 (15)
Saccade (S-R compatible)	Dual	1	260 (11)							
		2	258 (13)	240 (12)						
		4	252 (13)	257 (15)	238 (10)	249 (10)				
		8	257 (16)	266 (15)	245 (12)	249 (12)	251 (12)	253 (15)	226 (10)	267 (30)
	Single	1	229 (11)							
		2	240 (11)	230 (11)						
		4	241 (11)	232 (11)	223 (12)	221 (12)				
		8	223 (11)	229 (11)	222 (13)	232 (10)	217 (11)	212 (10)	224 (10)	212 (11)

(108 ms) than for saccades (16 ms). Response modality and trial position also interacted significantly, $F(3{,}63) = 13.61$, $p < .001$, $\eta_p^2 = .39$, indicating that particularly manual responses were affected by trial position within a run. The three-way interaction was not significant, $F < 1$.

Finally, a comparison of RTs with those in the corresponding conditions of Experiment 1 (i.e. incompatible responses in blocks involving switching between response alternatives) revealed that manual RTs in dual-response conditions were on average about 100 ms faster (and saccade RTs about 50 ms faster) in Experiment 2 than in Experiment 1. This performance advantage in Experiment 2 is very likely due to the increased overall number of response repetitions (47 % repetitions in Experiment 1 and 73 % in Experiment 2). To test the assumption that the lower probability of response repetitions prevented repetition priming effects to occur in Experiment 1, we specifically contrasted Experiment 1 and 2 by analysing only two-trial sequences consisting of a response switch directly followed by a repetition in manual dual-response conditions. A 2 × 2 ANOVA with repetition rate (medium in Experiment 1 vs. high in Experiment 2) and response demand (switch vs. repetition) as independent variables yielded a significant main effect of response demand, $F(1{,}44) = 4.35$, $p = .043$, $\eta_p^2 = .09$, indicating a general performance benefit of 23 ms for repetitions as opposed to switches (627 ms vs. 604 ms). However, this main effect was qualified by a significant interaction of response demand and repetition rate, $F(1{,}44) = 4.2$, $p = .046$, $\eta_p^2 = .08$, showing that the RT difference between response demands was clearly present for the high repetition rates in Experiment 2 (difference of 46 ms between switches and repetitions), but negligible for the medium repetition rates in Experiment 1 (3 ms difference). The main effect of repetition rate on RTs was close to significant, $F(1{,}44) = 3.93$, $p = .054$, $\eta_p^2 = .08$, indicating that the different response requirements across experiments may have slightly influenced the overall RT level.

Errors occurred in only 2.8 % of the trials. Since participants committed less than one error per trial position on average, further statistical analyses were considered meaningless.

2.4.3 Discussion

In Experiment 2, we investigated whether the lack of trial-by-trial effects in Experiment 1A was evidence for a general lack of such effects in cross-modal response compound control or the result of the specific conditions in Experiment 1, which fostered the expectation of response switches. Therefore, we employed a design in which response demand switches were substantially less likely, which should increase the probability (relatively to Experiment 1A) of observing repetition priming effects.

Unlike in Experiment 1, the data in Experiment 2 clearly provided evidence for local (trial-by-trial) adjustments of performance based on the sequential pattern of response switches and repetitions. Specifically, manual RTs monotonously decreased as response repetitions increased, probably representing cumulative response priming (e.g. Remington, 1969). Furthermore, a response switch generally caused longer RTs when compared with a response repetition. These findings are in line with the assumption of persisting activation of response representations (or codes) over successive trials. Apparently, the activation of a certain response compound in dual-response conditions cannot be completely overwritten from trial to trial but remains active, so that it can influence current response compound selection processes. This observation can be interpreted as evidence for *retrospective interference*, in which the amount of interference in the current trial is based on the content of previous behavioural demands.

The interplay of top-down factors (e.g. related to expectations, see the comparison of the data between experiments at the end of Experiment 2), factors related to statistical learning of transition probabilities, and bottom-up factors (residual interference and response priming) are well known from corresponding literature on basic single-task processing (Bertelson, 1965; Jentzsch & Sommer, 2002; Notebaert & Soetens, 2003; Remington, 1969). The present study can be interpreted as first evidence that similar mechanisms may also play a role in the control of cross-modal response compounds, but also calls for a more systematic approach to the analysis of trial-by-trial effects in cross-modal action control in future research (e.g. by disentangling factors related to stimulus and response transitions and by separating the various sources of influences in a more systematic way).

However, note that these local effects were only prevalent in manual response control, presumably because the S-R compatible saccades did not pose any substantial challenge to cognitive processing. This would be in line with the observation that saccades usually do not show an RT increase with increasing number of response alternatives (i.e. they represent an exception to Hick's law, see, e.g. Kveraga et al., 2002; Lawrence, St. John, Abrams, & Snyder, 2008) as well as the observation that saccades are typically prioritised over other concurrent response modalities (see Huestegge & Koch, 2013; Pieczykolan & Huestegge, 2014). In general, this observation calls for further basic research on trial-by-trial modulations of performance in the oculomotor system.

One side effect of the present run length design is that transition probabilities are not uniformly distributed across trial positions in a run of repetitions. For example, while the switch probability is relatively high after the 2nd repetition in a row, it is effectively zero after the 3rd repetition in a row (since the design did not include a run length of 3). However, we did not find evidence for a strong discontinuity of RT performance (e.g. between trial positions 3 and 4, see Table 2.1). While this observation does not rule out the possibility of an influence of transition probabilities in terms of a top-down influence on response control, the data do not suggest a major role of corresponding anticipations, either.

Based on the present data, we cannot distinguish between residual interference in switch trials (conflict based on persisting activation of a different previous response alternative) and repetition priming in repetition trials as sources for the trial position effects in manual response control. However, both explanations are consistent with our main goal of Experiment 2, which is the demonstration of a content-based influence of previous response alternatives on the selection of a current response in a dual-response setting. Finally, the comparison of two-trial sequences across experiments empirically supported our assumption that the low probability of response repetitions in Experiment 1 has counteracted the occurrence of local trial-by-trial effects – a finding that also supports our general claim that contextual factors greatly affect performance in multiple-response control.

2.5 General Discussion

The present study was aimed at examining the interplay of different mechanisms of interference in cross-modal action control by investigating two well-known sources of interference, crosstalk and response selection. In two experiments, participants responded to auditory stimuli by performing single responses and dual-response compounds in two response modalities (saccades and manual responses). In Experiment 1, response selection and crosstalk were manipulated independently by comparing performance in blocks with either repeating or switching response alternatives (addressing response selection) and by comparing conditions involving the simultaneous execution of spatially compatible or incompatible responses (addressing crosstalk). Previous research and theory on multiple-response control did not focus on the role of response selection in terms of a presence or absence of a choice between response alternatives while studying cross-response crosstalk effects, and instead only focused on examining cross-response crosstalk between the two independent tasks (e.g. Logan & Gordon, 2001; Meyer & Kieras, 1997a; Navon & Miller, 1987, 2002). Other studies on crosstalk focused on S-R based crosstalk in single tasks (e.g. Callan, Klisz, & Parsons, 1974) but not on cross-response conflict. Thus, the present data presents first insight into cross-response crosstalk effects in situations requiring two logically dependent responses by building on the redundant responses paradigm (Fagot & Pashler, 1992; Holender, 1980) but with the additional manipulation of both response crosstalk and the presence and absence of response selection demands.

Based on preliminary analyses of contextual effects on response compound control in Experiment 1, Experiment 2 further explored the underlying processing dynamics associated with switching between dual-response alternatives by systematically manipulating the run length of response (compound) repetitions. The experiments yielded several novel findings, along with some conceptual replications of previous results.

2.5.1 General dual-execution costs

One novel finding is that substantial dual-response costs for manual responses were observed in conditions without any response selection requirements and without the presence of adverse crosstalk potential based on spatial incompatibility. This is evidence for general, unspecific dual-execution costs that appear to be involved whenever a manual response is accompanied by another concurrent response (see the related, but rather unspecific notion of concurrence costs, e.g. Berlyne, 1957; Herman & Kantowitz, 1970; Logan & Gordon, 2001; Navon & Gopher, 1979).

The fact that dual-response costs were especially pronounced for manual responses is at odds with previous observations showing largely unaffected manual responses in the context of additional vocal demands in the single onset paradigm (Fagot & Pashler, 1992; Holender, 1980). Thus, the present findings suggest that the specific pattern of dual-response costs is not fixed for each effector system, but rather depends on the specific combination of effector systems – probably due to effector system prioritisation (Huestegge & Koch, 2013).

Previous studies in the context of multiple-action control usually did not include a condition in which a pre-selected response (compound) was repeatedly executed (i.e. without response selection requirements). A notable exception are few early studies involving two manual tasks that also reported evidence for dual-response costs in the absence of response selection requirements (Karlin & Kestenbaum, 1968; Reynolds, 1966). However, it is important to note that these studies utilised distinct, temporally separated stimuli (one for each response) instead of a common stimulus, so it is difficult to ascribe the observed costs solely to the coordination of dual-response execution. Specifically, while in a sequential stimulus paradigm the prolongation of RT_2 could be attributed to a temporal uncertainty about the occurrence of the second stimulus (see Pashler, 1994), the costs within the present single stimulus paradigm cannot be explained by such a temporal uncertainty account. In sum, the present results thus represent first unequivocal evidence for general dual-execution costs in cross-modal response control (see e.g. Garry & Franks, 2000, for similar observations in the field of bimanual motor coordination). Note that these cross-modal dual-response costs are reminiscent of effects of intra-modal effects of response complexity on RTs (e.g. double-press responses vs. single-press responses), suggesting similar underlying mechanisms related to motor programming complexity (e.g. Christina, Fischman, Vercruyssen, & Anson, 1982). It is important to note that our present manipulation of response selection presence or absence in Experiment 1 may have not selectively affected the presence or absence of the response selection stage. Instead, it has been suggested that such a manipulation may also affect, for example, preparatory states at stimulus onset (e.g. Danek & Mordkoff, 2011). However, our conclusions do not rely on the assumption of selectivity. Instead, it was important to find a condition with minimised response selection demands, and the repetition of the same demands across a block of trials is probably the most efficient measure to achieve this goal.

2.5.2 Impact of response selection and crosstalk on dual-response control

The data from Experiment 1 replicated many previous reports (starting with Donders, 1969) of a substantial impact of the presence of response selection on response control, in that selection requirements caused elevated RTs throughout all (single- and dual-response) conditions – also in the absence of crosstalk. Furthermore, when response selection was present, crosstalk not only affected overall RT levels but additionally the size of dual-response costs. Interestingly, and in line with previous observations regarding cross-modal response compounds (Huestegge & Koch, 2009, 2010), response incompatibility also affected the first (oculomotor) response in addition to the second (manual) response. A similar phenomenon termed ‘backward crosstalk’ is well-known from the dual-task literature (e.g. Ellenbogen & Meiran, 2010; Hommel & Eglau, 2002; Koch & Prinz, 2002; Lehle & Hübner, 2009; Lien & Proctor, 2000, 2002; Logan & Delheimer, 2001; Logan & Schulkind, 2000; Miller, 2006; Miller & Alderton, 2006; Navon & Miller, 1987), and is usually interpreted in terms of parallel response-related processing (e.g. by assuming parallel response activation processes, see Hommel, 1998a).

Another important novel finding of the present study is that the presence of response selection is a necessary prerequisite for the observation of substantial crosstalk effects. Thus, the mere execution of incompatible responses does not per se affect dual-response processing, since dual-response costs were similar in compatible and incompatible conditions when response selection requirements were absent, irrespective of the particular S-R compatibility (Experiment 1A vs. 1B). Therefore, it seems that cross-response crosstalk (based on incompatible response codes across responses) does not mainly operate at the level of response execution but rather at the (earlier) response selection stage.

2.5.3 Prospective and retrospective interference in dual-response control

The results across experiments showed a strong contextual modulation of dual-response costs in form of a performance dependency in the current trial on the requirements in the surrounding trials within a block. This is not only evident in the overall effects of the presence of response selection, which are necessarily associated with switching between response alternatives from trial to trial, but also in response alternative mixing costs (as observed in Experiment 1), which we interpreted in terms of (memory-based) *prospective interference*. Specifically, participants in response selection blocks may generally prepare for all potentially upcoming response alternatives by elevating the baseline activation of corresponding representations. In turn, this should lead to stronger competition (between the required response and the pre-activated alternative responses) in each trial when compared to a situation without response selection requirements.

In contrast to this rather *global* contextual effect, Experiment 2 revealed that dual-response performance can also be strongly affected by the *local* preceding trial history indicating a *retrospective interference* mechanism. Specifically, we observed a monotonous decrease of dual-response RTs immediately after a response compound switch. Principally, this effect may either be based on priming mechanisms associated with repeated response demands across trials or persisting activation of competing response alternatives in previous trials.

Huestegge and Koch (2010) provided a first sketch of a theoretical framework to explain crosstalk in situations involving cross-modal behaviour. Specifically, they assumed that participants need to correctly bind specific modality codes (here: for saccades and manual responses) to relevant spatial codes (left vs. right) based on instructions and current perceptual input. This framework does not involve distinct serial selection processes for each response but rather assumes that one conjoint binding pattern needs to be selected to execute a response (compound). The framework is also able to specify crosstalk by assuming that response conflict is based on biased competition between binding patterns that connect task-relevant codes (see Desimone & Duncan, 1995, for the introduction of this concept to the field of visual attention), as depicted in Figure 2.3. For example, adverse crosstalk (as implemented through incompatible responses in the present study) in the current trial involves the activation of two distinct spatial codes within a trial. Thus, the cognitive system should be engaged in resolving the issue of which modality code needs to be bound to which spatial code. In compatible conditions, this particular (time consuming) resolution process is not necessary because only one spatial code needs to be activated.

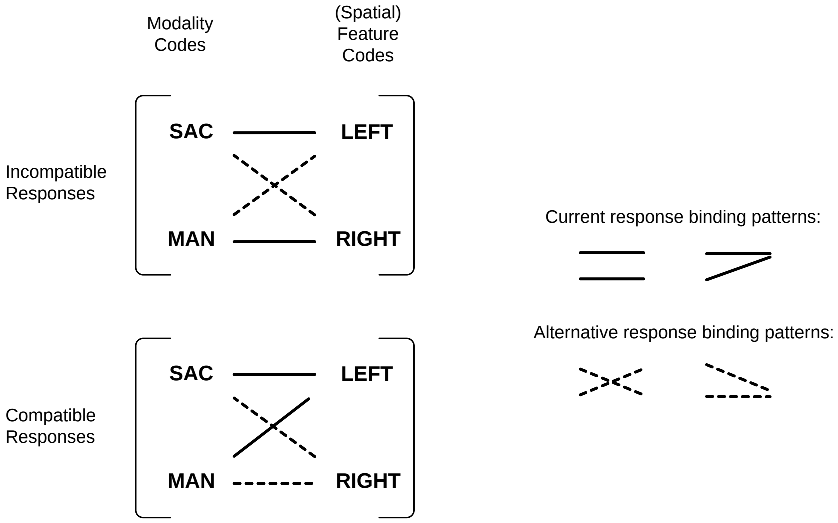

Figure 2.3. Mechanisms of response compound selection. Upper panel: Bindings in a current trial (straight lines) interfere with activation of alternative bindings from previous (or expected) trials (dotted lines). ‘SAC’ and ‘MAN’ denote saccade and manual responses, respectively. Lower panel: In compatible trials, in which one spatial codes needs to be bound to two modality codes, no conflict resolution process is necessary because only one relevant spatial code needs to be selected. Therefore, there is no previous or expected conflict that could cause memory-based crosstalk.

While the resolution process of binding conflicting response codes describes the mechanism of crosstalk within a trial, *memory-based* crosstalk, on the other hand, involves competition between potentially relevant code binding patterns from previous or expected trials. In contrast, the traditional notion of crosstalk usually refers to competition between two currently task-relevant representations (which response code goes with which modality code in a given trial), which is why a terminological differentiation into *online crosstalk* (i.e. crosstalk mechanisms in a current trial) and *memory-based crosstalk* (i.e. crosstalk between the current and surrounding trials) might be quite useful.

In the case of prospective crosstalk, activation of competing binding patterns in a current trial would be based on endogenous pre-activation of all task-relevant binding patterns throughout a block of trials in order to be prepared to act in accordance with instructions and the current stimulus. In the case of retrospective crosstalk (residual interference or repetition priming), we assume that persistent residual activation of binding patterns from previous trials may still be present in a current trial but will gradually diminish with temporal or instance-based distance. Note that while online crosstalk and retrospective crosstalk in this framework are rather driven by bottom-up (exogenous) processes, prospective crosstalk is unique in that it appears to involve a more strategic, endogenous component. However, we are not yet able to determine the extent to which this strategic process may be under voluntary control, which should thus be addressed in future work.

In addition, these present observations of trial-by-trial effects, which are well known within the field of basic single-task research (e.g. Bertelson, 1965; Jentzsch & Sommer, 2002; Notebaert & Soetens, 2003; Remington, 1969), might thus represent a specification of the mechanisms that are currently subsumed under the general label of ‘response selection’ in current theories of multiple-response control. However, more systematic research (in analogy to those in simple-RT task research) is certainly needed to fully unravel the interaction of the various top-down and bottom-up processes involved.

3 | Study B

Oculomotor Control and Dual-Task Interference – Evidence from the PRP paradigm

3.1 Introduction

Multitasking has a long tradition as a research field addressing the capacity to deal with several cognitive challenges at the same time. Although the brain is characterised by massive parallel firing of neurones, many cognitive dual-task studies have – quite startlingly – suggested that central mental operations (e.g. deciding what to do) can only be carried out serially.

Almost 90 years ago Telford (1931) described a cognitive phenomenon termed *psychological refractory period (PRP)*. Using neural refractoriness as an underlying (probably somewhat misguided) metaphor (see Pashler, 1994), the core assumption of the PRP was that a mental 'barrier against immediate repetition' accounts for longer response times (RTs) for the second of two successive responses when they were stimulated in rapid (vs. slow) succession (see also Welford, 1952). Typically, latencies of the second response (RT_2) increase as the temporal interval between the stimuli for the two responses (stimulus onset asynchrony, SOA) decreases, equivalent to a slope of nearly -1 especially at short SOAs. This *PRP effect* has been replicated many times (Herman & Kantowitz, 1970; Pashler, 1984, 1994), and usually is associated with the observation that latencies of the first response are largely unaffected by SOA (see Figure 3.1A).

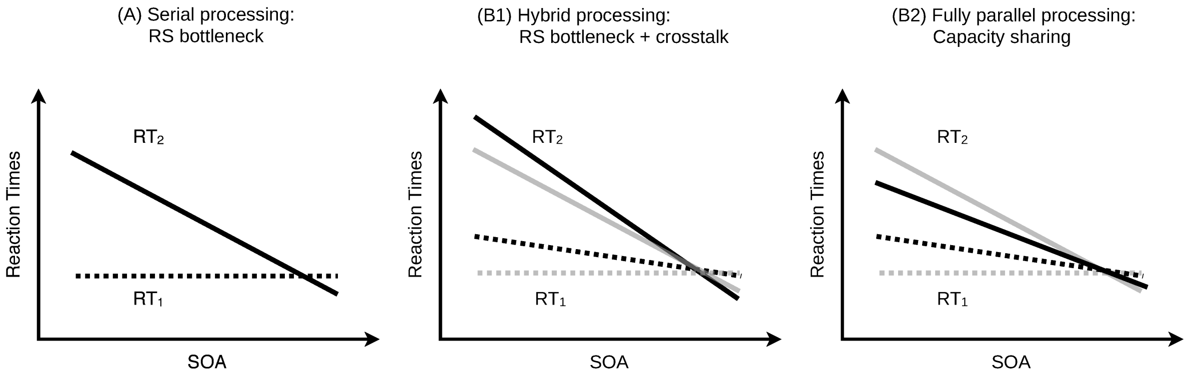

Figure 3.1. Different accounts of central processing interference in dual tasks (inspired by Fischer & Plessow, 2015): (A) Strictly serial response selection as predicted by a basic RSB account, in which SOA and compatibility selectively affect RT_2 but not RT_1. RT_2 decreases with increasing SOA (slope $= -1$ at short SOAs). (B1) Hybrid account assuming a parallel response activation (RA) stage prior to serial RS. Parallel RA allows for mutual between-task crosstalk resulting in RT_1 impairments (backward crosstalk). Note that effects on RT_1 should propagate onto RT_2 due to serial RS, resulting in a steeper RT_2 slope (< -1) at short SOAs. (B2) Central capacity sharing account allowing for fully parallel processing. Relative impairments in Task 1 at short SOAs are compensated for by (relative) benefits in Task 2, yielding a less steeper RT_2 slope (> -1). Black lines denote the expected data pattern for RT_1 and RT_2 relative to a basic RSB account (grey lines in panels B1 and B2).

One of the most prominent explanations for the PRP effect is based on the premise that cognitive task processing can be subdivided into three stages: Stimulus processing (SP), response selection (RS), and response execution (RE). Crucially, the central RS stage is assumed to constitute a structural bottleneck that allows only one response to be selected at a time (response selection bottleneck [RSB] model). As a result, RS stages for two temporally overlapping tasks must be carried out sequentially – an assumption that has been corroborated by numerous empirical observations (see Pashler, 1994).

The RSB is considered to represent a universal, generic mechanism that operates independent of specific stimulus and response characteristics (e.g. Lien, McCann, Ruthruff, & Proctor, 2005). Thus, effector systems associated with the two tasks (or their specific combination) should not affect central RS operations. Due to this assumption of an a-modal, rather abstract RS stage, the majority of PRP studies did not explicitly touch upon the issue of response modalities, and thus typically involved only a limited set of effector systems (e.g. manual-manual or manual-vocal task combinations, see Pashler, 1994; Huestegge & Hazeltine, 2011), with only very few exceptions (Osman & Moore, 1993; Pashler & Christian, 1994). However, everyday multitasking involves a much larger range of effectors, including movements of the eye. Surprisingly, until now only one PRP study addressed eye movements (Pashler, Carrier, & Hoffman, 1993).

Interestingly, this single pioneering attempt failed to demonstrate a typical PRP effect for eye movements. Specifically, Pashler et al. (1993) conducted four EOG experiments in which Task 1 was an auditory-manual task (left or right key press in response to a high or low tone) and Task 2 was a visual-oculomotor task (involving saccades to left or right targets). In the large majority of trials, the stimulus for the manual task was presented first (asymmetrical SOA range between -150 ms and $+750$ ms) in search for a PRP effect in oculomotor RTs (Task 2). Across experiments, the oculomotor task was varied: Experiments 1 and 2 required eye movements towards salient peripheral stimuli (i.e. stimulus and response target were the same object), yielding only small dual-task interference without any signs of a typical PRP effect. The authors concluded that eye movements to salient visual stimuli in the periphery (similar to visual orienting responses) are able to bypass central processing (see Huestegge & Koch, 2014, for similar evidence regarding the special role of saccades triggered by salient peripheral visual stimuli). However, in Experiments 3 and 4 involving left and right eye movements based on a rather arbitrary discrimination process (i.e. saccade to the larger of two peripherally presented numbers or to a left or right target based on a central colour cue) that required a more deliberate central decision process much larger cross-task interference was observed, resembling a PRP effect. However, this effect was less pronounced (with a slope closer to -0.5 than -1) than in a control experiment utilising vocal (instead of oculomotor) responses (Experiment 5). Based on results from Experiments 3 and 4, it was suggested that eye movements may have occupied the central bottleneck only briefly. In sum, the authors concluded that the ‘data do raise some interesting puzzles’ (Pashler et al., 1993, p. 74), which clearly calls for further research on the cognitive control of eye movements in the PRP paradigm. While it is surprising per se that this issue has not been pursued afterwards, some of the observations in Pashler et al.’s study (1993) that could not be reconciled with a RSB model at that time, however, might today be better understood within dual-task frameworks that have been developed since then. Particularly, mechanisms related to response order, crosstalk, and more recent theoretical frameworks (e.g. capacity sharing) served as starting points for the present study.

3.1.1 Potentially relevant mechanisms when considering oculomotor control in dual tasks

Response order

The data reported in Pashler et al. (1993) experiments involving oculomotor responses suggest the occurrence of a considerable number of response reversals (i.e. response sequence not according to the respective stimulus sequence) especially at short SOAs. Thus, even when the oculomotor response was triggered second it was still initiated first in a considerable amount of trials. However, a crucial precondition for the interpretation of effects on RT_2 within the RSB framework is that RS should occur first for the task that has completed SP first (first-come, first-served principle). Assuming comparable stage durations for both tasks, this precondition should result in non-reversed responses – a pattern that is indeed usually observed in PRP experiments involving manual and vocal responses (and occasionally reinforced through explicit response order instructions, see Pashler, 1994). Thus, the observation of many response reversals in Pashler et al. (1993), who did not utilise specific response order instructions, are either attributable to substantial differences in stage durations across tasks, or to violations of the first-come, first-served principle within the RSB framework. While Pashler et al. (1993) addressed these issues to some extent by carrying out post hoc analyses of inter-response intervals, an experimentally controlled situation would be desirable that involves more comparable SP and RS demands across tasks and that explicitly takes response order into account for the analyses of SOA effects.

Crosstalk

Another important source of dual-task interference beside the structural RSB is the notion of crosstalk. While the RSB is conceptualised as a content-blind mechanism that predicts structural interference whenever two responses need to be selected in close temporal proximity, crosstalk is assumed to occur when there is dimensional overlap between content across tasks, for example, when one task requires a (spatial) ‘left’ response and the other task requires a (spatial) ‘right’ response (Navon & Miller, 1987). Thus, this source of interference should be especially important when two inherently spatial (e.g. manual and oculomotor) tasks are combined. Note that Pashler et al. (1993) did not analyse effects of response compatibility, thus leaving room for novel theoretical insight regarding the role of crosstalk between oculomotor and manual responses in the PRP paradigm.

Interestingly, previous studies already demonstrated that crosstalk plays an important role in simultaneously executed saccades and manual responses, albeit not employing the PRP paradigm. Based on mixed evidence regarding interference between simultaneously executed saccades and manual responses (see Bekkering, Adam, Kingma, Huson, & Whiting, 1994; Huestegge, 2011, for a review), Huestegge & Koch (2009; see also Huestegge & Koch, 2010) systematically examined crosstalk in a series of experiments requiring participants to respond to auditory stimuli (i.e. tones on the left or right side) with a saccade towards a left or right target on the screen, a manual left or right key press, or both. Note that in this setup the (auditory) stimulus did not spatially coincide with the (visual) saccade target. Crucially, they manipulated spatial compatibility between stimuli and responses (via instructions), and found evidence for mutual interference (in terms of dual-response costs) which was especially pronounced when both responses were spatially incompatible to each other. This pattern of mutual crosstalk effects suggests that saccades suffer from dual-response interference (passive role) as well as induce costs in the concurrent manual response (active role). Note, however, that responses in this study were not triggered independently but by a common stimulus, thus constituting a special case of a dual-response compound, which might genuinely differ from a dual task situation involving two separate stimuli. Therefore, results from this study prevent any generalisation to commonly studied dual-task situations, such as the PRP paradigm.

In contrast, other studies addressed the role of crosstalk in the PRP paradigm, although without examining oculomotor control. These studies typically compared performance in trials involving spatially compatible responses with performance in trials involving incompatible responses. As a result, these studies report longer RTs in Task 2 for incompatible (than for compatible) trials (e.g. Hommel, 1998a), a finding that can be attributed to a beneficial or adverse influence of Task 1 characteristics on Task 2 performance. Crucially, these studies additionally report a compatibility effect on RT_1, a finding usually referred to as *backward crosstalk effect* (e.g. Hommel, 1998a; Janczyk, 2016; Janczyk, Pfister, Hommel, & Kunde, 2014; Logan & Schulkind, 2000; Miller, 2006; Miller & Alderton, 2006; Thomson, Watter, & Finkelshtein, 2010). This finding is intriguing since according to a basic RSB framework any response-related processing in Task 1 should be independent from response-related processing in a successive Task 2. Backward crosstalk is usually interpreted as evidence for parallel response-related processing (prior to RE) and has given rise to modifications of the basic RSB framework, which will be further outlined in the following section.

Alternative theoretical frameworks

Importantly, the data from Pashler et al. (1993) were discussed only against the backdrop of a *basic RSB framework* based on the assumptions of three consecutive processing stages and strictly serial processing of response-related information prior to RE. However, in the light of backward crosstalk effects the RSB framework was extended by challenging these two claims. Specifically, Hommel (1998a) proposed a framework that assumes both a parallel and a serial stage of response-related processing, thus representing a *hybrid* account. SP is assumed to be immediately followed by a response activation (RA) stage involving the parallel translation of stimulus codes into response codes in both tasks, thus allowing for mutual between-task crosstalk. The following (serial) RS stage then only involves the final selection among response alternatives and is assumed to constitute the central processing bottleneck (see also Schubert, Fischer, & Stelzel, 2008). One prediction of this hybrid model is that any adverse effects of backward crosstalk on RT_1 should propagate onto RT_2 (see Figure 3.1.B1), eventually resulting in a steeper slope (i.e. steeper than -1) for RT_2.

Finally, a further alternative set of dual-task accounts that was not explicitly considered by Pashler et al. (1993) is based on the idea of continuous (parallel) *capacity sharing* among tasks (e.g. Navon & Miller, 2002; Tombu & Jolicœur, 2003). These accounts negate the necessity of a generic bottleneck but rather assume that the cognitive system is principally capable of parallel processing throughout all stages. PRP effects are typically explained in terms of strategic shifts of (limited) resource allocation routines. One prediction of these limited single-resource accounts is that a relative performance benefit in one task should be compensated for by a (relative) performance decrease in the other task (see Figure 3.1.B2). However, it should be noted that it is difficult to clearly distinguish between the hybrid account and the capacity sharing account based on experimental data (especially when potential propagation effects must be accounted for, see individual Discussion sections of the present experiments). For example, an RT_2 slope less steeper than -1 in conjunction with a moderate negative RT_1 slope at first sight appears to represent evidence for a fully parallel model, but an RT_2 slope less steeper than -1 is also consistent with a hybrid model when assuming a very short RS stage (see Pashler et al., 1993). However, both the hybrid and the parallel account have in common that they assume parallel response-related processing prior to RE, thus both are inconsistent with a purely serial response-related processing (prior to RE) account that served as a theoretical backdrop of the study by Pashler et al. (1993). Thus, the present study aims to distinguish between a serial and a (partially) parallel response-related processing account of oculomotor-manual interference in the PRP paradigm.

3.1.2 The present study

The present study addressed the control of manual and oculomotor responses in the PRP paradigm. Following up on the pioneering study by Pashler et al. (1993), our present experiments aimed at implementing comparable SP stage durations and S-R mapping demands across tasks while avoiding the special case of oculomotor responses towards salient visual peripheral stimuli (i.e. spatially coinciding location of stimulus and target). Additionally, we aimed at taking response order and crosstalk into account in our analyses, which ultimately allows us to test a basic RSB framework (serial RS without any prior response-related processing) against more recent accounts assuming (partially) parallel response-related processing prior to RE.

Specifically, we utilised two (comparable) auditory stimuli, a pure tone and a noise burst, triggering an oculomotor response to a left or right target (both peripheral targets were permanently visible throughout the experiment) and a left or right manual key press response. Note that both tasks involved a comparable S-R translation effort that was greater than in tasks with spatially coinciding stimulation and response location, but smaller than in tasks involving completely arbitrary S-R mappings. We implemented three different SOAs (120 ms, 240 ms, and 360 ms) in two stimulus order conditions, in which the stimulus for the oculomotor response either preceded the stimulus for the manual response (S_OS_M) or vice versa (S_MS_O). By utilising such a symmetrical SOA manipulation (unlike in Pashler et al., 1993) we aimed at studying the role of saccades from two different perspectives, namely as Task 1 in S_OS_M conditions (*active* role of oculomotor control by causing delayed processing in the manual task) and as Task 2 in S_MS_O conditions (*passive* role of oculomotor control being subject to a potential processing bottleneck). By distinguishing between these two roles of oculomotor responses in dual tasks, we explicitly take response order into account. Finally, by manipulating spatial between-task compatibility we are able to address (backward) crosstalk as a potentially important additional source of interference.

Based on this design, the following main hypotheses were tested: First, if oculomotor control bypasses any response-related processing limitations in our setup, we would expect to find neither effects of SOA (e.g. in terms of a PRP effect) nor effects of task compatibility (e.g. in terms of crosstalk) in any of the two tasks. Second, a basic RSB account would predict a marked SOA effect (and potentially a crosstalk effect) on RT_2 but no effects on RT_1. Third, if we assume (partially) parallel response-related processing prior to RE, we would expect to observe both SOA and compatibility effects on RT_1 and RT_2.

Experiment 1 involved the presentation of stimuli in mixed order without any specific instructions regarding response order. To anticipate an important aspect of the results, this experiment yielded only very few cases in which the manual response preceded the oculomotor response. Thus, it was impossible to examine the passive role of saccades as R_2 in S_MS_O stimulus order conditions (as envisioned in Pashler et al., 1993; see also Study D, for a detailed analysis of response order control mechanisms in the present paradigm). We addressed this issue by introducing two measures typically utilised in PRP studies to discourage response reversals. In Experiment 2, we replicated Experiment 1 but *explicitly* instructed participants to respond according to stimulus order. In Experiment 3, we utilised a fixed stimulus order instead (i.e. the stimulus for the oculomotor response was always presented second), serving as an *implicit* measure to decrease the likelihood of response reversals.

3.2 Experiment 1

In Experiment 1 we aimed at studying dual-task mechanisms underlying oculomotor control in the PRP paradigm. We utilised a symmetrical SOA design (involving an equal amount of trials for both S_OS_M and S_MS_O conditions) without any explicit instructions regarding response order. Between-task compatibility was manipulated to address crosstalk.

3.2.1 Method

Participants

Twenty-four participants (16 female and 8 male) with a mean age of 23.2 years (range = 20–30) participated in Experiment 1. They had normal or corrected-to-normal vision and hearing and received course credits or monetary reimbursement.

Apparatus

Participants were seated 67 cm in front of a 21 inch cathode ray monitor (temporal resolution: 100 Hz; spatial resolution: 1024 px × 768 px) with a keyboard in front of them. The space bar of the keyboard was used during calibration routines. Saccades were registered using a head-mounted Eyelink II infrared reflection system (SR Research, Osgoode, Ontario, Canada) by measuring the position of the right eye's pupil (temporal resolution $= 500$ Hz and spatial resolution $< 0.0022°$). A chin rest was used to minimise head movements.

Stimuli

The display, which remined unchanged throughout each block, consisted of a green fixation cross in the centre of a black screen as well as two green rectangular squares as saccade targets at 8.3° of visual angle to the left and right of the fixation cross. The size of the fixation cross and the targets was 0.33° ($=$ 10 px) each. Two keys (*left Ctrl* and *right arrow*) served as response keys. Two unilateral auditory stimuli (one for each task), a 1000 Hz pure tone and a pink noise burst with a duration of 50 ms each, were presented via supra-aural headphones. Both stimuli were easily audible and of comparable loudness.

Procedure

Each block started with an on-screen instruction followed by a calibration of the eye tracking system. In dual-task blocks both stimuli appeared sequentially with a variable SOA in random order. The experiment also contained an SOA of 0 ms (simultaneous presentation of both stimuli). While this condition was implemented for the sake of comparison to other experiments at our laboratory, it is not relevant for the present study and corresponding data will not be reported in the analyses.

Participants were instructed to execute the two responses as fast and accurately as possible without being informed or instructed about the order of stimuli or about response order (similar to Pashler et al., 1993). The two auditory stimuli (pure tone and noise burst, each presented to the left or right ear) were each assigned to the manual and oculomotor task, respectively (counterbalanced across participants). In the oculomotor task participants were required to respond with a gaze shift to the target on the screen that spatially corresponded to the ear the stimulus was presented to. Note that the auditory stimuli were played via headphones and did not originate at the position of the saccade targets to rule out quasi-reflexive visual orientation responses. For the manual task, participants were required to press the key that spatially corresponded to the stimulus. The trial duration (i.e. the interval between the first stimuli of two consecutive trials) was held constant at 3500 ms. Additionally, participants completed two single task blocks, one for each task, in which only one stimulus was presented and only one single response was required. These single-task conditions were implemented to assess oculomotor and manual performance in isolation without any additional secondary task demands. The inter-stimulus interval in single-task blocks was varied randomly (2750 ms, 3250 ms, 3750 ms, and 4250 ms, resulting in 3500 ms on average) to prevent anticipation of the stimulus onset in these very simple tasks.

Each participant completed four dual-task blocks consisting of 56 trials each and two single-task blocks (one for each component task) containing 32 trials each. The order of these six blocks was counterbalanced across participants utilising a 6 × 6 latin square.

Design

Task (oculomotor and manual), stimulus order (oculomotor stimulus first, i.e. $S_O S_M$, and manual stimulus first, i.e. $S_M S_O$), spatial between-task compatibility (compatible and incompatible), and SOA (120 ms, 240 ms, and 360 ms) were manipulated within participants.

The mapping of stimulus type (pure tone and noise burst) to response modality (saccade and manual key press) was counterbalanced across participants. Each SOA was presented 16 times in each compatibility condition so that the four possible stimulus combinations were presented equally often per SOA and compatibility condition (i.e. both stimuli on the left, both on the right, tone on the left and noise on the right, or noise on the left and tone on the right). Response times and response accuracy were measured as dependent variables.

3.2.2 Results

Valid data were determined by removing trials with technical irregularities, anticipative responses ($<$ 70 ms for saccades and $<$ 150 ms for manual responses), and trials in manual single blocks with erroneously executed saccades. One participant was excluded from the analysis because of an unusually high amount of errors ($>$ 40 %). This procedure yielded 94.1 % valid data. Additionally, we separately analysed the data by response order ($R_O R_M$ and $R_M R_O$) in both stimulus order conditions ($S_O S_M$ and $S_M S_O$) and removed trials in which response order did not match stimulus order. Oculomotor RTs in baseline single-task conditions were significantly faster than manual RTs (274 ms vs. 394 ms), $t(22) = 9.55$, $p < .001$.

Active role of oculomotor responses ($S_O S_M$ order)

Responses in the $S_O S_M$ order condition were executed according to stimulus order in 95.3 % of the trials. RT analyses included correct trials only. Figure 3.2 shows mean RTs and error rates of oculomotor and manual responses as a function of compatibility and SOA.

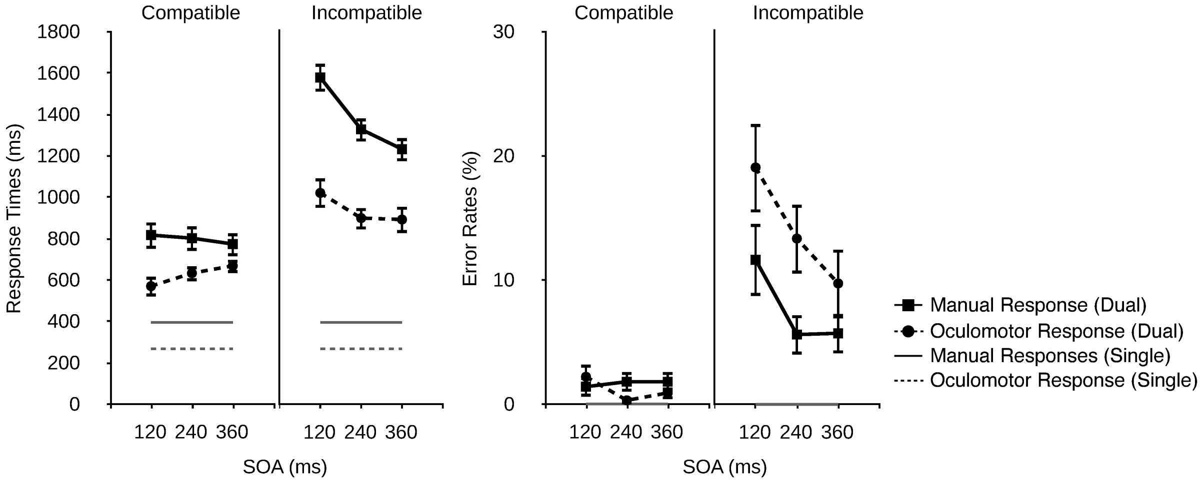

Figure 3.2. RTs (left panel) and error rates (right panel) of oculomotor and manual responses as a function of between-task compatibility (compatible and incompatible) and SOA in the $S_O S_M$ order condition in Experiment 1. Horizontal lines (without indicators) represent baseline RTs in single-task conditions. Error bars represent standard errors. Note that error rates virtually amounted to 0 % in single-task conditions and were therefore not included in the figure.

RT_1 (oculomotor task). The main effect of compatibility was significant, $F(1,22) = 44.87$, $p < .001$, $\eta_p^2 = .67$, indicating longer oculomotor RTs for incompatible (934 ms) than for compatible responses (623 ms). While there was no main effect of SOA, $F < 1$, we observed a significant interaction with compatibility, $F(2,44) = 12.93$, $p < .001$, $\eta_p^2 = .37$. Post hoc contrasts indicated that oculomotor RTs significantly increased with larger SOAs for compatible tasks, $F(2,44) = 7.72$, $p = .005$, $\eta_p^2 = .26$, while they decreased for incompatible tasks, $F(2,44) = 5.8$, $p = .006$, $\eta_p^2 = .21$.

RT_2 (manual task). The main effect of compatibility was significant, $F(1,22) = 99.91$, $p < .001$, $\eta_p^2 = .82$, indicating a large compatibility effect of 578 ms. Importantly, there was a main effect of SOA, $F(2,44) = 22.97$, $p < .001$, $\eta_p^2 = .51$, signifying decreasing RTs with larger SOAs. However, the two-way interaction was also significant, $F(2,44) = 24.5$, $p < .001$, $\eta_p^2 = .53$. Post hoc analyses revealed that the effect of SOA was only significant for incompatible responses, $F(2,44) = 29.69$, $p < .001$, $\eta_p^2 = .57$, but not for compatible responses, $F(2,44) = 1.61$, $p = .212$.

Error rates. As in the RT analysis, we removed reversal trials (1.8 % of the valid data) prior to the analysis of error rates. Thus, percentage values are based on non-reversed trials only (see Figure 3.2, right panel). Single-task error rates virtually amounted to 0 % in both tasks. Error rates for oculomotor responses were higher for incompatible (vs. compatible) trials (14 % vs. 1.1 %), $F(1,22) = 26.23$, $p < .001$, $\eta_p^2 = .54$, (main effect of compatibility), and overall decreasing with increasing SOA, $F(2,44) = 8.72$, $p = .001$, $\eta_p^2 = .28$, (main effect of SOA). However, a significant interaction of compatibility and SOA, $F(2,44) = 5.59$, $p = .007$, $\eta_p^2 = .20$, indicates that SOA only affected incompatible trials.

Manual error rates were also affected by compatibility (7.6 % in incompatible and 1.6 % in compatible trials), $F(1,22) = 17.3$, $p < .001$, $\eta_p^2 = .44$, and by SOA, $F(2,44) = 4.79$, $p = .013$, $\eta_p^2 = .17$. The interaction was also significant, $F(2,44) = 4.63$, $p = .027$, $\eta_p^2 = .17$, again indicating that SOA only affected incompatible trials (similar to oculomotor responses).

Passive role of oculomotor responses ($\mathrm{S_M S_O}$ order)

The reversal rate (including trials containing an error in at least one of the responses) in the $\mathrm{S_M S_O}$ order condition amounted to 83.3 %. Only five participants sometimes executed responses in accordance with stimulus order. Consequently, there were not enough data across all SOA conditions for a meaningful analysis regarding the passive role of saccades as being subject to central processing postponement.

Additional analysis: Reversed responses in the $\mathrm{S_M S_O}$ order condition. While it is difficult to interpret the results of reversed responses in the PRP paradigm against the backdrop of RSB theory (see Introduction), we reasoned that corresponding performance can still be informative to explain certain aspects of the data reported above. Specifically, it is important to keep in mind that in order to reverse responses in $\mathrm{S_M S_O}$ order conditions participants must have buffered $\mathrm{S_M}$ until $\mathrm{S_O}$ is processed and translated into a response, in order to select the appropriate response for $\mathrm{S_M}$ afterwards (i.e. a violation of the first-come, first-served principle for entering the RS stage). Hence, the SOA manipulation cannot be interpreted in the usual way (i.e. in the context of RSB theory assumptions). RTs and error rates of reversed responses in the $\mathrm{S_M S_O}$ order condition are depicted in Table 3.1.

Given that the SOA manipulation is difficult to interpret in that it mainly affects the necessary buffering time for $\mathrm{S_M}$ (see above), a comparison with the data from non-reversed responses in the $\mathrm{S_O S_M}$ order condition (Figure 3.2) should mainly focus on the means averaged across SOA conditions (see corresponding column in Table 3.1). Visual inspection shows that responses generally tend to be delayed (and in the case of incompatible task conditions also more error-prone for oculomotor responses) for reversed responses in the $\mathrm{S_M S_O}$ order condition when compared to the non-reversed responses in the $\mathrm{S_O S_M}$ order condition. However, there is one notable exception, namely oculomotor responses in compatible task conditions. A corresponding statistical comparison of oculomotor RTs

Table 3.1

RTs (ms) and error rates (%) of oculomotor and manual responses in the reversed response order trials (R_OR_M) in the S_MS_O order condition.

Between-Task Compatibility	Task	RTs (ms)				Error rates (%)			
		SOA (ms)				SOA (ms)			
		120	240	360	Mean	120	240	360	Mean
Compatible	Oculomotor (RT_1)	462	398	417	425	1.8	2.8	2.5	2.4
	Manual (RT_2)	919	981	1129	1010	0.7	0.4	0.4	0.5
Incompatible	Oculomotor (RT_1)	1071	1040	937	1016	26.2	31.7	27.6	28.5
	Manual (RT_2)	1749	1766	1690	1735	11.9	5.5	5.2	8.5

Note. Data are based on $N = 19$ participants.

in compatible trials between both stimulus order conditions revealed faster oculomotor RTs (425 ms) for reversed responses in S_MS_O order conditions than for non-reversed responses in S_OS_M order conditions (mean = 618 ms), $F(1,18) = 269.9$, $p < .001$, $\eta_p^2 = .94$, despite the fact that S_O was available much earlier in the latter condition. In contrast, compatible manual RTs in the S_MS_O order condition were slower (1010 ms) than corresponding manual RTs in the S_OS_M order condition (761 ms), $F(1,18) = 226.6$, $p < .001$, $\eta_p^2 = .93$. These data, along with the very large gap between single-task RTs and RT_1 in dual-task conditions (see Figure 3.2), suggest a processing strategy which is not in line with the assumption of an immediate and continuous SP and RS processing in Task 1 (as envisioned in basic RSB theory) in either of the two stimulus order conditions (see Discussion for more details).

3.2.3 Discussion

The results do not reflect a clear picture of strictly serial response-related processing prior to RE. Specifically, such a basic RSB mechanism (see Figure 3.1.A) would predict that in the S_OS_M order condition manual RTs should increase with decreasing SOAs with a slope of approximately -1 at short SOAs (i.e. between 120 ms and 240 ms, whereas oculomotor RTs should be largely unaffected. However, an SOA effect on manual RTs was either absent (in compatible trials) or beyond typical PRP effects (i.e. a slope of -2.1 in incompatible trials), and SOA clearly affected oculomotor RTs. While the discrepancy of our current data with a basic RSB framework is generally in line with similar conclusions in Pashler et al. (1993), some important differences should be noted. Most importantly, the majority of trials in Pashler et al. (1993) consisted of S_MS_O order conditions in order to specifically search for a PRP effect in oculomotor responses as a second response. The substantial amount of response reversals in the corresponding condition of the present study, however, renders any clear conclusion regarding a PRP effect in oculomotor responses (‘passive role’ of oculomotor responses) impossible. Probably, the symmetrical SOA manipulation in the present study (compared to the asymmetric SOA manipulation in Pashler et al. (1993) is responsible for the high reversal rates, a claim that will be directly addressed in Experiment 3.

In contrast to a basic RSB framework with strictly serial response-related processing prior to RE, the current data are more in line with the assumption of (partially) parallel response-related processing prior to RE (see Figure 3.1.B1/B2). Especially in incompatible trials the data pattern could be explained by assuming a hybrid account consisting of a parallel RA stage and a serial RS stage (Figure 3.1.B1, e.g. Hommel, 1998a; Watter & Logan, 2006). The latter is reflected in the manual RT increase for decreasing SOAs, whereas crosstalk based on parallel RA could explain the SOA effect on oculomotor responses. The fact that manual RTs exhibited a slope of close to -2 rather than -1 at short SOAs (see Figure 3.2) can be attributed to the propagation of the backward crosstalk effect in RT_1 (which is characterised by a slope of about -1) onto RT_2. In addition, the observation that task incompatibility also elevated error rates in Task 1 further supports the assumption of (partial) parallel processing, because responses within each task were always spatially compatible to the location of the stimulus and thus easy to select (as evidenced by the negligible error rates in single-task conditions). In contrast, a fully parallel capacity sharing account (Figure 3.1.B2) is not in the same way suited to explain these data, since it would typically predict that the *relative* slope of RT_2 (i.e. $\text{slope}_{RT_2} - \text{slope}_{RT_1}$) should be less steep than -1.

The data from the compatible condition, however, are more difficult to interpret. Apart from the lack of a PRP effect in manual RTs, an interesting observation here is the increase of oculomotor RTs with SOA (i.e. of 98 ms from SOA $=$ 120 ms to 360 ms). This finding suggests that the execution of the oculomotor response was strategically withheld until the response selection of the manual response was finished, an interpretation which is consistent with constant manual RTs across all SOA levels. Interestingly, De Jong (1995) found a similar (although not significant) RT_1 increase with increasing SOA in conditions when participants were not specifically instructed to match response order to stimulus order. However, since inter-response intervals (367 ms, 409 ms, and 465 ms for SOA = 120 ms, 240 ms, and 360 ms, respectively) were much larger than intervals typically associated with response grouping (i.e. intervals up to max. 200 ms, e.g. Ulrich & Miller, 2008) it is implausible that participants withheld the oculomotor response in order to execute a grouped response compound.

One possibility is that oculomotor task processing was withheld with the goal to compare both stimuli in order to adjust the processing mode based on task compatibility. Such a dedicated stimulus comparison process together with the assumption of diverging processing modes in compatible and incompatible task conditions would also be able to explain the pronounced difference in RT patterns between compatibility conditions. This possibility is further supported by the observation from the additional analysis of reversed responses in the S_MS_O order condition, which revealed that oculomotor responses were initiated faster in trials with reversed responses in the S_MS_O order condition than in trials with non-reversed responses in the S_OS_M order condition. This finding, together with the very large RT gap between oculomotor single- and dual-task RTs, further suggests that oculomotor task processing in the S_OS_M order condition was withheld at some point, probably due to stimulus comparison processes.

The general observation of a substantial amount of response reversals in the S_MS_O order condition can be interpreted in terms of a general prioritisation of oculomotor responses over manual responses. Previous research has demonstrated such response modality-based dominance effects in terms of characteristic patterns of dual-task interference in RTs (Huestegge & Koch, 2013; Pieczykolan & Huestegge, 2014), and the present data suggest that prioritisation may also impact on response order decisions (see also Study D on response order control). It appears conceivable that this prioritisation (mostly reflected in the high reversal rates in the S_MS_O order condition) also affected processing in the S_OS_M order condition. Assuming that participants pursued an overall oculomotor-first strategy during the entire experimental session, oculomotor responses in compatible trials might have been especially fast in S_MS_O order conditions because participants already had processed S_M and then used the onset of a spatially compatible S_O as a trigger to immediately initiate the (prioritised) saccade based on the spatial code generated for S_M. In incompatible trials, however, the onset of an incompatible S_O might have started another resource-demanding processing mode associated with the spatial disambiguation of the mapping of spatial codes to the two response modalities (which is not necessary in the case of compatible tasks). If this functional strategy (i.e. to wait for and to compare both stimuli) spilled over onto the S_OS_M order conditions, this would explain why oculomotor responses in these conditions increased with increasing SOA. Note that this functionally strategic account (i.e. waiting until all environmental cues are present) would also explain why both responses were always executed after the presentation of both stimuli, despite the fact that saccade latencies in single-task conditions ranged substantially below the largest SOA.

3.3 Experiment 2

In Experiment 1, the substantial amount of response reversals in the $S_M S_O$ order condition prevented the examination of a PRP effect in the oculomotor responses (as RT_2). Since in many (albeit not all) PRP studies participants are explicitly encouraged to respond in accordance with stimulus order, we hypothesised that the absence of a corresponding instruction in Experiment 1 may have promoted the occurrence of response reversals. Therefore, we repeated the same experiment but now explicitly instructed participants to respond according to stimulus order.

3.3.1 Method

Participants

Twenty-four new participants (6 male and 18 female) with a mean age of 24.9 years (range = 19–30) were recruited and received course credits or monetary reimbursement for participation.

Apparatus, Stimuli, Procedure, and Design

The experimental setup was exactly the same as in Experiment 1 with two exceptions. First, a desktop-mounted Eyelink 1000 (instead of a head-mounted Eyelink II) was used for recording eye movements with a temporal resolution of 1000 Hz. Second, participants were explicitly instructed to carry out their responses in correspondence with stimulus order.

3.3.2 Results

Applying the same data cleansing procedure as in Experiment 1 and excluding one participant from the analysis because of an unusual amount of erroneous saccades in incompatible trials ($> 60\,\%$ incorrect) resulted in $95.2\,\%$ valid data. As in Experiment 1, the analysis only contained trials in which participants responded in the instructed response order (thus, in accordance with stimulus order). Unlike Experiment 1, Experiment 2 enabled us to examine potential PRP effects in both manual and oculomotor responses (i.e. when they represented the second response and were triggered by the second stimulus, respectively). Because five participants still executed the oculomotor response first in the majority of trials in the $S_M S_O$ conditions (causing empty cells for many SOA conditions), corresponding analyses are based on 18 complete data sets.

Active role of oculomotor responses ($S_O S_M$ order)

Reversals in the $S_O S_M$ order condition occurred only rarely (6.1 %) and were removed from the analysis. Results for RTs and error rates are depicted in Figure 3.3.

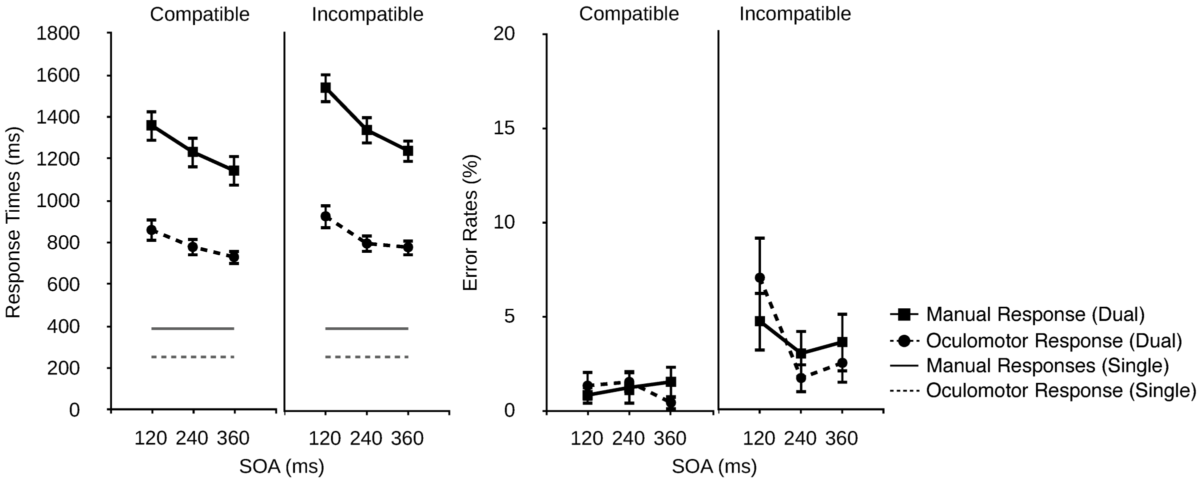

Figure 3.3. RTs (left panel) and error rates (right panel) of oculomotor and manual responses as a function of between-task compatibility (compatible and incompatible) and SOA in the $S_O S_M$ order condition in Experiment 2. Horizontal lines (without indicators) represent baseline RTs in single-task conditions. Error bars represent standard errors. Note that error rates virtually amounted to 0 % in single-task conditions and were therefore not included in the figure.

RT_1 (oculomotor task). There was no significant main effect of compatibility, $F(1,17) = 3.37$, $p = .084$, $\eta_p^2 = .17$, but a significant main effect of SOA, $F(2,34) = 20.64$, $p < .001$, $\eta_p^2 = .55$, with decreasing RTs with increasing SOA (893 ms, 786 ms, and 753 ms). There was no significant interaction, $F < 1$.

RT_2 (manual task). There was a significant main effect of compatibility, $F(1,17) = 12.71$, $p = .002$, $\eta_p^2 = .43$, indicating longer manual RTs in incompatible trials (1367 ms) than in compatible trials (1245 ms). Additionally, there was a significant main effect of SOA, $F(2,34) = 60.98$, $p < .001$, $\eta_p^2 = .78$, indicating a decrease of RTs with increasing SOA (1447 ms, 1283 ms, and 1189 ms). The interaction was not significant, $F(2,34) = 1.58$, $p = .22$.

Error rates. Error rates in the oculomotor task (R_1) were higher for incompatible compared to compatible trials (3.8 % vs. 1.1 %), $F(1,17) = 4.94$, $p = .04$, $\eta_p^2 = .23$, and decreased with increasing SOAs, $F(2,34) = 6.21$, $p = .011$, $\eta_p^2 = .27$. The interaction of compatibility and SOA did not reach significance, $F(2,34) = 3.21$, $p = .076$, $\eta_p^2 = .16$, although descriptively SOA had a stronger effect in incompatible trials (see Figure 3.3, right panel). Manual error rates (R_2) were also affected by compatibility (3.8 % for incompatible and 1.2 % for compatible trials), $F(1,17) = 7.28$, $p = .015$, $\eta_p^2 = .30$, but not by SOA, $F < 1$. The interaction was not significant, $F < 1$.

Passive role of oculomotor responses ($S_M S_O$ order)

Trials, in which responses were executed according to stimulus order, amounted to 54.4 % of the recorded data (including error trials). For the sake of consistency, only data of the same 18 participants as in the $S_O S_M$ order conditions were analysed in $S_O S_M$ order conditions. Figure 3.4 depicts RTs and error rates in the manual and oculomotor tasks as a function of compatibility and SOA.

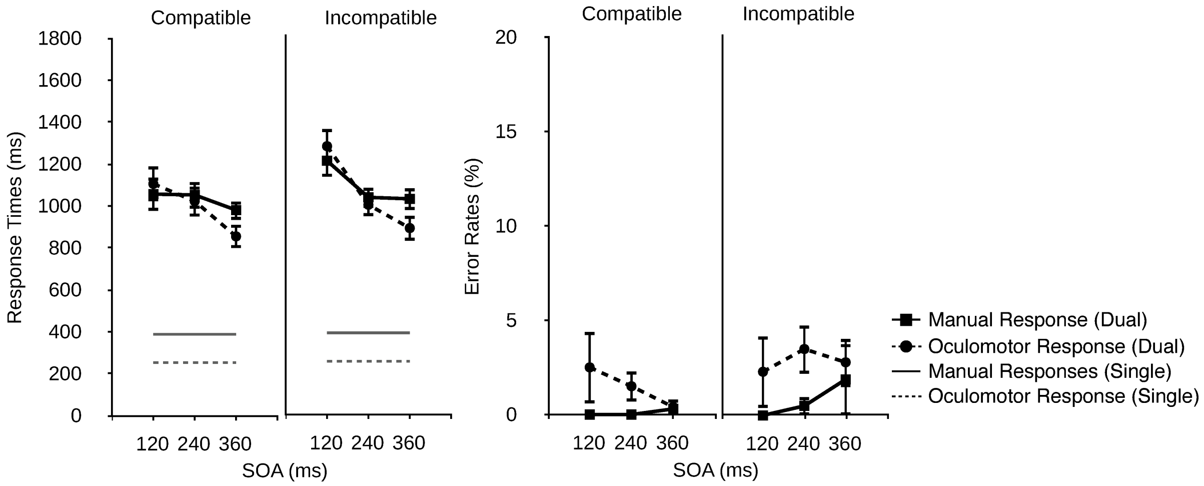

Figure 3.4. RTs (left panel) and error rates (right panel) of oculomotor and manual responses as a function of between-task compatibility (compatible and incompatible) and SOA in the $S_M S_O$ order condition in Experiment 2. Horizontal lines (without indicators) represent baseline RTs in single-task conditions. Error bars represent standard errors. Note that error rates virtually amounted to 0 % in single-task conditions and were therefore not included in the figure.

RT_1 (manual task). There was a significant main effect of compatibility, $F(1,17) = 7.36$, $p = .015$, $\eta_p^2 = .30$, indicating that on average responses in incompatible trials (1089 ms) were slower than in compatible trials (1029 ms). The effect of SOA was significant, too, $F(2,34) = 7.17$, $p = .003$, $\eta_p^2 = .30$, suggesting that RTs decreased with increasing SOA (1130 ms, 1042 ms, and

1002 ms). The two-way interaction was also significant, $F(2{,}34) = 4.04$, $p = .027$, $\eta_p^2 = .19$, indicating a more pronounced SOA effect for incompatible trials. Separate post hoc analyses confirmed a significant SOA effect in incompatible trials, $F(2{,}34) = 7.56$, $p = .002$, $\eta_p^2 = .31$, but not in compatible trials, $F(2{,}34) = 2.52$, $p = .095$.

RT_2 (oculomotor task). There was a significant main effect of compatibility, $F(1{,}17)$ =10.5, $p = .005$, $\eta_p^2 = .38$, indicating faster RTs for compatible (994 ms) than for incompatible conditions (1052 ms). The main effect of SOA was significant, too, $F(2{,}34) = 36.7$, $p < .001$, $\eta_p^2 = .68$, indicating a PRP-like pattern with decreasing RTs for increasing SOAs (1190 ms, 1009 ms, and 870 ms for 120 ms, 240 ms, and 360 ms). There also was a significant interaction, $F(2{,}34) = 4.28$, $p = .022$, $\eta_p^2 = .20$ indicating a more pronounced SOA effect for incompatible than for compatible responses.

Error rates. Similar to the RT analysis, we only included non-reversed trials for the error analysis. Error rates in these trials were very low and amounted to 5 % in the manual task (R_1) and to 2.2 % in the oculomotor task (however, note that within the reversal trials 36.3 % of the trials contained at least one error in one of the tasks). There were neither significant main effects of compatibility or SOA nor a significant interaction.

3.3.3 Discussion

The introduction of an explicit response order instruction in Experiment 2 was successful, in that we obtained a sufficient amount of trials for analysing both the active and passive role of oculomotor responses in the PRP paradigm. First, we will discuss non-reversed responses in the S_OS_M order conditions, which are equivalent to the analyses from Experiment 1.

The data from the incompatible trials in the S_OS_M order condition are very similar to the results obtained in the comparable condition in Experiment 1 and are thus in line with a hybrid account of dual-task processing. Again, there were SOA effects for oculomotor responses (slope of -1 at short SOAs) and manual responses (slope of -1.7). However, the data from compatible trials are quite different from those in Experiment 1. Specifically, we here observed similar SOA effects for oculomotor responses (slope at short SOAs of -0.7) and manual responses (slope at short SOAs of -1), thus the *relative* RT_2 slope (i.e. $\text{slope}_{RT_2} - \text{slope}_{RT_1}$) in compatible trials was far from -1. This could either indicate a very short response selection stage (see Pashler et al., 1993) in compatible trials within a hybrid account, or alternatively, mutual interference with nearly equal resources allocated to both tasks within a fully parallel account (Figure 3.1.B2). The selectively different RT pattern for compatible responses compared to those from Experiment 1 might be due to the voluntary attenuation of oculomotor prioritisation (which was still evident given that about 50 % of responses were reversed in the $S_M S_O$ order condition). This could have been elicited by the explicit response order instructions, suggesting that strategic factors also play a role in determining a processing mode (e.g. after a stimulus comparison process, see Discussion in Experiment 1).

Eventually, Experiment 2 allows us to address the issue of PRP effects for oculomotor responses as Task 2, since we obtained enough trials in the $S_M S_O$ order condition. In contrast to Pashler et al. (1993), we excluded all trials with reversed responses to enable a clearer interpretation of the data with respect to the alternative processing accounts. Taken together, the results are altogether in line with a hybrid account. In compatible trials, we observed a PRP effect in oculomotor RTs (slope of -0.7 at short SOAs), while manual RTs remained largely unaffected. In incompatible trials, the corresponding slope of oculomotor RTs was much steeper (slope of -2.3), but can be explained in terms of propagation of the backward crosstalk effect in manual RTs (manual RT slope $= -1.5$, resulting in a *relative* oculomotor RT slope of -0.8). Given that both the slope of oculomotor RTs in compatible trials and the relative slope of oculomotor RTs in incompatible trials are less steep than -1 (possibly due to a very short RS stage, see Pashler et al., 1993), we cannot finally rule out a fully parallel processing model. Nevertheless, we can clearly conclude that (partially) parallel response-related processing (prior to RE) occurred.

3.4 Experiment 3

It is possible that participants in Experiments 1 and 2 to some extent adopted a strategic processing mode in order to be prepared for both stimulus order conditions within a block of trials. Thus, it would be relevant to analyse performance under fixed stimulus order conditions. In Experiment 3, we utilised the same tasks as in Experiment 1 (i.e. without explicit response order instructions), but the stimulus for the oculomotor response was always presented second. Additionally, we extended the SOA range to further encourage processing in accordance with stimulus order (see Miller, Ulrich, & Rolke, 2009, for effects of SOA distributions on processing). Hence, this should allow an even more conclusive interpretation of the passive role of oculomotor responses in the PRP paradigm.

3.4.1 Method

Participants

Twenty-four new participants (23 female and 1 male) with a mean age of 22.2 years (range = 18–28) were recruited and received course credits or monetary reimbursement for participation.

Apparatus, Stimuli and Procedure

The experimental setup was the same as in Experiment 1. However, Experiment 3 only involved S_MS_O order conditions and included longer SOAs. As in Experiment 1, participants were not informed about stimulus order nor were they given instructions regarding response order.

Design

Task (oculomotor and manual), task compatibility (compatible and incompatible), and SOA (120, 240, 360, 480, 720, 960, and 1200 ms) were manipulated within participants.

3.4.2 Results

97.7 % of the recorded data remained valid after the same data cleansing procedures utilised in the previous experiments. Then, trials with response reversals (17.2 %) were removed from the analysis. RTs and error rates are depicted in Figure 3.5. We conducted two 2×7 ANOVAs with the factors compatibility and SOA, separately for each response modality.

$\mathbf{RT_1}$ (manual task). The analysis yielded a main effect of compatibility, $F(1,23) = 27.07$, $p < .001$, $\eta_p^2 = .54$, indicating prolonged RTs for incompatible (vs. compatible) responses (623 ms vs. 534 ms), and a main effect of SOA, $F(6,138) = 3.01$, $p = .029$, $\eta_p^2 = .14$, suggesting that RTs decreased with increasing SOA. Importantly, compatibility interacted with SOA, $F(6,138) = 8.95$, $p < .001$, $\eta_p^2 = .28$, signifying that the compatibility effect was only effective at short SOAs up to 360 ms, likely indicating a backward crosstalk effect (Hommel, 1998a; Miller, 2006). A separate post hoc analysis of the compatible condition revealed that manual RT_1 was not significantly affected by SOA, $F(6,138) = 1.31$, $p = .28$.

$\mathbf{RT_2}$ (oculomotor task). There was a significant main effect of compatibility, $F(1,23) = 20.6$, $p < .001$, $\eta_p^2 = .47$, in that responses in incompatible trials were slower than in compatible trials. Importantly, oculomotor responses were significantly affected by SOA, $F(6,138) = 43.81$, $p < .001$, $\eta_p^2 = .66$, indicating a PRP effect with strongly decreasing RTs for increasing SOAs (at least for shorter SOAs). Longer SOAs ($\geq$ 720 ms) were rather characterised by an asymptotic trend, nearly reaching the (single-task) baseline RT level (see Figure 3.5). Finally, SOA interacted with compatibility, $F(6{,}138) = 24.69$, $p < .001$, $\eta_p^2 = .52$, showing that – similar to manual responses – spatial incompatibility affected performance mainly at short SOAs.

Error rates. Error rates in the manual task (R_1) were higher for incompatible compared to compatible trials (1 % vs. 0.2 %), $F(1{,}23) = 5.12$, $p = .033$, $\eta_p^2 = .18$. There was no significant main effect of SOA, $F(6{,}138) = 1.34$, $p = .265$, nor a significant interaction, $F(6{,}138) = 1.58$, $p = .198$. In the oculomotor task (R_2) more errors occurred for incompatible responses (7.9 %) than for compatible responses (2.8 %), $F(1{,}23) = 31.67$, $p < .001$, $\eta_p^2 = .58$. Also, there was a significant decrease of errors with increasing SOA (8.9 %, 7.0 %, 5.8 %, 6.4 %, 4.1 %, 3.1 %, 2.6 % for SOAs ranging from 120 ms to 1200 ms, respectively), $F(6{,}138) = 6.44$, $p < .001$, $\eta_p^2 = .22$, and a significant interaction, $F(6{,}138) = 11.05$, $p < .001$, $\eta_p^2 = .33$, indicating that SOA only had an impact on incompatible trials (see lower panel in Figure 3.5).

3.4.3 Discussion

In Experiment 3, task order was constant and highly predictable. Specifically, the oculomotor task was always triggered second, allowing us to search for a PRP effect in oculomotor responses. In line with our expectations, we observed relatively low (but still notable) reversal rates.

As in the previous experiments, the data pattern is in line with a hybrid account (e.g. Hommel, 1998a; Watter & Logan, 2006). In incompatible trials, we observed strong backward crosstalk effects in manual RT_1 (slope of -1), which likely propagated to oculomotor RT_2, resulting in a steep slope of about -1.9 at short SOAs for the latter. Thus, the *relative* RT_2 slope amounted to -0.9, which is perfectly in line with predictions based on a serial RS bottleneck.

In compatible task conditions, the RT data pattern is also in line with a bottleneck account with a clear SOA effect on oculomotor RTs in the absence of an SOA effect on manual RTs. The fact that oculomotor responses decreased with a slope of -0.5 (instead of -1) can again be explained by assuming a short RS stage (Pashler et al., 1993), probably due to the fact that RS can benefit from response code priming in the case of compatible responses (Watter & Logan, 2006). Principally, of course, the data in compatible trials are also consistent with a fully parallel model assuming that most resources were dedicated to Task 1 processing first (e.g. Navon & Miller, 2002; Tombu & Jolicœur,

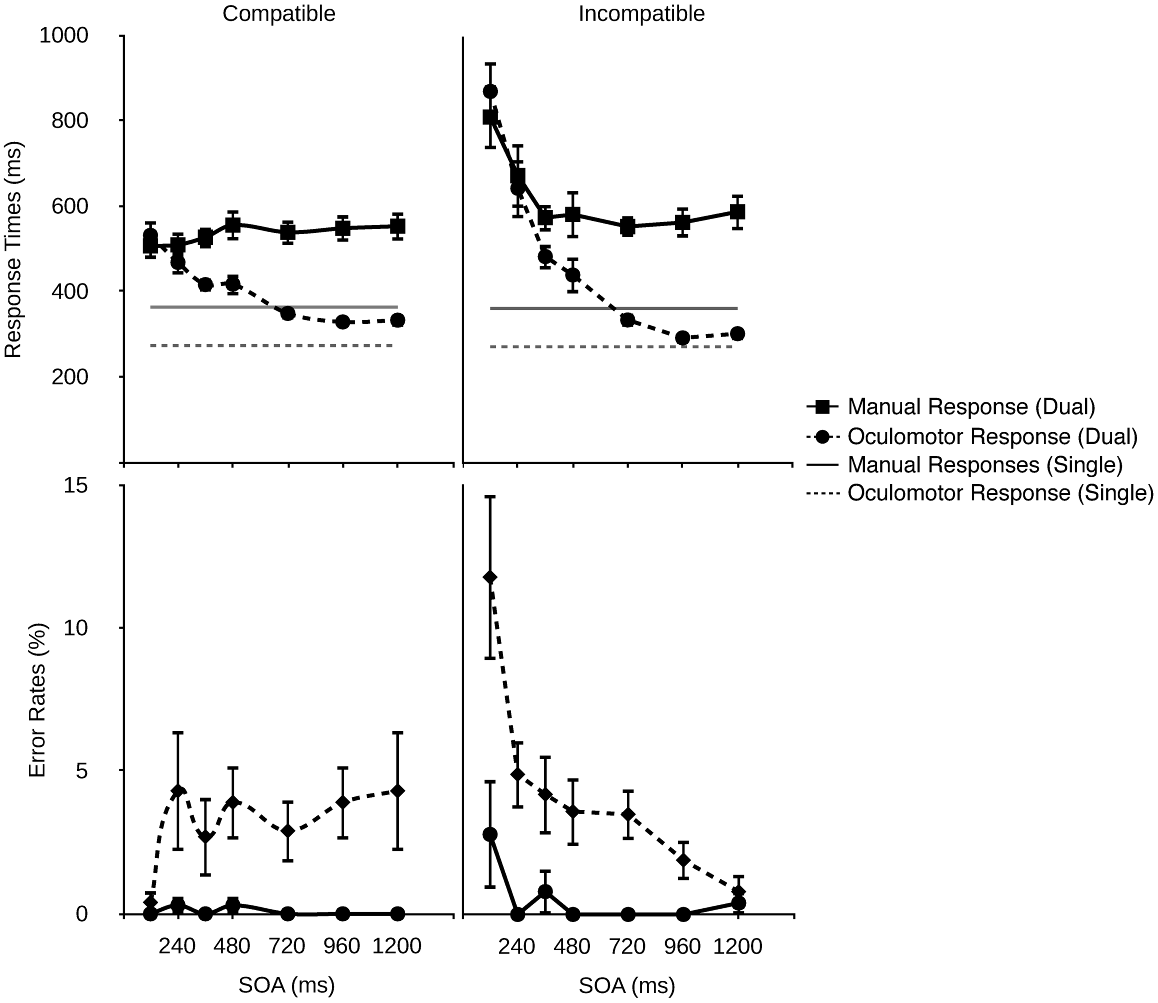

Figure 3.5. RTs (upper panel) and error rates (lower panel) of oculomotor and manual responses as a function of between-task compatibility (compatible and incompatible) and SOA in Experiment 3, which only involved in S_MS_O order conditions. Horizontal lines (without indicators) represent baseline RTs in single-task conditions. Error bars represent standard errors. Note that error rates virtually amounted to 0 % in single-task conditions and were therefore not included in the figure.

2003). Taken together, Experiment 3 again shows clear evidence for (partially) parallel response-related processing (prior to RE).

Importantly, at long SOAs (720 ms and above), the first response is usually initiated before the onset of the second stimulus resulting in non-overlapping tasks, thus explaining why compatibility effects are absent in these conditions. However, it is interesting that despite this fact manual RTs never came close to the (single-task) baseline level, while oculomotor responses showed little residual costs. This could be interpreted as a general tendency to withhold manual task processing at some point in the processing chain, probably due to a tendency to compare both stimuli with respect to their spatial characteristics, either in order to benefit from spatially compatible codes (via response code priming or via a more integrated response selection process, see Fagot & Pashler, 1992), or to initiate a more distinct, strictly serial processing mode in the case of incompatible spatial codes (see Discussions in Experiment 1 and 2). Another possible explanation could be that oculomotor responses are inherently prioritised and therefore hard to suppress as evidenced by a notable amount of reversals at short SOAs (see also Study D). As a result, oculomotor responses still would receive processing priorities despite being Task 2.

3.5 General Discussion

The present study addressed the question of whether oculomotor control is able to bypass central processing limitations, or alternatively, interferes with other concurrent processing demands, either in terms of structural interference (serial RS due to a central processing bottleneck) or in terms of content-based interference (crosstalk based on dimensional overlap between tasks). Following up on the only, previous attempt to address oculomotor responses within the PRP paradigm in terms of structural interference (Pashler et al., 1993), we specifically focused on stimulus and response order as well as crosstalk in order to situate our results within current dual-task processing accounts.

In particular, we studied oculomotor responses in the PRP paradigm from two perspectives: First, we examined if the oculomotor task is subject to a central processing bottleneck when executed as Task 2 (passive role of oculomotor responses), and second, if response selection of the oculomotor task as Task 1 constitutes a central limitation for another (secondary) task (active role of oculomotor responses due to the same structural bottleneck). Therefore, we combined the oculomotor task with a manual task, each requiring an S-R compatible left or right decision in response to a respective auditory stimulus. This setup also allowed a manipulation of between-task compatibility in order to investigate the issue of crosstalk as an important additional (content-based) source of dual-task interference in the PRP paradigm. While in Experiment 1 we introduced symmetrical SOAs (i.e. the same for both task orders) without response order instructions, in Experiment 2 we added explicit response order instructions. In Experiment 3, we introduced a fixed stimulus sequence (i.e. oculomotor responses were always triggered second).

3.5.1 Structural and content-based interference: Evidence for a response selection bottleneck and crosstalk

As a general result, we found evidence for substantial dual-task interference across all three experiments for both manual and oculomotor responses regardless of response order. More specifically, we observed evidence for a PRP effect, suggesting that oculomotor responses (as well as manual responses in the context of oculomotor responses) are subject to structural central limitations (i.e. a response selection bottleneck). Additionally, we observed strong evidence for (backward) crosstalk effects (e.g. Hommel, 1998a; Janczyk, 2016; Janczyk et al., 2014; Logan & Schulkind, 2000; Miller, 2006; Miller & Alderton, 2006; Thomson et al., 2010), suggesting that oculomotor responses are subject to content-based central interference during a parallel response-related processing stage (response activation, RA) prior to response execution (RE). Thus, we can safely reject the claim that oculomotor responses generally bypass central processing limitations, a possibility that was discussed based on the rather inconclusive results discussed by Pashler et al. (1993).

Overall, the present results are mostly in line with a hybrid (serial + parallel) response-related processing account, according to which serial response selection is preceded by a parallel response activation stage. The latter accounts for the backward crosstalk effects observed across all experiments, which are not compatible with a basic RSB account without any possibility of parallel response-related processing prior to RE. Thus, unlike Pashler et al. (1993), who mainly discussed their results against the backdrop of a basic RSB account (see Figure 3.1A), we are able to match our pattern of results to a more extended (and more recent) hybrid processing framework (e.g. Hommel, 1998a; Watter & Logan, 2006), which, nevertheless, preserves the notion of central serial processing for response selection.

3.5.2 Flexible, strategic processing modes?

Generally, it is difficult to distinguish between the hybrid model referred to above and a fully parallel resource sharing account (e.g. Meyer & Kieras, 1997a, 1997b; Navon & Miller, 2002; Tombu & Jolicœur, 2003). Particularly, while the data from incompatible conditions were more clearly in line with a hybrid model, some of the results from compatible conditions (due to a relative RT_2 slope less steep than -1 at short SOAs) are also consistent with a fully parallel account (Figure 3.1B2). While it is principally possible to assume that in the case of compatible trials, the RS stages were particularly short and thus led to slightly attenuated PRP effects (e.g. based on response code priming, see Watter & Logan, 2006), it is also possible to assume that compatible trials were generally processed in a more integrated (or ‘more parallel’) manner than incompatible trials (for the notion of different processing modes, see, e.g. Lehle & Hübner, 2009; for a discussion see Fischer & Plessow, 2015). Specifically, incompatible spatial codes may have resulted in a strictly serial RS processing mode, while in the case of compatible codes participants may have benefitted from a more integrated (or more parallel) RS process (Fagot & Pashler, 1992).

Based on the substantial differences in overall RT patterns between compatible and incompatible trials that we observed across all experiments (except for the S_OS_M order condition in Experiment 2) and considering that both responses were always made after the presentation of both stimuli, we propose, that it is possible to flexibly select a certain processing mode after SP has been finished for both tasks. Specifically, we suggest that the specific mode of processing in a trial might not be completely determined until both stimuli are processed, in that after a dedicated stimulus comparison process has determined the spatial compatibility or incompatibility between tasks. Generally, the idea would be in line with previous research suggesting that participants tend towards a rather serial processing mode in order to avoid crosstalk-based interference (e.g. Lehle & Hübner, 2009; Paucke, Oppermann, Koch, & Jescheniak, 2015) while a (moderate) parallel processing mode is assumed to be associated with less cognitive effort (Lehle, Steinhauser, & Hübner, 2009) and could therefore be regarded as a default mode. Resorting to a more serial processing mode might be especially helpful when environmental cues (in terms of incompatible spatial codes) call for a more difficult process related to disambiguation during the mapping of two different spatial codes to effector systems in accordance with the task rules (dual-task binding problem, see Logan & Gordon, 2001).

Another finding that is in line with the assumption of a dedicated code comparison process comes from performance in compatible trials in Experiment 1, which suggested that participants indeed withheld Task 1 processing. Finally, we generally observed a large RT gap between RT_1 levels in dual-task conditions and respective single-task RTs across all experiments. These observations leave room for a temporal window during which participants (at least sometimes) may have been engaged in a code comparison process.

Further evidence for an influence of strategic factors in the present experiments in addition to those discussed above comes from the observed differences between comparable conditions, namely compatible trials in the S_OS_M order conditions in Experiment 1 and 2. These differences can be explained by spill-over effects from processing decisions in the S_MS_O order conditions that differed between the two experiments (i.e. the voluntary attenuation of reversal rates in Experiment 2). This again suggests that particular processing modes can to some extent be flexibly adjusted, for example, in terms of effector-based prioritisation or the voluntary attenuation of thereof.

3.5.3 Characteristics of oculomotor tasks

Finally, any direct comparison to the results from the Pashler et al. (1993) must consider that we used somewhat different tasks (see rationale in the Introduction). Specifically, we avoided the special case in which stimulus and response target spatially coincided for the oculomotor task. However, we also avoided rather artificial conditions in which a saccade was selected based on the identity of a digit or colour, which we considered an untypical situation for oculomotor control in general. Instead, we chose an oculomotor task which is more comparable to the manual task (in terms of SP and RS stage processing demands) and realistic with respect to oculomotor control situations, in which a saccade is neither often directed towards a target that is identical with the stimulus (except for the special case of visual orientation responses), nor based on completely non-spatial (arbitrary) environmental cues. In general, it is plausible to assume that different oculomotor tasks (than those in the present experiments) result in different data patterns. For example, we would expect that quasi-reflexive saccades to very salient (suddenly appearing) targets in the periphery should indeed (nearly) bypass any central limitations, since it has already been shown that such visual orientation responses are in fact more difficult to inhibit than to execute (Huestegge & Koch, 2014).

3.5.4 Conclusions

In the present study, we addressed the issue of structural and content-based interference in dual-task control by investigating oculomotor responses in the PRP paradigm. We followed up on a pioneering study by Pashler et al. (1993) with the aim to address unresolved issues – especially regarding the question of whether oculomotor responses generally bypass central processing limitations – by focusing on effects of stimulus and response order as well as crosstalk. Our results clearly provided evidence for both structural interference in terms of a response selection bottleneck and interference based on crosstalk during parallel processing. While we cannot finally decide between a strictly hybrid (serial + parallel) and a more flexible, strategic processing account based on task characteristics, our results convincingly demonstrated (partially) parallel response-related processing of oculomotor responses prior to the response execution.

4 | Study C

Oculomotor Dominance in Multitasking – Mechanisms of Conflict Resolution in Cross-Modal Action

4.1 Introduction

Visual orienting is typically characterised by regular switches between rapid movements of the eyes (saccades) and phases of relative rest (fixations) (Findlay & Gilchrist, 2003; Rayner, 2009). In the past decades, the underlying oculomotor control processes have been thoroughly studied on the level of both their neural underpinnings and their cognitive foundations (e.g. Findlay & Walker, 1999; Liversedge, Gilchrist, & Everling, 2011; Hallett, 1978). However, most of these previous research efforts focused on the control of eye movements in isolation, for instance, in reading (Kliegl, Nuthmann, & Engbert, 2006; Rayner, 1998) or in attention and perception processes (Kowler, 2011; Schütz, Braun, & Gegenfurtner, 2011), even though oculomotor control in daily life is clearly embedded into a vast array of simultaneous action demands in other motor domains, such as manual or vocal actions, for example during typewriting or reading aloud. In the present study, we address the issue of how oculomotor control interacts with concurrent motor control demands in other effector domains (i.e. cross-modal action, Huestegge & Hazeltine, 2011).

4.1.1 Dominance patterns among response modalities

Recently, a study (Huestegge & Koch, 2013) explicitly addressed cognitive processes underlying multiple-action control across three response modalities (oculomotor, manual, vocal) and reported first evidence for an oculomotor dominance effect. Specifically, participants responded to unilaterally presented auditory stimuli with a single response or with two concurrent responses (in dual-response conditions) that were always spatially compatible to the stimuli. Across three experiments, three different response modalities were studied pairwise, that is saccades and manual responses, manual and vocal responses, and saccades and vocal responses. In each experiment asymmetric dual-response costs were observed, meaning that response time differences between single- and dual-response conditions varied between response modalities. Crucially, this dual-response cost asymmetry was interpreted as an empirical marker for prioritisation of response processing, during which the modality with smaller dual-response costs received more processing priority. Together, the pattern of cost asymmetries across experiments suggested an ordinal structure of priorities across response modalities: Saccades were prioritised over vocal and manual responses (oculomotor dominance effect), whereas vocal responses were prioritised over manual responses. Importantly, this dominance pattern could not be explained in terms of differences in single-response speed, for example, in accordance with a first-come, first-served principle of priority scheduling as in response selection bottleneck theory (Pashler, 1994). The results rather appeared to represent modality-specific patterns of resource scheduling. It is notable that the observed oculomotor dominance effect on the output side of processing resembles similar visual dominance effects on the input side of processing, where visual stimuli are usually processed with greater priority than auditory stimuli when both are presented at the same time (Colavita, 1974; Posner, Nissen, & Klein, 1976; Spence, 2009). Thus, the occurrence of oculomotor dominance complements the interpretation of the well-established visual dominance effect by suggesting that the visual system in principle (including both input and output processing) dominates other concurrent processing demands.

However, some aspects of the study of Huestegge and Koch (2013) limit the generalisability of the postulated dominance scheme. On a general level, it is unclear to what extent the result pattern may depend on the specific paradigm and conditions used. More specifically, responses in dual-response conditions were always spatially compatible, suggesting that there were no reasonable conflict resolution demands involved. However, any prioritisation mechanisms regarding resource scheduling among effector systems may be considered especially important in situations that involve spatial conflict between the required action demands, for example typing in numbers on the number pad located at the right side of a keyboard while at the same time looking at the resulting changes on the left part of the screen. Furthermore, it is well known from dual-task studies utilising the psychological refractory period (PRP) paradigm that the temporal distance by which two responses are separated in an experimental trial determines the amount of between-task interference and therefore the observed dual-response costs (Pashler, 1984; Pashler & Johnston, 1989). Typically, the reaction time of the later response (RT_2) is slower when both responses are executed at smaller temporal distances, while the same reaction is much faster when the execution of the two responses is further apart (known as the PRP effect, Pashler, 1994). Therefore, it should be particularly interesting to study modality dominance effects in a paradigm that a) involves conflict, for example, in terms of spatially incompatible response demands, and b) also allows for temporal response distance manipulations.

In another previous study, Huestegge and Koch (2010) introduced a paradigm that appears ideally suited to address the particular issue of response distance manipulation, namely the crossed-incompatibility (CI) paradigm. This paradigm is comparable to the one employed by Huestegge and Koch (2013, see above), but involves spatially incompatible instead of compatible responses. For example, an auditory stimulus on the left ear requires two simultaneous responses in from of a left (i.e. spatially compatible) saccade and a right (i.e. spatially incompatible) manual response. In another group of participants, the reversed assignment is implemented (i.e. an incompatible saccade and a compatible manual response). Crucially, these reversed stimulus-response (S-R) assignments cause responses to be temporally close together in one group and more distant to each other in the other group, while the fact that both responses are spatially incompatible to each other (i.e. the spatial response-response conflict) remains the same in both temporal distance groups. However, this previous study was restricted to the combination of saccades and manual responses only, and was not explicitly designed to address the issue of response modality dominance. While the observed asymmetry of dual-response costs (i.e. smaller dual-response costs for saccades than for manual responses) could be interpreted in terms of an oculomotor dominance effect, the two other combinations of response modalities (saccades and vocal responses, manual and vocal responses) were lacking. Consequently, it was not possible to provide conclusive results regarding response modality dominance patterns in situations involving response conflict.

4.1.2 The present study

In the present study, we intended to contribute the following novel aspects to the issue of eye movements and response modality dominance: First, we aimed at broadening the implications of Huestegge and Koch (2013) by introducing cross-response conflict while still utilising dual-response cost asymmetries to derive priority assignments. Specifically, in Experiment 1 we employed the CI paradigm to study the simultaneous execution of spatially incompatible oculomotor responses and vocal responses. Note that the combination of oculomotor responses and manual responses within the CI paradigm were already studied previously (Huestegge & Koch, 2010). Second, we aimed at comparing these results from Experiment 1 with those of Experiment 2, where we combined vocal and manual responses under controlled fixation conditions. Experiment 2 is necessary in order to obtain a comprehensive view of prioritisation patterns among all three effector systems (oculomotor, vocal, and manual), because only a comparison across experiments allows us to assess resource scheduling priorities among the three effector systems. This can be achieved by comparing the same (here: vocal) response demands in the context of eye movements manual responses, since a complete prioritisation pattern among modalities can not be concluded from one single experiment alone. Note that prior studies on conflict resolution in dual-response control which typically combined vocal and manual responses as in the present Experiment 2 never controlled for the occurrence of eye movements (see also Huestegge & Hazeltine, 2011). This has probably led to an additional source of response interference based on saccade execution, which naturally occurs whenever visuospatial stimulation is utilised. Finally, the opportunity to manipulate temporal response distance within the CI paradigm allows us to additionally vary the potential for response conflict, since a temporally close execution of incompatible responses should be associated with greater conflict potential compared to responses that are executed with a substantial temporal delay. Consequently, this manipulation might also imply shifts of priority patterns. In particular, three potential theoretical scenarios are at stake:

A. Rigid modality-independent resource scheduling: If dual-response cost asymmetries were based on an a-modal, inflexible first-come, first-served mechanism (e.g. similar to that in response selection bottleneck theory (see Pashler, 1994), the slower response in each dual-response combination should always exhibit larger dual-response costs.

B. Strict modality-based prioritisation: If regardless of the specific combination of response modalities and regardless of the amount of conflict present, specific effector modalities were consistently preferred over others, we would expect a dual-response costs priority pattern similar to Huestegge and Koch (2013), but without any modulation as a function of the potential for conflict.

C. Flexible modality-based prioritisation: If resource scheduling was affected by the temporal distance of conflicting responses, this should become evident in additional significant shifts of the dual-response cost pattern as a function of response distance. Furthermore, the manipulation of response distance in both experiments can also be informative regarding the issue of serial vs. parallel response processing in the context of cross-modal dual-response demands (see Huestegge & Koch, 2010), and the final part of the General Discussion).

4.2 Experiment 1

Experiment 1 was designed to test the prioritisation hypotheses referred to above by comparing dual-response costs of simultaneously executed saccades and vocal responses within the CI paradigm. Thus, the overall method (i.e. the CI paradigm rationale) is largely comparable to the procedure described by Huestegge and Koch (2010). For example, a left auditory stimulus in dual-response conditions required two simultaneous responses, namely a left (spatially compatible) saccade and a 'right' (spatially incompatible) vocal response (i.e. uttering the word 'right'). This particular S-R assignment causes temporally distant responses, since the (already generally slower) vocal response is further delayed through the spatially incompatible S-R rule. In another group of participants, we implemented the reversed S-R assignment, that is an incompatible saccade and a compatible vocal response. This assignment caused both responses to be executed temporally closer to each other, while the fact that both responses were spatially incompatible to each other (i.e. the spatial response-response conflict) remained the same in both temporal distance groups. Additionally, both groups were tested in single-response blocks to calculate dual-response costs – defined as the difference between single-response and dual-response performance.

4.2.1 Method

Participants

Twenty-four participants were randomly assigned to two groups (equivalent to the two response distance conditions). The mean age amounted to 22.5 years ($SD = 3.0$) in the distant responses group (11 female and 1 male) and 22.4 years ($SD = 3.2$) in the close responses group (9 female and 3 male).

All participants were naïve regarding the purpose of the experiment and received either course credits or reimbursement for participation.

Stimuli and Apparatus

Participants were seated in front of a 21 inch cathode ray tube monitor (temporal resolution: 100 Hz; spatial resolution: 1024 px × 768 px) with a keyboard in front of them. A chin rest was installed at a distance of 67 cm to the monitor to control for major head movements. A microphone to record the participants' vocal responses was placed at a distance of approximately 10 cm to the chin rest. Vocal latencies were defined as the time from stimulus onset until the sound pressure of an utterance exceeded a predefined threshold (voice key procedure implemented in the experiment presentation software *ExperimentBuilder*) that was determined in a pilot experiment[1]. Eye movements were registered using an EyeLink II system (SR Research, Canada). The space bar of the keyboard was used during calibration routines (horizontal 3-point calibration). On the screen, a green central fixation cross (on black background) was flanked by two rectangular green squares that served as saccade targets at 8.3° visual angle to the left and right and were permanently present during an experimental block. The size of both the fixation cross and the rectangular saccade targets amounted to 0.33° each. Auditory stimuli consisted of unilateral 1000 Hz pure tones (easily audible, duration: 50 ms) and were presented via supra-aural headphones.

Procedure

In each trial, the imperative auditory stimulus was presented either to the left or right ear in random order. In the distant responses group, participants were instructed to move their gaze to the spatially compatible rectangle (saccade single-response blocks), to utter the word with the spatially incompatible content 'links' (left) or 'rechts' (right) in vocal single-response blocks, or to perform both responses simultaneously in dual-response blocks. Participants in the close responses group were instructed with inverted S-R mappings (i.e. S-R incompatible gaze shifts and S-R compatible vocal responses, see Figure 4.1). Participants were asked to execute responses as fast and accurately as possible without any instructions about the response order. In trials requiring a saccade reaction, participants were told to return to the central fixation cross afterwards, while in vocal single-response

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[1] This method of measurement overestimates vocal response times by about 200 ms (as determined through different, but comparable experiments using off-line, manual speech-onset coding) because the sound pressure level at the beginning of a spoken word is significantly lower compared to the average sound pressure level of the word. Thus the voice key trigger cannot detect the immediate speech onset.

trials the gaze should remain on the central fixation cross. Each participant completed 9 blocks consisting of 30 trials each (3 blocks for each of the three block types). At the beginning of each block, the eye tracking system was calibrated.

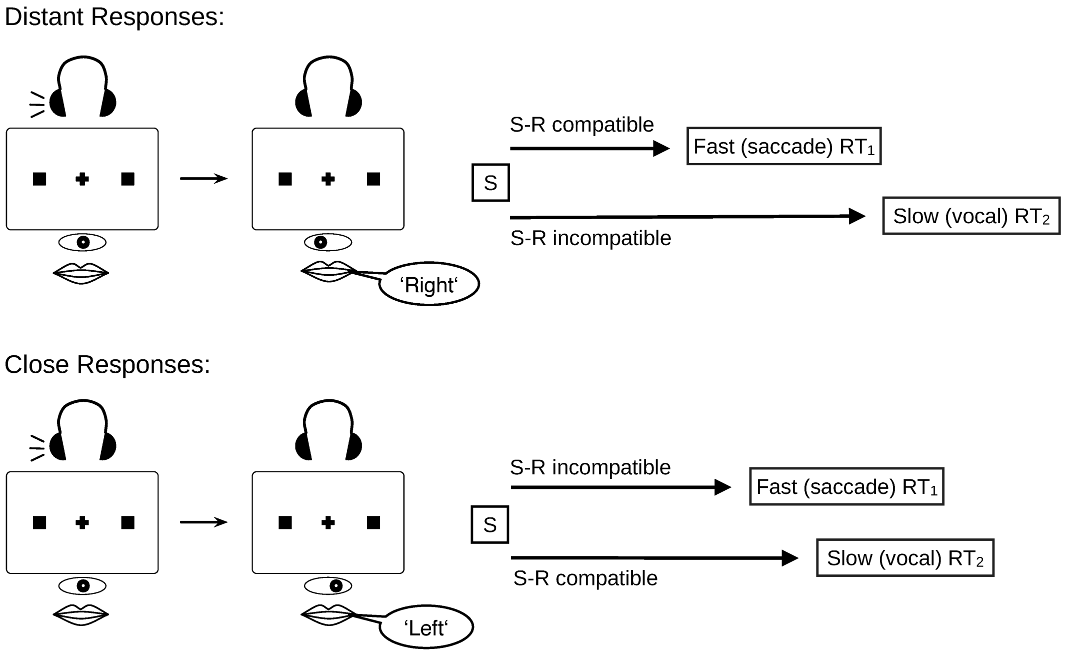


Figure 4.1. Crossed-incompatibility (CI) paradigm: Trial structure (left part) and corresponding manipulation of temporal response distance (right part) in the two response distance groups in Experiment 1.

Design

The design consisted of three independent variables, namely response modality (saccade and vocal response), response condition (single and dual), and response distance (close and distant). While the former two variables were manipulated within-subjects, response distance was a group factor. The order of the three block types (two single-response blocks and one dual-response block) was counterbalanced across participants. RTs and errors for saccades and vocal responses were measured as dependent variables.

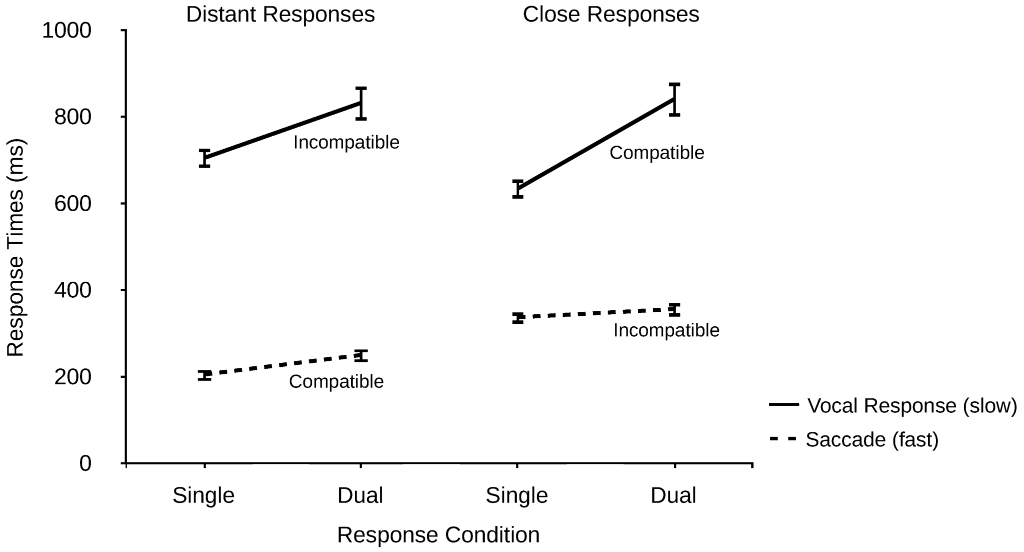
4.2.2 Results and Discussion

Correct saccades required a minimal amplitude of 4° (half of the visual angle of the lateral saccade targets) in the instructed direction as indicated by a landing position on the left or right of the central fixation cross. Saccades in vocal single trials with an amplitude larger than 2° were defined as erroneously executed. We excluded trials with anticipatory responses (saccade RTs < 70 ms and vocal RTs < 150 ms), trials involving technical malfunction and trials in vocal single-response conditions with erroneously executed eye movements. Taken together, this procedure resulted in 95.9 % valid data. Furthermore, we excluded trials in which the vocal response was executed prior to the saccade (0.2 % of the valid data).

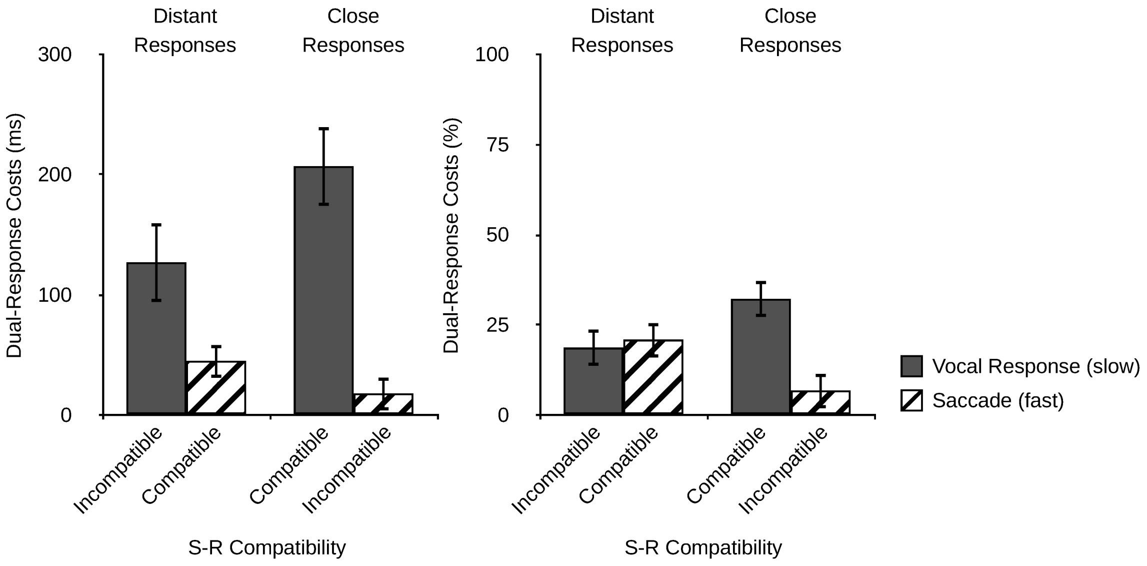
For the RT analysis, only data from correct trials were submitted to a mixed three-way ANOVA. Figure 4.2A shows mean RTs of saccades and vocal responses as a function of response condition and response distance. Statistical analyses revealed a significant main effect of modality, $F(1{,}22) = 639.9$, $p < .001$, $\eta_p^2 = .97$, indicating the typical observation that vocal RTs (753 ms) are longer than saccade RTs (287 ms). The main effect of response condition was significant, too, $F(1{,}22) = 61$, $p < .001$, $\eta_p^2 = .74$, indicating overall dual-response costs of 100 ms. We did not observe a significant main effect of response distance, $F(1{,}22) = 2.8$, $p > .10$, suggesting that overall mean RTs did not differ substantially between groups. This observation is nicely in line with the fact that the two responses were spatially incompatible to each other (and thus producing a similar amount of crosstalk) in both temporal distance conditions.

The interaction of response modality and response condition, $F(1{,}22) = 31.7$, $p < .001$, $\eta_p^2 = .59$, indicates significantly larger dual-response costs for vocal responses (167 ms) than for saccades (32 ms), which is in line with prior observations of asymmetrical costs across modalities (Huestegge & Koch, 2010, 2013). Post hoc comparisons revealed that dual-response costs for vocal responses were larger than for saccades in both response distance conditions (127 ms vs. 45 ms in the distant responses group, $t(11) = 2.9$, $p = .015$, and 207 ms vs. 18 ms, in the close responses group, $t(11) = 4.9$, $p < .001$). Overall, this pattern is in line with the assumption of an oculomotor dominance effect in that performance costs for saccades was always smaller than for vocal responses. The interaction of response modality and response distance, $F(1{,}22) = 16.6$, $p = .001$, $\eta_p^2 = .43$, shows that responses in the close responses group were indeed executed significantly closer to each other (with a difference of 390 ms) than in the distant response group (where responses were executed with a mean distance of 540 ms). This demonstrates the effectiveness of our response distance manipulation.

Interestingly, the interaction of response condition and response distance was far from being statistically significant, $F(1{,}22) = 1.1$, $p > .30$, suggesting that dual-response costs were not significantly affected by response distance. While this result resembles the results of Huestegge and Koch (2010), where dual-response costs were equal for each modality in both response conditions,



A. Mean response times (RTs) for vocal responses and saccades as a function of response conditions (single and dual) and response distance (distant and close). Error bars represent standard errors.



B. Left panel: Dual-response costs (in milliseconds) for vocal responses and saccades as a function of S-R compatibility in both response distance groups. Right panel: Proportional dual-response costs (in percentages) for vocal responses and saccades as a function of S-R compatibility in both response distance groups. Error bars represent standard errors.

Figure 4.2. Response times (A) and dual-response costs (B) in Experiment 1.

it may appear surprising since previous research on multiple-action control usually reports greater dual-response costs when two responses need to be executed at close temporal proximity (e.g. Pashler, 1994).

Importantly, in addition we found a significant three-way interaction, $F(1{,}22) = 4.8$, $p = .039$, $\eta_p^2 = .18$, suggesting that dual-response costs for saccades decreased from distant to close response conditions, while dual-response costs for vocal responses increased (see Figure 4.2B). This three-way interaction suggests that processing priorities among the two response modalities are shifted from one modality to the other across the two response distance conditions, indicating flexible resource scheduling. Specifically, it appears as if costs in one response modality have been compensated for by a relative benefit in the other modality, indicating a trade-off between common limited resources across response modalities. Probably, when saccades need to be performed in an S-R incompatible and thus more difficult way (similar to an anti-saccade task, see Hallett, 1978) in the close responses condition they are prioritised stronger than usual (i.e. compared to being S-R compatible), so that the remaining (vocal) response modality shows relatively larger dual-response costs. Taken together, this observation is clearly in line with the assumption of an adjustable modality-dependent processing prioritisation.

Because of the large single-response RT difference between response distance groups and based on the fact that modalities differ in their absolute RT level we additionally analysed proportional (instead of absolute) dual-response costs (in %) in order to control for any effects that might be caused simply by baseline (i.e. single RT level) differences. Proportional costs were computed for each individual participant ($[\mathrm{RT}_{\mathrm{dual}} - \mathrm{RT}_{\mathrm{single}}]/\mathrm{RT}_{\mathrm{single}}$) and then submitted to a 2×2 ANOVA with the factors response modality and response distance. The analysis revealed the same statistical pattern as the analysis of absolute RTs reported above: Proportional dual-response costs were significantly greater for vocal responses (25 %) than for saccades (14 %), $F(1{,}22) = 5.8$, $p = .025$, $\eta_p^2 = .21$, while there was no significant difference between the response distance conditions, $F < 1$. Importantly, the interaction of modality and response distance was again significant, $F(1{,}22) = 8.3$, $p = .009$, $\eta_p^2 = .27$, confirming the cost trade-off pattern across modalities as a function of response distance, equivalent to that observed in absolute dual-response costs (see the three-way interaction for absolute RTs).

To check for response accuracy we also analysed errors, although the overall error rate was very low and amounted only to 3.8 %. A mixed three-way ANOVA on the error data revealed a significant main effect of response modality, $F(1,22) = 14.6$, $p = .001$, $\eta_p^2 = .40$, demonstrating the usual finding that saccades exhibit more errors (5.8 %) than vocal responses (1.8 %). Interestingly, the main effect of response distance was significant, too, $F(1,22) = 8.9$, $p = .007$, $\eta_p^2 = .29$, indicating that more errors were committed in conditions with close responses (6.2 %) than in conditions with distant responses (2.4 %). Thus, executing two responses at a close temporal distance appeared to be more difficult than the execution of distant responses. This observation might be due to the fact that the execution of incompatible saccades (which is only necessary in close responses conditions) is particularly difficult. In line with this interpretation, we found a significant interaction of response modality and response distance, $F(1,22) = 6.4$, $p = .019$, $\eta_p^2 = .27$, indicating that the difference in saccade errors between the distant and close responses conditions (2.1 % vs. 9.5 %) was much larger than for vocal responses (0.7 % vs. 2.9 %). We did not find a significant main effect of response condition, $F(1,22) = 2.9$, $p > .10$. Finally, there was no significant interaction of response distance and response condition, $F(1,22) = 2.1$, $p > .15$, no interaction of response modality and response condition, $F < 1$, and no three-way interaction, $F < 1$.

Taken together, the results from this experiment strengthen the assumption of an oculomotor dominance effect (Huestegge & Koch, 2013), which appears to be also present in situations involving response conflict. However, the present results also offer novel insight in that modality-specific resource allocation across effector systems can be flexibly adjusted based on the temporal distance (and thus, the potential for conflict) between the two responses.

Based on the data from the (slower) vocal responses alone, one might at first sight conclude that the increase of vocal dual-response costs in the close response distance condition appears to be quite in line with a first-come, first-served principle according to a serial processing (RSB) account, which explicitly predicts that under close response processing conditions the processing of the second response is delayed until response selection for the first response is finished. However, the corresponding reversed pattern of dual-response costs for saccades is clearly at odds with a serial processing account, since dual-response costs for saccades even increase with a larger response distance. Thus, this result pattern rather indicated a trade-off of response assignments across response modalities.

Unfortunately, the data from this experiment alone do not allow us to derive a conclusive assessment of prioritisation patterns among effector modalities, since we cannot compare the dual-response costs in the present experiment with similar conditions involving other combinations of response modalities. To address this issue, we conducted Experiment 2, which involves the simultaneous execution of manual and vocal responses, but under controlled conditions regarding the occurrence of eye movements. Even though Experiment 2 does not explicitly involve the execution of eye movements, a comparison of data patterns across experiments will enable us to indirectly infer the impact of contextual responses on the prioritisation pattern observed in Experiment 1, and thus it can be informative regarding prioritisation patterns with respect to eye movements.

4.3 Experiment 2

Experiment 2 addresses the issue of multiple-response control in combined vocal and manual responses within the CI paradigm under controlled eye movement demands (i.e. remain fixated instructions). The main goal is to be able to interpret the prioritisation pattern of Experiment 1 more conclusively by studying one of the two response modalities from Experiment 1 (i.e. the vocal responses) again, but in the context of another (here: manual) response modality. Apart from the replacement of saccades with manual key press responses, all other methodological aspects are the same as in Experiment 1.

4.3.1 Method

Participants

A new sample of 24 participants (21 female, 3 male) was randomly assigned to the two response distance groups. The mean age amounted to 21.4 years ($SD = 2.7$) in the distant responses group (11 female) and 22.6 years ($SD = 3.2$) in the close responses group (10 female). They were naïve regarding the purpose of the experiment and received either course credits or reimbursement for participation.

Stimuli and Apparatus

The hardware setup was identical to that in Experiment 1. Additionally, the keyboard was used to record manual key press responses. Two keys (*left Ctrl* and *right arrow*) served as response keys and were operated by the participants’ left and right index fingers. The eye tracking system was utilised to control for the occurrence of eye movements.

Procedure and Design

The overall procedure and design was the same as in Experiment 1 except that manual responses were required instead of saccade responses. Instructions for the vocal task were the same as in Experiment 1. In conditions involving a manual response, participants in the distant responses group were instructed to press the spatially compatible key. Conversely, participants in the close responses group were asked to press the spatially incompatible key. Throughout the experiment, participants were instructed to remain their gaze on the central fixation cross.

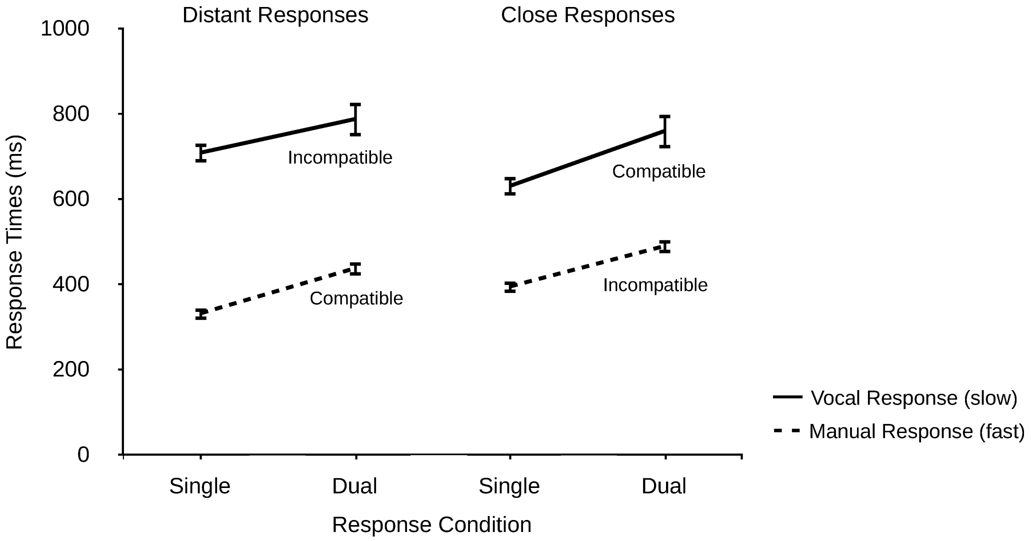
4.3.2 Results and Discussion

We excluded trials with anticipatory responses (RTs < 150 ms in both effector modalities) and trials with erroneously executed eye movements (saccade error definition as in Experiment 1) which resulted in $95.5\,\%$ valid data. Furthermore, we excluded trials in which the vocal response was executed prior to the manual response ($1.4\,\%$ of the valid data).

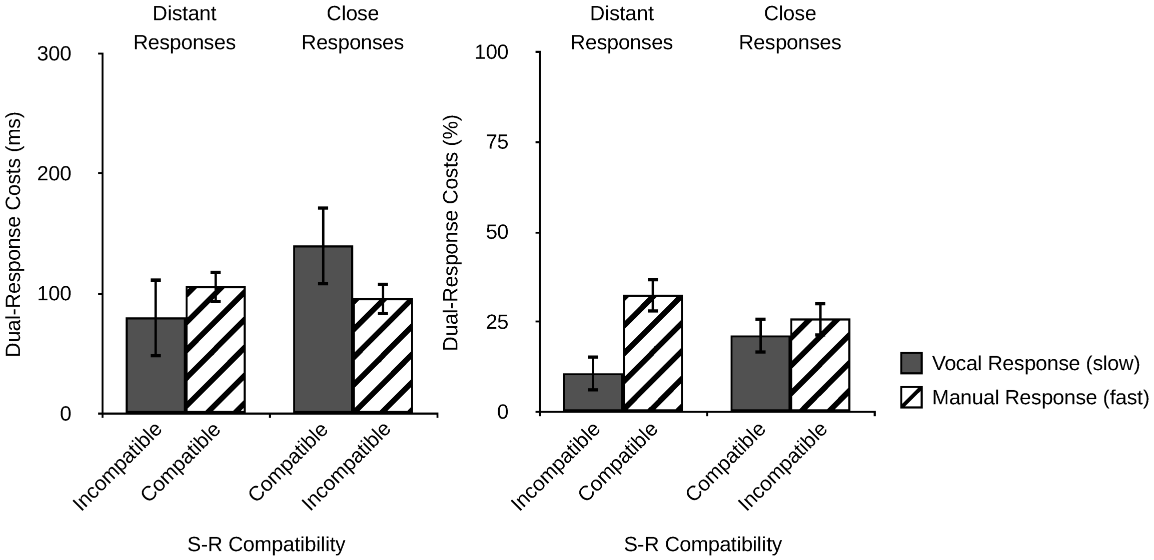
For the RT analysis, only data from correct trials were submitted to a mixed three-way ANOVA. Figure 4.3A shows manual and vocal RTs as a function of response distance and response condition. The main effect of response modality was significant, $F(1{,}22) = 254.5$, $p < .001$, $\eta_p^2 = .92$, showing that vocal responses (721 ms) were slower than manual responses (413 ms). The main effect of response condition was significant, too, $F(1{,}22) = 105.1$, $p < .001$, $\eta_p^2 = .83$, indicating longer RTs in dual-response conditions (618 ms) than in single-response conditions (515 ms). There was no significant main effect of response distance, $F < 1$.

We observed a significant interaction of response modality and response distance $F(1{,}22) = 8.1$, $p = .009$, $\eta_p^2 = .27$, indicating that responses in the close responses group were indeed executed significantly closer to each other (difference of 254 ms) than in the distant response group (difference of 363 ms). Again, this indicates that our temporal response distance manipulation was successful.

Importantly, there was no significant interaction of response condition and response distance, $F < 1$. Thus, similar to Experiment 1, there was no robust indication of a difference in overall dual-response costs between the two response distance conditions. The interaction of response condition and response modality was not significant, either, suggesting that there was no reliable difference in dual-response costs between modalities, $F < 1$, and thus no clear prioritisation of one modality over the other. This observation differs from the data by Huestegge and Koch (2013),



A. Mean response times (RTs) for vocal and manual responses as a function of response conditions (single and dual) and response distance (distant and close). Error bars represent standard errors.



B. Left panel: Dual-response costs (in milliseconds) for vocal and manual responses as a function of S-R compatibility in both response distance groups. Right panel: Proportional dual-response costs (in percentages) for vocal and manual responses as a function of S-R compatibility in both response distance groups. Error bars represent standard errors.

Figure 4.3. Response times (A) and dual-response costs (B) in Experiment 2.

where vocal responses exhibited significantly smaller dual-response costs than manual responses in an experimental paradigm without cross-response conflict.

The three-way interaction was marginally significant, $F(1{,}22) = 3.4$, $p = .078$, $\eta_p^2 = .13$, resembling the observed trend in Experiment 1 (Figure 4.3B): Dual-response costs for vocal responses (i.e. the slower response) tended to be larger when responses are executed closer together compared to the distant responses condition (129 ms vs. 79 ms), while manual dual-response costs show a reversed pattern (95 ms vs. 106 ms). Thus, similar to the corresponding results in Experiment 1, we observed a tendency towards a trade-off between modality-based resources as a function of response distance, indicating a certain degree of flexibility in resource scheduling.

Given the substantial difference in overall RT levels across response modalities, we again computed proportional dual-response costs for each participant in both modalities and submitted them to an ANOVA with the independent variables response modality and response distance. This analysis revealed no significant main effect of response distance, $F < 1$. However, unlike in the absolute RT data, we found a significant main effect of response modality, $F(1{,}22) = 15.3$, $p < .001$, $\eta_p^2 = .41$, indicating larger proportional dual-response costs for manual responses (29 %) than for vocal responses (16 %), which can be interpreted in terms of a prioritisation of the vocal response (cf. Huestegge & Koch, 2013). Importantly, this result is further qualified by a significant interaction of response modality and response distance, $F(1{,}22) = 6.3$, $p = .020$, $\eta_p^2 = .22$, revealing that proportional dual-response costs of the (in terms of single RT speed slower) vocal response were larger for close responses conditions (21 %) than for distant responses conditions (11 %), while dual-response costs for manual responses exhibited a reversed pattern (26 % vs. 33 %). This result further substantiates the claim that central resources were strategically allocated across response modalities, in that the conflict-afflicted S-R incompatible response tended to be (relatively) prioritised over the S-R compatible response. The mean rate of errors only amounted to 1.6 %. A corresponding ANOVA revealed no statistically significant main effects or interactions.

It should be noted that the ‘remain fixated’ instructions in the present experiment might have slightly increased the overall cognitive load due to the corresponding inhibitory control demands. However, given that these demands persisted throughout all conditions of the present experiment, this may have increased the overall RT level, but should not have compromised any of the critical patterns of results reported here.

Although Experiment 1 might have suggested a serial processing account in which the faster response is processed with a higher priority than the slower one, the data of Experiment 2 clearly demonstrate the contrary. Here, the faster manual response exhibits at least the same amount of dual-response cost as the slower vocal response, thus suggesting a rather parallel processing mechanism (see also General Discussion). Nevertheless, especially with respect to the analysis of proportional dual-response costs, the results of Experiment 2 are again in line with the assumption of flexible resource adjustment modulated by the potential for conflict, and indicate that the cognitive mechanisms proposed in Experiment 1 may not only hold for the special case of combined saccades and vocal responses but rather represent cross-modal action control mechanisms in general.

4.4 Comparison Across Experiments

Experiment 1 provided strong evidence that oculomotor responses are prioritised over vocal responses, while overall analyses of Experiment 2 suggest that vocal responses show the tendency to be prioritised over manual responses. This ordinal prioritisation pattern derived from situations involving response conflict nicely converges with previous observations in situations without such conflict (Huestegge & Koch, 2013). However, a comparison of data across experiments is necessary in order to check if saccades are also prioritised over manual responses, and to test the hypothesis (see Introduction, hypothesis B) whether resource allocation for a specific response modality depends on the contextual response demand, not only in terms of its proximity or S-R compatibility but also in terms of its effector modality.

In order to compare results of Experiment 1 and 2 we applied the same logic for the interpretation of dual-response cost asymmetries as before. The observed cost asymmetry served as a marker for prioritisation, in that lower costs represent a higher priority. For determining a comprehensive priority pattern among modalities we compared dual-response costs of the same modality (vocal responses) in two different contexts, here the two modalities (saccade and manual response). The difference in dual-response costs for the vocal modality between the two context response conditions tells us which context modality is dominant in terms of the amount of dual-response costs in the vocal response. Directly comparing dual-response costs of the context responses is additionally applied to corroborate the priority pattern.

To ensure that reaction time levels of the vocal response are comparable and did not differ between experiments due to inter-individual differences, we calculated a cross-experiment ANOVA on single vocal response RTs as dependent variable and experiment (1 vs. 2) and S-R compatibility[2] (compatible vs. incompatible) as independent variables. Crucially, the main effect of experiment was not significant, $F < 1$, $p = .98$, providing no evidence for an overall difference in single vocal RTs (mean of 669 ms in both experiments). The main effect of S-R compatibility was significant, $F(1{,}44) = 7.16$, $p = .01$, $\eta_p^2 = .14$, which shows that S-R incompatible responses (706 ms) took longer than compatible responses (632 ms), (compatibility effect). The interaction was not significant, $F < 1$, $p = .90$, indicating that the compatibility effect did not differ between experiments. Taken together, absolute vocal RTs were almost identical across both experiments, providing a valid basis for further comparisons.

In order to compare the amount of vocal dual-response costs between Experiment 1 and 2, we conducted a cross-experiment ANOVA for vocal dual-response costs. In addition, we computed a similar, separate analysis comparing dual-response costs of the context responses (i.e. saccades in Experiment 1 and manual responses in Experiment 2). Figure 4.4 shows the dual-response costs of vocal responses (black bars) in both experiments in form of absolute (A) and relative RT differences (B). Note that in Figure 4.4, we averaged across the two response distance groups.

The 2 × 2 ANOVA for dual-response costs of *vocal responses* with the independent variables context response modality (saccades in Experiment 1 and manual responses in Experiment 2) and response distance (close and distant) revealed a main effect of the context modality, $F(1{,}44) = 5.3$, $p = .026$, $\eta_p^2 = .11$, indicating that dual-response costs for the same vocal responses were 62 ms larger when they were combined with saccades (167 ms) than with manual responses (105 ms). This finding shows that vocal costs are strongly determined by the identity of the context response, in that a vocal-saccade combination gives rise to greater vocal costs compared to a vocal-manual combination. This finding indicates an oculomotor dominance over manual responses. The main effect of response distance was significant, too, $F(1{,}22) = 5.7$, $p = .021$, $\eta_p^2 = .12$, showing that vocal dual-response costs were larger in the close response conditions (168 ms) than in the distant response conditions (104 ms). This result supports the observations from Experiment 1 and 2 that the relatively faster (S-R compatible) vocal response (compared to the S-R incompatible vocal response) suffers more dual-response interference. However, the two-way interaction was not significant, $F < 1$, indicating

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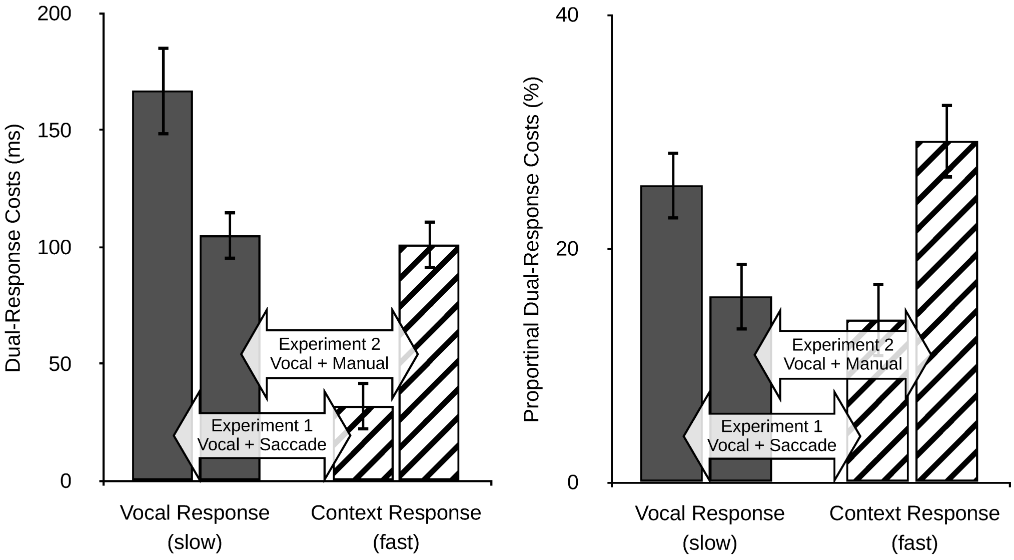
[2] Note that this factor is equivalent to the variable *response distance* in Experiment 1 and 2. This different labelling was utilised to facilitate the comprehension of the argumentation.



A. Absolute dual-response costs.

B. Proportional dual-response costs.

Figure 4.4. Dual-response costs (in milliseconds) for vocal responses (filled bars) in the context of saccades and manual responses (striped bars), and dual-response costs for saccades (Experiment 1) and manual responses (Experiment 2) in the context of the same (i.e. vocal) response demands. Error bars represent standard errors.

that the main effect of response distance was simply additive to the main effect of the context response modality.

The ANOVA on dual-response costs of the *context response modality* with the independent variables response modality and response distance also revealed a main effect of modality, $F(1{,}44) = 22.3$, $p < .001$, $\eta_p^2 = .34$, indicating that saccades exhibited smaller costs (32 ms) than manual responses (101 ms) when executed simultaneously with vocal responses. This observation again provides evidence that saccades are prioritised over manual responses. There was no significant main effect of response distance, $F(1{,}44) = 1.6$, $p = .212$, and no significant interaction, $F < 1$.

Due to the large difference in absolute RT levels between saccades and manual responses we computed an additional analysis of proportional dual-response costs across the two experiments. The ANOVA revealed a significant main effect of response modality, $F(1{,}44) = 11.3$, $p = .002$, $\eta_p^2 = .20$, confirming that saccades exhibited smaller costs (14 %) than manual responses (30 %) when combined with identical responses in the vocal modality. In this analysis, the main effect of response distance was significant, too, $F(1,44) = 5.1$, $p = .028$, $\eta_p^2 = .10$, indicating larger proportional costs in the close responses condition (27 %) than in the distant responses condition (16 %).

Taken together, the modulation of the amount of vocal dual-response costs as a function of the context response is direct evidence for the claim that resource scheduling for a specific response modality flexibly depends on the identity of the context response modality (Huestegge & Koch, 2013). When combined with manual responses instead of saccades, the same vocal response appears to suffer less, indicating that vocal responses receive relatively more processing resources. This is again in line with the assumption that vocal responses are prioritised over manual responses. Also, the finding that vocal responses exhibited much larger costs when combined with saccades than with manual responses reflects an ordinal prioritisation structure in which saccades are strongly prioritised over vocal responses. The cross-experiment comparison of saccades and manual responses (in the context of comparable vocal contextual demands) again corroborates the assumption of oculomotor dominance.

4.5 General Discussion

The present study was designed to study the coordination of eye movements in the context of concurrent action demands in other effector domains (i.e. response modalities). Previous evidence for an oculomotor dominance effect – the prioritisation of eye movement control in the context of other response demands – has been limited to situations without any potential for cognitive conflict (Huestegge & Koch, 2013). However, we reasoned that any prioritisation mechanism regarding resource scheduling among effector systems should be particularly important in situations that involve strong conflict between action demands. Therefore, we studied modality dominance effects in a paradigm with spatially conflicting response demands by utilising the crossed-incompatibility (CI) paradigm (Huestegge & Koch, 2010), which involves the execution of two spatially incompatible responses (in two different modalities) triggered by a unilateral auditory stimulus. While the results of Huestegge and Koch (2013), who combined saccades and manual responses, already indicated oculomotor prioritisation in terms of smaller dual-response costs for saccades than for manual responses, this previous study was not specifically designed to investigate response modality dominance. Based on this particular research question in mind, the present study provides the ‘missing’ response combinations (oculomotor and vocal responses, vocal and manual responses) needed to come up with conclusive results regarding effector system dominance during response conflict. The CI paradigm also provides a manipulation of the potential for response conflict by varying temporal response proximity. In Experiment 1, we combined oculomotor and vocal responses within a group with temporally close responses and within a group with temporally distant responses. In Experiment 2, we employed the same paradigm but combined manual and vocal responses to be able to compare the pattern of dual-response costs across experiments.

4.5.1 Flexible modality-based prioritisation

Across both experimental groups, the results from Experiment 1 revealed clear evidence for an oculomotor dominance effect in terms of smaller dual-response costs for saccades than for vocal responses. This finding is in line with similar previous results within a paradigm involving spatially compatible responses only. Therefore, the present results suggest that resource scheduling mechanisms generalise to different experimental paradigms, that is they are also effective when cross-response conflict (Huestegge & Koch, 2009) is present. The observation of an oculomotor dominance effect in particular is strikingly similar to visual dominance effects reported in research on cross-modal attention (Colavita, 1974; Posner et al., 1976; Spence, 2009). From a more global, functional perspective, the prioritisation of the visual system on both the input and output side of information processing may be considered helpful to detect (or look for) important (e.g. life-threatening) environmental changes, representing a prerequisite to any subsequent action involving other response modalities (e.g. calling for help). However, since from studies regarding eye-hand coordination in object manipulation it is known that the eyes land on the target before the hand (e.g. Land & Hayhoe, 2001), it might also be that moving the eyes first is our ‘default’ behaviour which also transfers to situations with non-overlapping objects for eye and hand.

Another interesting issue is the comparison of the pattern of dual-response costs across experiments, because it allows us to assess resource scheduling priorities among the three effector systems. Two major conclusions can be drawn: First, the comparison of dual-response costs for saccades from Experiment 1 and for manual responses from Experiment 2 clearly confirmed smaller costs for saccades, again supporting the assumption of an oculomotor dominance effect. Second, we found a strong modulation of the amount of dual-response costs for the same vocal response demand across experiments. This highlights the flexible nature of resource scheduling with respect to action modalities, which apparently depends on the specific requirements (here: effector modality) of the context response. The specific data pattern also suggests an oculomotor dominance, in that vocal responses suffer more in the context of (highly prioritised) saccades compared to (less prioritised) manual responses. Additionally, vocal responses appear to dominate manual responses. Although the absolute RT data in Experiment 2 did not provide evidence for a vocal over manual dominance, three observations clearly support this assumption, namely the data from the proportional analyses in Experiment 2, the analyses from the comparison across experiments, and corresponding (both absolute and proportional) data from a previous study on cross-modal response control without response conflict (Huestegge & Koch, 2013).

Furthermore, the results regarding the manipulation of temporal distance between the two simultaneous responses (i.e. the group comparison within each experiment) indicate that resource scheduling patterns are flexibly adjustable contingent upon the temporal proximity of the two actions that need to be performed. While the overall amount of dual-response costs was comparable across groups, closer responses (presumably associated with greater overall conflict between responses) led to a significant shift in the resource allocation pattern. Specifically, relatively more resources were allocated towards the response demand with the more difficult (i.e. incompatible) S-R assignment (compared to the S-R compatible response of the same modality). This assumption of processing dependency indicates that the two response processing demands are not perfectly shielded against each other. It has been argued that the execution of one task can – under certain conditions – be shielded against distraction from other ongoing processing demands (e.g. Dreisbach & Wenke, 2011; Fischer, Gottschalk, & Dreisbach, 2014; see also Miller & Durst, 2014, 2015, for interference during prioritised task processing). Despite the lack of perfect shielding here, this theoretical framework generally fits into our interpretation of flexible resource scheduling. For example, it is possible that in conditions with temporally close responses the S-R incompatible response is shielded in order to provide optimal performance, so that a relatively larger portion of dual-response costs is strategically transferred to the (easier) S-R compatible response without changing the overall effector-based response dominance pattern. Additionally, the observation that the costs of the dominant (oculomotor) response decrease from distant to close in Experiment 1 while the costs of the dominant vocal response increase in Experiment 2 implies that S-R compatibility is able to ‘override’ the beneficial effects of response modality dominance. The observation that S-R incompatible saccades dominate vocal responses even more than compatible saccades in Experiment 1 together with the lack of a clear vocal dominance effect in absolute RTs in Experiment 2, may indicate that the *vocal over manual dominance* is less pronounced than the *oculomotor over vocal* dominance.

Thus, although the general modality dominance pattern seems to be strong and hardly alterable, the actual strength of the modality prioritisation appears to be variable and dependent on the specific response combination.

The observation of strategic shifts of resource allocation corresponds with current theories of multiple-action control that assume flexible resource scheduling among parallel response requirements (Lehle & Hübner, 2009; Meyer & Kieras, 1997a; Navon & Miller, 2002; Tombu & Jolicœur, 2003). For example, a specific computational model of resource scheduling in task-set control is ECTVA (Logan & Gordon, 2001), which involves the specification of sets of control parameters. While ECTVA has not explicitly specified response modality weighting mechanisms yet, this could probably be incorporated in the model (see General Discussion in Chapter 6 for a more in-depth discussion).

4.5.2 Parallel versus serial processing and oculomotor control

Note that the theoretical frameworks mentioned above (e.g. parallel resource allocation, shielding etc.) have in common that they presuppose the possibility of parallel selection and processing of responses, which stands in direct contrast to other frameworks that assume strictly serial response selection operations. Interestingly, the issue of parallel or serial processing of attentional processes has been intensively debated over the last 30 years in the vision literature, especially within the fields of visual search (e.g. Nakayama & Silverman, 1986; Thornton & Gilden, 2007) and reading (e.g. Engbert, Nuthmann, Richter, & Kliegl, 2005; Reichle, Rayner, & Pollatsek, 2003). However, this debate is mainly centred upon attention to objects and words, and hence on the input side of processing, rather than upon attention to response control on the output side. Since the present study specifically addresses the issue of multiple-response control, it seems important to take a further look at our present data to speculate about the mode of processing (serial vs. parallel) in the CI paradigm based on the relevant theoretical frameworks that model attention in multiple-action control.

The idea of serial response selection mechanisms in multiple-action control was mainly derived from PRP studies in which processing overlap is varied by manipulating the time interval between the onset of two stimuli (Welford, 1952) and was further developed by assuming a central response selection bottleneck (RSB, Pashler, 1994). A clear prediction of the RSB framework is that whenever two responses are processed in close temporal proximity overall RTs increase and especially the second of the two responses should suffer from RT costs, since response selection for the second response has to wait until selection of the first response is completed. A corresponding pattern of results has been replicated repeatedly within a range of PRP studies (Pashler, 1994), with eye movements to salient peripheral stimuli representing a single but notable exception (Pashler, Carrier, & Hoffman, 1993).

Some of our present results appear to be in line with the assumption of serial response selection in the CI paradigm. For example, Experiment 1 showed that the slower (vocal) response modality exhibits greater dual-response costs than the faster (saccade) response modality, a finding that is similar to the typical PRP effect in form of a particular prolongation of the second response latency due to a first-come, first-served principle of a processing bottleneck. Although the overall effect size in Experiment 1 is much smaller than a typical PRP effect, it has been claimed that adverse effects of a central bottleneck can be comparatively small under certain conditions (e.g. Anderson, Taatgen, & Byrne, 2005). Nevertheless, the data from Experiment 2 are not in line with the assumption of smaller costs for the faster response modality, since the data clearly indicates equal (or even relatively greater) costs for the faster (manual) response. Furthermore, a general prediction of the PRP framework, namely greater overall conflict for conditions in which two responses are processed in closer temporal proximity, is not compatible with our data, since overall dual-response costs in RTs were not affected by temporal response distance. Thus, and in line with similar data from a previous CI paradigm study (Huestegge & Koch, 2010), our results do not appear to fit into a classic bottleneck framework.

However, it should be noted that our present study design, the CI paradigm, substantially differs from the PRP paradigm, which might prevent a meaningful application of the RSB framework to our present data. Most importantly, our design involved two responses based on a single stimulus, which has two potential implications. First, it is possible that only a single compound response selection occurs for both responses, effectively eliminating the need for serial or parallel response selection processes. Evidence for this claim has previously been presented by Fagot and Pashler (1992), who showed that compound selection occurs when two responses are mapped to the same (attribute of a) stimulus. However, Fagot and Pashler (1992) only examined conditions without response incompatibility, therefore it is unclear to what extent this reasoning should also hold for incompatible response demands. Thus, a second possibility is the assumption of two distinct response selection processes in the CI paradigm. Based on traditional serial processing stage logic, response selection should begin right after the completion of stimulus processing, that is both response selection processes should begin with an equal probability for both responses and should thus (on average) lead to similar costs. However, the prediction of similar costs is clearly at odds with the results from Experiment 1 and the proportional cost data in Experiment 2. Finally, under the assumption of two parallel response selection processes one might have expected that the shorter response would always show fewer dual-response costs, because a short response has less time to suffer from negative interference, or that both responses show an equal amount of costs based on the time period in which both responses overlap. However, these general, more rigid mechanisms are clearly at odds with the present results that demonstrate a priority of (slower) vocal responses over (faster) manual responses. Thus, the data rather point towards a highly flexible resource scheduling regime. Taken together, the notion of simultaneous processing of both responses appears to be a better overall framework to explain our present data compared to the concept of a serial response processing bottleneck, which may be more suited to account for typical PRP experiments and data.

Another concern for the interpretation of our present data could be the claim that our response distance manipulation was not effective enough to invoke much conflict. Within the PRP framework, a similar discussion is based on the notion of a 'latent' response selection bottleneck (e.g. when the duration of response selection is too short to allow for the occurrence of a processing slack in a reasonable number of trials, see Ruthruff, Johnston, Van Selst, Whitsell, & Remington, 2003a). Indeed, the single-RT differences between response modalities were still substantial (about 200 ms–300 ms) in both experiments. However, at least two observations speak against a lack of effectiveness of our response distance manipulation. First, the voice key procedure implemented here is known to overestimate actual speech onset times. In fact, we ran a control experiment with a similar setup and the same vocal responses and found that the voice key overestimated actual speech onset times by about 230 ms. If we take this into account, the actual response onset times (in single-response conditions) are much more similar (and thus, the effectiveness of our response distance manipulation was more effective) than suggested by our voice key data. Second, and probably more importantly, the elevated error rates in the close responses condition of Experiment 1 clearly showed that cross-response conflict increased. Additionally, the observed trade-off of dual-response costs across modalities as a function of response processing distance also suggests conflict resolution processes. These empirical markers of conflict are clearly not supporting the assumption that our manipulation of response distance was ineffective.

While the results from the previous CI paradigm study (Huestegge & Koch, 2010) also suggested parallel instead of serial processing, there were also important differences: Dual-response costs in this previous study were not only unaffected by response processing distance overall, but also individually for each response modality. Based on these previous results alone, one might have concluded that parallel processing occurs, but that the two processing streams do not interact (i.e. independent parallel processing). In contrast, the present results rather suggest a strong and flexible interaction between response modalities (dependent interactive parallel processing), which is especially apparent in the observation that reduced temporal separation of response processing increased error rates in Experiment 1 (i.e. response processing effectiveness in one response modality was affected by the relative temporal distance of the context response). This interaction between response modalities is further underlined by the fact that the temporal structure of responses (and the specific combination of response modalities across experiments) affected the pattern of resource allocation across modalities.

Because our observation that eye movements are preferred over other effector systems is a very recent finding and the literature on oculomotor action in multitasking is currently quite sparse, the origins and specific mechanisms of oculomotor dominance still need to be examined more closely. Although the present data present clear evidence for effector system prioritisation, there seems to be room for flexible adjustments based on the particular task demands (e.g. resolving response conflict). Hence, it appears principally possible that the ordinal structure of effector system prioritisation may change under certain task conditions, so that, for example, eye movements would not be processed with the highest priority anymore. The finding that multitasking performance also depends on the specific combinations of input (i.e. stimulus) modality and output (i.e. response) modalities (Hazeltine, Ruthruff, & Remington, 2006; Stephan, Koch, Hendler, & Huestegge, 2013) in that some S-R combinations are processed with less interference than others might serve as a starting point for further investigations regarding the flexibility of effector system prioritisation.

4.5.3 Conclusions

The present results together with those from Huestegge and Koch (2010) suggest that multiple-response processing across response domains occurs in parallel, but in a strongly interactive and flexible manner. The interaction mechanisms are based on constraints imposed through the temporal structure and modalities of the response demands involved, with a priority on the control of the oculomotor system. The evidence for interactive processing across response processing streams also fits into a larger framework suggesting that information crosstalk is a major factor determining the efficiency of multiple-response control (Navon & Miller, 1987; Bekkering, Adam, Kingma, Huson, & Whiting, 1994; Logan & Gordon, 2001).

We conclude that despite some limitations (e.g. the limited range for manipulating response processing distance), the CI paradigm appears to be a useful and powerful paradigm to study multiple-response control in order to move theory on multiple-action processing forward by overcoming some of the inherent drawbacks of other paradigms, in particular the necessity of serial stimulus presentation in the PRP paradigm (see Meyer & Kieras, 1997a). Thus, the CI paradigm nicely complements other paradigms in the field of multiple-response control, such as task switching (Stephan et al., 2013; Kiesel et al., 2010, for a review), the PRP paradigm, and other dual-task paradigms.

Finally, and with respect to the cognitive processes underlying oculomotor control, our results also show that it is theoretically rewarding to view the eyes not only in terms of an input modality (i.e. as a prerequisite of visual information uptake), but also as a response modality on its own that dominates other, concurrent response demands in other effector domains (oculomotor dominance effect), but in an interactive way.

5 | Study D

Action Scheduling in Multitasking – A Multi-Phase Framework of Response Order Control

5.1 Introduction

Research on human action control can be subdivided into two main areas of inquiry, namely determining *what* to do in order to ensure task-relevant action and, crucially, determining *when* to do it, the latter requiring that actions must be scheduled along a timeline. Since humans frequently handle more than just one task at once, they need to schedule the tasks at hand in order to efficiently execute the required actions. Given that our bodily and cognitive limitations usually do not allow us to easily perform many actions simultaneously, an important quest of cognitive research relates to understanding the underlying mechanisms of action scheduling decisions in multitasking, a field of research that has received only sparse attention yet. In the present chapter, a step forward will be made towards a comprehensive picture of mechanisms that determine the outcome of temporal action scheduling by studying both bottom-up and top-down factors, including potential measures to enhance multitasking performance accuracy.

5.1.1 Temporal processing dynamics and response scheduling in the PRP paradigm

A classic paradigm to study the temporal processing dynamics of dual-task control is the psychological refractory period (PRP) paradigm (Telford, 1931; Welford, 1952), which allows for a systematic manipulation of the temporal overlap between two tasks and hence a detailed analysis of the underlying processing time course. Usually, it is utilised to study structural limitations in dual-task control and not response order scheduling in particular. However, the theoretical framework underlying the typical interpretation of PRP data also allows for deriving hypotheses regarding response order control. Thus, we will briefly outline the PRP paradigm including the associated theoretical assumptions.

In the PRP paradigm, two stimuli S_1 and S_2 (each requiring a separate response R_1 and R_2) are presented sequentially while the time delay between the two stimuli, the stimulus onset asynchrony (SOA), is varied systematically. The PRP effect refers to the typical finding that the reaction time for the second response (RT_2) is larger at short than at long SOAs (Herman & Kantowitz, 1970; Pashler, 1984, 1994) while RT_1 remains largely unaffected. The most prominent explanation for this pattern is based on the assumption that task processing immediately starts with stimulus onset and consists of three consecutive stages, namely stimulus processing, response selection, and response execution. The prolongation of RT_2 at short SOAs is then explained through the presence of a structural (generic) bottleneck that coerces a serial processing schedule specifically at the central stage of response selection (response selection bottleneck [RSB] model). Hence, this processing stage cannot proceed simultaneously in both tasks, which forces response selection in Task 2 to wait until response selection in Task 1 is finished (Pashler, 1984). Note that within this explanatory framework response order scheduling according to stimulus presentation order (i.e. a non-reversed response order), represents an important precondition for such an interpretation of the data. More specifically, the RSB framework assumes that the task in which response selection (and ultimately response execution) is initiated first is determined by the task in which stimulus processing is finished first (i.e. typically Task 1). Thus, this *first-come, first-served principle* implies that, given comparable stimulus processing duration across both tasks, stimulus order should be the major determinant of response order – an assumption that represents a pure bottom-up account of response-order control. In line with this claim, R_1 is observed to be initiated prior to R_2 in most cases, whereas response reversals (i.e. response order reversed to stimulus order) occur only rarely and could be attributed to stochastic fluctuations of stimulus processing stage durations.

In typical studies of the PRP effect, the likelihood of this premise is often increased by explicitly instructing participants to respond in accordance with the stimulus order by prioritizing Task 1 processing (e.g. Hommel, 1998a; Logan & Delheimer, 2001; Logan & Schulkind, 2000; Pashler & Johnston, 1989; Ruthruff, Johnston, & Van Selst, 2001). Thus, typical PRP experiments which are focused on studying structural limitations (instead of response order scheduling) usually regard reversals as being *abnormal* (cf., Pashler, 1990) or as occurring *by accident* (cf., Wu & Liu, 2008). As such, they are excluded from further analysis (e.g. Bratzke, Rolke, & Ulrich, 2009; Hommel, 1998a; Tombu & Jolicœur, 2002) or not reported in the first place. Based on the theoretical assumptions and methodological practices reported so far, at least two factors in many PRP experiments are usually assumed to play an important role in response order scheduling, namely stimulus order and explicit instructions to prioritise Task 1.

Some researchers explicitly disagreed with the assumption that the PRP effect reflects a *generic* cognitive limitation and instead suggested that both stimulus order and instruction might rather lead to a *strategic* prioritisation of Task 1 within a serial processing strategy (e.g. Meyer & Kieras, 1997a; Schumacher et al., 2001). To support the claim of strategic processing decisions (as opposed to the idea of generic structural limitations) in the PRP paradigm, Schumacher et al. (2001) showed that the RSB could be virtually abolished after a certain amount of practice (see also Hazeltine, Teague, & Ivry, 2002; Strobach, Liepelt, Pashler, Frensch, & Schubert, 2013). Furthermore, Israel and Cohen (2011) trained participants to execute dual tasks without significant costs at $\text{SOA} = 0\,\text{ms}$, but demonstrated a re-emergence of the PRP effect at $\text{SOA} = 0\,\text{ms}$ trials when they were later presented in the context of other trials with variable SOAs (i.e. $\text{SOA} \neq 0\,\text{ms}$). These findings can thus be interpreted as first evidence that processing decisions may also be driven by top-down factors related to strategies and context, while serial stimulus processing can indeed trigger serial response processing. However, strategic decisions in these studies were always discussed with respect to serial vs. parallel processing but not response order.

5.1.2 Previous studies on response order scheduling in the PRP paradigm

As outlined above, the classic RSB framework was mainly developed to account for the PRP effect instead of response order scheduling decisions. However, in line with the cited evidence for a more flexible, strategic view on cognitive control in multitasking some researchers explicitly suggested that response order might to some extent be scheduled actively (De Jong, 1995; Leonhard, Ruiz Fernández, Ulrich, & Miller, 2011; Luria & Meiran, 2003; Sigman & Dehaene, 2008; Szameitat, Lepsien, von Cramon, Sterr, & Schubert, 2006) instead of being determined in a purely stimulus-driven (bottom-up) manner. For example, De Jong (1995) studied the impact of *instructions* on response order control by comparing one condition in which participants were instructed to respond in accordance with the stimulus order with another condition in which participants freely chose response order. Fewer response reversals occurred in the instructed-order condition, indicating the possibility of top-down control of response order. However, the instructed-order condition additionally involved the presence of error-feedback, which makes it difficult to assess the contribution of instruction alone. Additionally, De Jong (1995) studied *stimulus order predictability* by comparing conditions involving predictable vs. unpredictable stimulus order and found a stronger tendency towards repeating the processing order from the previous trial in the unpredictable stimulus order condition, indicating contextual modulation of response order control. Probably, this effect can be explained by assuming that participants tend to avoid performance costs associated with trial-to-trial switches of response order (Luria & Meiran, 2003).

Finally, empirical evidence was reported suggesting that response order scheduling may depend on the *anticipated duration of the response selection* (RS) stage, which was manipulated through different task difficulty conditions (Leonhard et al., 2011; Ruiz Fernández, Leonhard, Rolke, & Ulrich, 2011). Specifically, these studies reported a tendency towards executing the response in a task with short RS duration first even when the stimulus of this particular task was presented second. The authors argued that this strategy helped in reducing slack time (i.e. the time, during which one task has to wait for clearance of the bottleneck) in order to minimise total reaction time (i.e. the sum of RTs in both tasks). While this explanation appears to be plausible, the study does not rule out the possibility of alternative accounts. For example, it is conceivable that – instead of the relatively complex process of anticipating and minimizing slack time – a general a priori prioritisation of the easy task was responsible for the observed response scheduling pattern (i.e. a strategy without explicit reference to the optimisation of overall processing efficiency). Despite this limitation, the study represents clear evidence against a simple first-come, first-served (bottom up) principle to account for response order control in dual tasks and indicates that properties of stages *after* stimulus processing can be relevant, too. This raises the novel question of whether even characteristics of effector systems (i.e. factors related to the final response execution stage) will affect scheduling decisions, since such a finding could not explained by assuming a strategy to minimise slack time as a major mechanism underlying response order control.

Taken together, the few previous studies on response order scheduling provide first (but sparse) evidence against the assumption that a first-come, first-served principle as envisioned in a basic RSB framework fully accounts for response order control in multitasking. Instead, they indicate that instructions, contextual factors (such as the surrounding trial demands within a block), or characteristics of processing stages *after* completion of stimulus processing may play an important role. However, these studies are not sufficient to fully unravel the potentially complex interplay of bottom-up and top-down factors affecting the temporal organisation of behaviour in multitasking.

5.1.3 The impact of effector systems and spatial compatibility on response prioritisation

In the previous section it was highlighted that a focus on response characteristics involved in dual tasks may be theoretically informative to further understand response scheduling decisions. In the present section, we will further elaborate on the role of response modalities (in terms of effector systems) in dual-task control. Given the assumption of sequential stage processing within each task in the RSB model, one would not expect a strong influence of response modalities on central processes, including those determining temporal scheduling. This assumption might have led to the fact that the majority of PRP studies utilised only a limited range of potential combinations of effector systems, namely manual-manual or manual-vocal (see reviews by Huestegge & Hazeltine, 2011; Pashler, 1994). However, in line with accumulating evidence for ‘embodied cognition’ in the last decades (see Wilson, 2002) several observations indicate that response modalities might play a more important role for central processing than previously assumed.

First, it has been demonstrated that certain combinations of stimulus (= input) and response (= output) modalities for the two tasks in the PRP paradigm cause much larger dual-task interference that other combinations (input-output modality compatibility (IOMC) effect, e.g. Hazeltine, Ruthruff, & Remington, 2006). Second, recent research (Huestegge & Koch, 2013) suggested that the specific response modalities involved in processing two simultaneous action demands (i.e. compatible responses triggered by a common stimulus) determine the distribution of performance costs across effector systems. By utilising the amount of dual-response costs (i.e. the additional time needed to initiate a response when another response demand is present) as an inverse marker for prioritisation, they showed that oculomotor responses are typically prioritised over both vocal and manual responses (oculomotor dominance effect), whereas vocal responses are prioritised over manual responses. Interestingly, this pattern could not simply be explained in terms of the overall RT level associated with effector systems (i.e. differences that should be closely related to the duration of the response execution stage within the serial processing stage logic), but rather appeared to reflect differential attentional weighting of certain output modules. In a recent study, we confirmed the overall effector prioritisation pattern in a different experimental paradigm requiring the execution of two responses which were spatially incompatible to each other, but additionally showed that the relative difficulty of response selection (manipulated via S-R (in)compatibility) affected prioritisation strength, suggesting a rather flexible weighting mechanism (Pieczykolan & Huestegge, 2014). Taken together, these observations suggest that a) the specific response modalities and their associated prioritisation gradient and b) spatial compatibility impact on attentional weighting mechanisms in multiple-response control and may thus not only be of great importance for the pattern of dual-response costs (as shown in previous studies), but also for response order scheduling decisions – a hypothesis that still awaits empirical testing. Hence, it should be highly informative to study temporal order control in a paradigm involving compatibility manipulations as well as a strong prioritisation gradient among effector systems, for example, by combining saccades and manual responses.

5.1.4 The present study

The present study aims at drawing a more comprehensive picture of the mechanisms underlying response order control in multitasking. Based on the literature review above, an ideal experimental setting to study temporal scheduling dynamics is the PRP paradigm due to its inherent potential for systematically studying relevant bottom-up factors such as stimulus order and the temporal separation of stimuli (i.e. SOA) while maintaining relatively high experimental control over the timing of cognitive processes. Here, we will not utilise the PRP paradigm for the usual goal, that is to study Task 2 response deferment resulting from structural processing limitations (i.e. the typical PRP effect on RT_2 as a function of SOA), reflecting processes *after* a response scheduling decision has been made. Instead, we will focus on the fundamental decisions that need to be made prior to any RSB-related processing, namely response order scheduling decisions. Therefore, an analysis of

PRP effects in manual and saccade control (see Pashler, Carrier, & Hoffman, 1993), an interesting and complex story on its own, is not directly relevant for the research questions in the present study and is reported in Study B.

A precondition of studying response order control is to establish an experimental situation that, unlike most previous PRP studies, is likely to yield substantial variability of response order (i.e. a sufficient amount of response reversals) in the first place to avoid floor effects. A survey of the previous literature revealed that especially the combination of oculomotor and manual responses in the PRP paradigm yields many response reversals (Pashler et al., 1993). Although this previous study did not explicitly examine response reversals as a central dependent variable, the reported data showed that the oculomotor response was still initiated earlier than the manual response in a substantial proportion of trials, especially at short SOAs, even when the stimulus associated with the oculomotor response was presented second. Furthermore, this particular combination of effector systems is also highly informative regarding the potential impact of different response characteristics (in terms of overall prioritisation and response execution stage duration) on response order control (as outlined in the previous section). Based on these considerations, the combination of oculomotor and manual responses in the PRP paradigm represents an ideal setting for studying response order control in multitasking.

The present study comprises three PRP experiments. Experiment 1 involved blocks of trials with mixed stimulus order without specific response order instructions. Experiment 2 addressed the impact of explicit response order instructions as an approach to adjust performance-related decisions in multitasking under otherwise identical conditions as in Experiment 1. Finally, instead of an explicit approach, Experiment 3 involved a change in task environment by implementing a fixed (instead of mixed) and therefore predictable stimulus order. Similar to De Jong (1995) and Leonhard et al. (2011), we measured the rate of response reversals as an indicator of response order scheduling, and additionally analysed errors to assess the impact of scheduling decisions on multitasking performance accuracy.

It must be noted that current dual-task theories – apart from the cited basic RSB framework – do not allow for deriving clear predictions regarding response order control or for distinguishing between alternative accounts, since they rather focus on mechanisms *after* response order has been determined (e.g. PRP effects). For example, some dual-task theories discuss the occurrence of processing deferment within (or flexible resource allocation between) the component tasks, but do not consider its potential impact on response order control (Meyer & Kieras, 1997a; Tombu & Jolicœur, 2003). Other theories assume that non-reversed response processing represents the solution to the dual-task binding problem (Logan & Gordon, 2001, see General Discussion for details). Finally, some theories are built on the explicit assumption of non-reversed response processing for the sake of simplicity by arguing that due to particular design decisions in previous studies response reversals rarely occurred (Navon & Miller, 2002). Thus, the aim of the present study is not to test diverging predictions based on competing current theories, but to provide a first comprehensive assessment of potential response order determinants. Because response order control represents a fundamental and important aspect of dual-task control that has yet been neglected mostly because of the prevalence of specific (but eventually arbitrary) methodological research approaches (Navon & Miller, 2002), the present work should be helpful in developing a framework of the underlying mechanisms of temporal action scheduling. Since we aimed at presenting a relatively broad picture of the determinants and mechanisms of response order control (especially when compared to the specific research questions in each of the previous studies on this issue), we focused on the following six factors and corresponding hypotheses (either within or across experiments):

Characteristics of response modalities

In all three PRP experiments, we combined two effector systems (oculomotor and manual responses) that substantially differ in their response characteristics (e.g. regarding response execution stage duration and a priori prioritisation) in order to test whether these response characteristics also affect response order scheduling decisions. If response order decisions were not significantly affected by response characteristics, we would expect that stimulus order (or any of the remaining variables mentioned below) should be the main factor determining response order (indicated by a low number of response reversals). In contrast, a large number of response reversals would indicate an important role of response characteristics in response scheduling.

Stimulus order

Based on the assumption of a passive first-come, first-served principle (e.g. Pashler, 1994), one would expect stimulus order to represent a major factor in determining response order. If the role of stimulus order has been overestimated in previous research, our design allows us to assess the degree to which stimulus order may interact with other factors affecting response scheduling decisions, which appears especially interesting in a setting involving different response characteristics. The corresponding predictions follow from the reasoning outlined in the previous paragraph: If stimulus order had no impact on response scheduling, we would expect that, for example, oculomotor responses were nearly always executed first irrespective of stimulus order. In contrast, if stimulus order were the dominant factor determining response order, we would expect low reversal rates regardless of stimulus order (in line with a first-come, first-served bottom-up mechanism).

Temporal stimulus distance

One essential feature of the PRP paradigm is the SOA manipulation. Within the context of response order control, the temporal stimulus distance could have the following effects: First, within a first-come, first-served (pure bottom-up) framework an increased stimulus distance (i.e. long SOAs) should render the few cases of response reversals, which could be attributable to unsystematic stochastic fluctuations of stimulus processing duration across tasks even less likely (see influence of stimulus order above). Second, long SOAs may generally increase stimulus order salience (i.e. the temporal distinctiveness of the stimuli) and as such amplify the overall impact of bottom-up factors within a framework in which both bottom-up and top-down factors play a role. Corresponding mechanisms will be further outlined in the General Discussion.

Between-task compatibility

Previous research on dual-task control in general and within the PRP paradigm in particular has demonstrated that compatibility between tasks can strongly affect processing efficiency. For example, spatial incompatibility between the two responses are known to affect Task 1 performance, a finding known as *backward crosstalk effect* (e.g. Ellenbogen & Meiran, 2008; Hommel, 1998a; Janczyk, 2016; Miller, 2006; Miller & Alderton, 2006). Interestingly, no study has specifically addressed the impact of between-task compatibility on response scheduling decisions yet. If between-task compatibility played a role for response order decisions (e.g. in a similar way as for the relative amount of dual-response costs, see Pieczykolan & Huestegge, 2014), we would expect different rates of response reversals for spatially compatible and incompatible trials. Furthermore, such a compatibility effect would indicate that task compatibility is processed prior to the determination of response order, which would be informative regarding the temporal processing dynamics.

Instructions

The between-experiment comparison of two different instruction conditions (unspecific in Experiment 1, explicit in Experiment 2 under otherwise controlled conditions (unlike in De Jong,

1995) should be informative regarding the extent to which participants are able to self-regulate response-order control in a top-down manner (without being reminded during the block by feedback). Thus, if participants are able to voluntarily apply an instructed response order in accordance with stimulus order, we expect fewer response reversals compared to a condition without specific order instructions.

Predictability of stimulus order

Finally, we attempt to assess the influence of stimulus order variability as a contextual factor on response order scheduling by comparing performance of identical trials (i.e. under identical SOA and stimulus order conditions) in mixed stimulus order blocks (Experiment 1) with performance in fixed stimulus order blocks (Experiment 3). A difference regarding response reversals would suggest that response scheduling in a current trial strongly depends on the environmental context established by the surrounding trials (see similar observations in De Jong, 1995, albeit only with respect to RTs instead of response order). Consequently, response reversals should be less likely under highly predictable circumstances (i.e. in fixed stimulus order conditions).

5.2 Experiment 1

The aim of Experiment 1 was twofold: First, we intended to investigate the interplay of stimulus order and response characteristics (different response execution stage duration and prioritisation, see Huestegge & Koch, 2013; Pieczykolan & Huestegge, 2014) on response order scheduling in a PRP experiment that required the scheduling of two distinct actions, namely oculomotor responses (saccade towards a left or right target on the screen) and manual responses (left or right key press). Note that both actions were directed towards different targets and thus are not subject to the special circumstances underlying visuomotor control of coordinated eye and hand movements towards a common target. Further note that the two actions were comparable in that both were auditorily triggered and required a certain amount of spatial transformation (hearing a sound on one ear must be transformed into a spatially compatible action which is not simply directed towards the sound source). Specifically, we compared conditions in which the stimulus for the oculomotor response precedes the stimulus for the manual response ($S_O S_M$) with conditions in which this order was reversed ($S_M S_O$) to measure corresponding effects on response reversal frequency. Secondly, we compared between-task compatible and incompatible conditions. Unlike in many PRP studies, we refrained from instructing participants to follow a certain response order (as in Pashler et al., 1993) with the aim to observe scheduling decisions that are unrestricted by explicit instructions. By utilising the same SOAs (120 ms, 240 ms, and 360 ms) for both stimulus order conditions, this symmetrical implementation was intended to minimise any implicit bias towards a certain response order.

5.2.1 Method

Participants

Twenty-four participants (16 female, 8 male) with a mean age of 23.2 years (range = 20–30) took part in Experiment 1. They had normal or corrected-to-normal vision and hearing, gave informed consent, and received course credits or monetary reimbursement for participation.

Apparatus

Participants were seated 67 cm in front of a 21 inch cathode ray monitor (temporal resolution: 100 Hz; spatial resolution: 1024 px × 768 px) with a keyboard in front of them. The space bar of the keyboard was used during calibration routines. Saccades were registered using a head-mounted Eyelink II infrared reflection system (SR Research, Osgoode, Ontario, Canada) by measuring the position of the right eye's pupil with a temporal resolution of 500 Hz and a spatial resolution of less than 0.0022°. A chin rest was used to minimise head movements.

Stimuli

The visual display consisted of a black background on the screen with a green fixation cross in the center and two green rectangular squares that served as saccade targets at 8.3° visual angle to the left and right of the fixation cross. This display was permanently visible during each experimental block. The size of the fixation cross and the targets was 0.33° (= 10 px) each. Two keys on the keyboard (*left Ctrl* and *right arrow*) served as response keys. Two unilateral auditory stimuli (left or right), a 1000 Hz pure tone (indicating response location in one task) and a pink noise burst (indicating response location in the other task) with a duration of 50 ms each, were presented via supra-aural headphones. Both stimuli were easily distinguishable and of equal perceived loudness.

Procedure

Each block started with an on-screen instruction followed by the calibration of the eye tracking system. In each trial, both stimuli appeared sequentially with a variable SOA (120 ms, 240 ms, and 360 ms) in random order. Participants were instructed to execute the two responses as fast and accurately as possible. No information or instruction was given regarding stimulus order and response order. The experiment also included an $\text{SOA} = 0$ ms condition (simultaneous stimulus presentation) in order to compare these data with those from other experiments in our laboratory, but this condition (because it imposes different processing demands compared to sequential stimulus presentation) was irrelevant for the purpose of the present study and thus not further analysed.

In the oculomotor task participants were required to move their gaze to the target on the screen that was spatially compatible to the stimulus and afterwards return to the central fixation cross. In the manual task, participants were required to press the key that spatially corresponded to the stimulus. The assignment of stimulus type (pure tone and noise burst) to response modality (oculomotor and manual) was specified in the instruction and counterbalanced across participants. The interval between the first stimuli of two consecutive trials was 3500 ms. Each participant completed four dual-task blocks consisting of 56 trials each and two single task blocks containing 32 trials of each component task, respectively. The single-task blocks, in which only one stimulus was presented, were not relevant for the purpose of the present research questions. Block order was counterbalanced across participants.

Design

Stimulus order (S_OS_M and S_MS_O), task compatibility (spatially compatible and incompatible), and SOA (120 ms, 240 ms, and 360 ms) were manipulated within participants. Each SOA was presented 32 times. All four possible combinations of stimuli (i.e. both tone and noise on left or right side, tone left + noise right, and tone right + noise left) occurred equally often, resulting in the same amount of spatially compatible and incompatible trials. The relative frequency of response order reversals, response errors, and response times (RTs) were measured as the main dependent variables.

5.2.2 Results and Discussion

Valid data were selected by removing trials with technical irregularities (e.g. missing data because of eye tracking signal loss). Additionally, one participant with an unusual high error rate ($> 40\,\%$)

was excluded. This procedure led to 94.1 % valid data. Response error trials were defined as trials, in which a response error occurred in any of the two tasks. The overall error rate amounted to 15 %. These trials were discarded from analyses of response order decisions.

Response order reversals

Response order reversals were defined as response sequences that did not correspond to the respective stimulus order. Prior to the analysis of this dichotomous variable, we wanted to ensure that our experimental setting did not promote an excessive occurrence of grouped responses, which would probably represent an additional category of response scheduling decisions and as such potentially compromise our conclusions. Common definitions of response grouping are usually based on a certain range of temporal inter-response intervals (IRIs), specifically, typically up to 150 ms (Adam, Hommel, & Umiltà, 2003; Ulrich & Miller, 2008). Here, IRIs were defined as the temporal difference between the onset between the manual response t_{R_M} and the oculomotor response t_{R_O} ($\mathrm{IRI} = t_{R_M} - t_{R_O}$). Based on the fact that goal-directed saccades are known to be executed relatively fast (i.e. with a mean latency of about 125 ms, see, e.g. Findlay & Walker, 1999), we reasoned that a reasonable criterion for grouped responses should not exceed this value in our study. A visual inspection of Figure 5.1 clearly rules out that excessive response grouping (in terms of a strong peak of the IRI distribution within the $+/-$ 125 ms range) occurred in Experiment 1.

Figure 5.2 depicts the mean relative frequency of response order reversals. The overall mean reversal rate amounted to 42.4 % and significantly different from 0 %, $t(22) = 20.3$, $p < .001$, suggesting that in nearly half of the trials participants did not respond in correspondence with the stimulus order. Instead, oculomotor responses were executed first in 89.5 % of all trials. Apparently, response modality characteristics had a greater impact on scheduling decisions than mere stimulus order, at least within the (rather typical) SOA range selected in the present experiment. Since these effects cannot be attributed to differences in stimulus processing stage duration, they are clear evidence against a simple first-come, first-served (or passive queuing) mechanism as predicted by a basic RSB framework without any further assumptions. However, if characteristics of the response modalities were the only factor determining response order (and stimulus order played no meaningful role whatsoever), we would have expected an amount of oculomotor-first trials in the S_MS_O condition that corresponds to the amount of oculomotor-first trials in the S_OS_M condition.

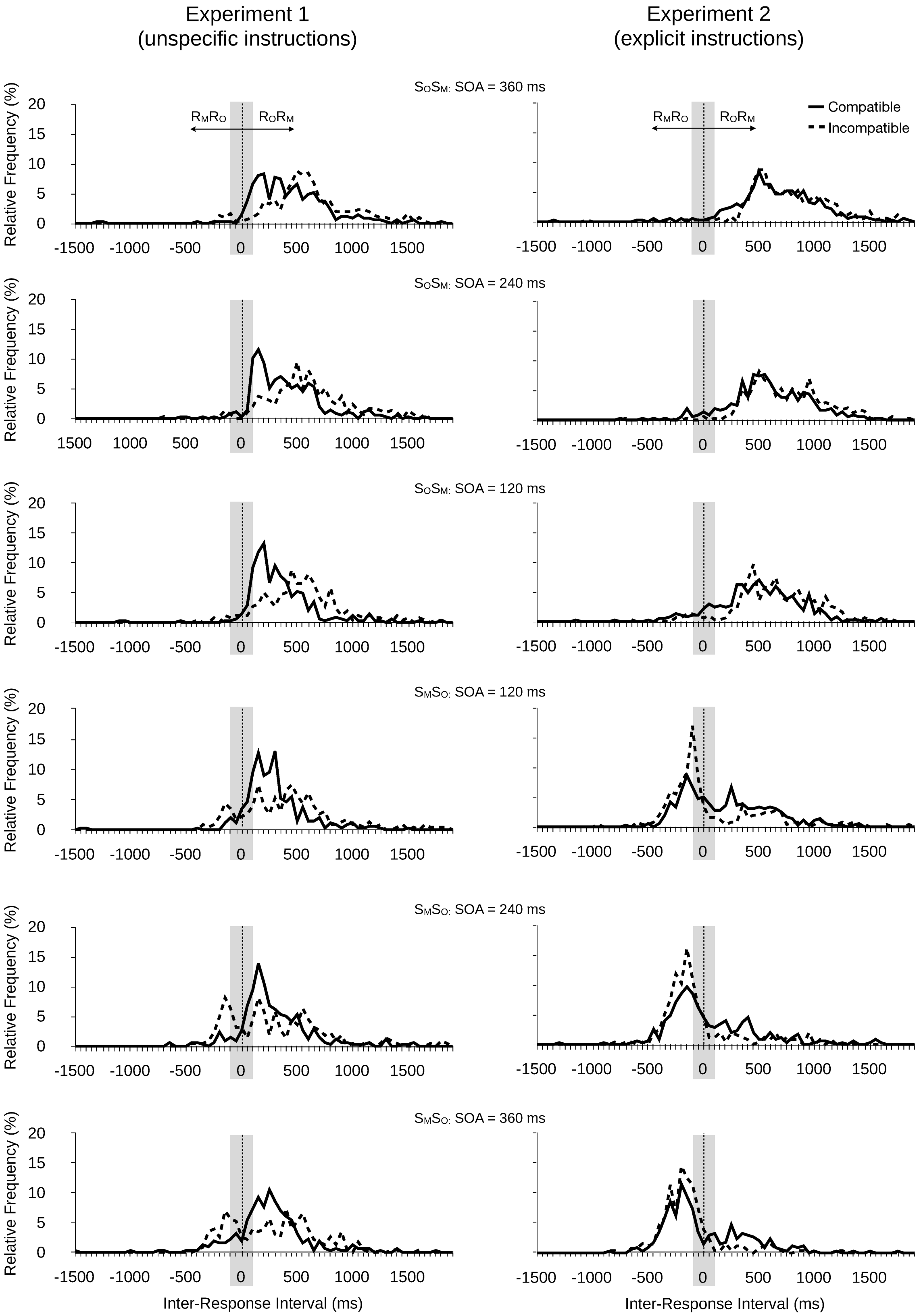


Figure 5.1. Distribution of inter-response intervals (pooled in 50 ms bins) as a function of SOA and spatial between-task compatibility (compatible and incompatible) in Experiment 1 and 2. The grey area indicates the IRI range between −125 ms and 125 ms (potential grouping range). S_OS_M indicates that the stimulus for the oculomotor response was presented first (vice versa for S_MS_O). Negative IRIs indicate that the manual response was initiated first (R_MR_O; vice versa for positive IRIs: R_OR_M).

However, this was not the case, $t(22) = 3.38$, $p = .003$, suggesting that stimulus order still had a significant (although small) impact on response order scheduling.

Taken together, these results suggest that both response-related and stimulus-related factors contribute to response order decisions. If we assume that the prioritisation of oculomotor responses (in terms of a tendency to execute these responses first) represents a top-down regulated attentional weighting process affecting response scheduling decisions (see Huestegge & Koch, 2013), our results suggest that in the present experimental setting top-down factors had a greater overall impact than bottom-up factors such as stimulus order. Therefore, the present novel results suggest that oculomotor prioritisation effects that were previously observed regarding the pattern of dual-response costs across effector systems related to RTs (cf., Huestegge & Koch, 2013; Pieczykolan & Huestegge, 2014) also generalise to response order decisions in the PRP paradigm.

Due to the markedly different reversal rates in the two stimulus order conditions, we further analysed the effects of task compatibility and SOA on reversal rates by calculating separate 2 × 3 ANOVAs for each stimulus order condition. This separation of analyses is also important since the occurrence of a reversal refers to opposed empirical phenomena across the two stimulus order conditions (e.g. a *manual-first* decision represents a reversal in the S_OS_M condition, but not in the S_MS_O condition).

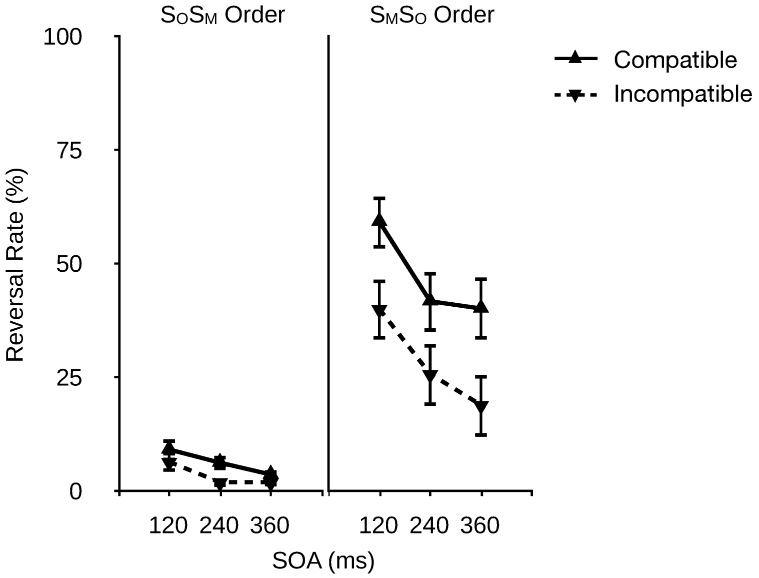


Figure 5.2. Reversal rate as a function of stimulus order (S_OS_M = stimulus for oculomotor response first, S_MS_O = stimulus for manual response first), spatial between-task compatibility (compatible and incompatible), and SOA in Experiment 1. Error bars represent standard errors.

The reversal rate in the S_OS_M condition was very low (3.6 %), but still significantly different from 0 %, $t(22) = 2.9$, $p = .008$. It was not significantly affected by SOA, compatibility, or the interaction of SOA and compatibility, all ps $> .14$.

In contrast, the reversal rate in the S_MS_O condition amounted to 81.1 %. Here, we observed a significant main effect of SOA, $F(2,44) = 13.25$, $p < .001$, $\eta_p^2 = .38$, indicating that the overall preference for executing the oculomotor response first was attenuated when stimuli were temporally further apart (88.6 %, 80.5 %, 74.2 % reversals at SOAs of 120 ms, 240 ms, and 360 ms, respectively). This result indicates that response scheduling decisions were not only affected by the stimulus order per se but additionally by the temporal distance between stimuli. Since a pure bottom-up account could already be ruled out, the SOA effect may be explained in several ways. For example, it is possible that oculomotor-first decisions represent a default response order strategy, which is plausible given the substantial proportion of reversals. Probably, this default mode is particularly applied as an economic scheduling regime in situations with relatively high uncertainty (e.g. regarding stimulus order, that changes from trial to trial). In this context, a larger temporal stimulus distance may increase the salience of stimulus order (thus lowering uncertainty) and eventually lead to a decreased necessity for applying the default mode. Such a mechanism would then result in a priority shift away from oculomotor prioritisation and thus towards fewer response reversals. However, it is additionally possible that large SOAs may reduce the likelihood that subjects wait with their final response order decision until both stimuli are processed (and compared, e.g. regarding their compatibility, see following paragraph), so that after some time they deliberately switch to a task processing mode that corresponds to the stimulus order. Thus, one would expect that for more extreme SOAs (which render non-overlapping task processing more likely) stimulus order should be the main factor determining response order (see Experiment 3 for corresponding data).

In line with the latter processing assumption, we observed a main effect of between-task compatibility in the S_MS_O condition, $F(1,22) = 5.05$, $p = .035$, $\eta_p^2 = .19$, with 87.1 % reversals in compatible trials and 75.1 % reversals in incompatible trials, while the interaction between SOA and task compatibility failed to reach significance, $F(2,44) = 2.1$, $p = .076$, $\eta_p^2 = .11$. The compatibility effect suggests that final response scheduling decisions (at least partially) occur temporally *after* the processing and comparison of *both* stimuli, which again is not in line with a framework, in which stimulus processing in Task 1 is immediately followed by response selection. This interpretation is also consistent with the observation that numerous reversals still occurred at long SOAs in the

$\mathrm{S_M S_O}$ condition, suggesting that participants withheld the manual response and therefore established a time window in which a stimulus comparison process could take place (see General Discussion for further details). Finally, since error trials were not considered in the response order analysis we further analysed the compatibility effect to rule out the possibility that it represents an artifact due to an unequal distribution of errors across compatibility conditions (see error rates below). Therefore, we calculated an ANOVA on reversals without the exclusion of error trials, which yielded the same statistical pattern, that is significant compatibility and SOA effects.

Error rates

Due to the substantial reversal rates and the fact that only twelve participants responded in accordance with the stimulus order in $\mathrm{S_M S_O}$ conditions more than just occasionally, a meaningful statistical comparison of error rates between reversal and non-reversal trials was not possible (but see Comparison Across Experiments for a more powerful combined analysis). Nevertheless, an analysis of error rates can still be informative regarding the overall difficulty of the task conditions. As mentioned above – and in analogy to the dichotomous reversal measure – an error trial was defined as containing an incorrect response in at least one of the two tasks. We computed separate ANOVAs for both stimulus order conditions (analogous to the reversal rate analysis) with the independent factors compatibility and SOA. Table 5.1 depicts the mean error rates.

Table 5.1

Percentage of error trials in Experiment 1 as a function of stimulus order (S_OS_M and S_MS_O), between-task compatibility, and SOA. Numbers in parentheses represent standard errors.

$\mathrm{S_O S_M}$						$\mathrm{S_M S_O}$					
Compatible			Incompatible			Compatible			Incompatible		
SOA (ms)			SOA (ms)			SOA (ms)			SOA (ms)		
120	240	360	120	240	360	120	240	360	120	240	360
2.2	3.8	3.0	16.7	8.6	10.1	2.6	2.6	3.2	31.3	29.5	25.7
(0.8)	(1.1)	(1.0)	(2.7)	(2.0)	(2.0)	(0.9)	(0.6)	(1.5)	(3.7)	(3.1)	(3.0)

Note. *S_OS_M = stimulus for oculomotor response presented first; S_MS_O = stimulus for manual response presented first.*

In the $\mathrm{S_O S_M}$ condition errors differed significantly between compatible (3.5 %) and incompatible (20.6 %) trials, $F(1,22) = 28.69$, $p < .001$, $\eta_p^2 = .57$, and decreased with longer SOAs (16.7 %, 10.7 %, and 8.7 % for 120 ms, 240 ms, and 360 ms), $F(2,44) = 15.1$, $p < .001$, $\eta_p^2 = .41$, confirming the expectation that larger temporal stimulus distance is accompanied by a lower potential for interference. The interaction was significant, too, $F(2,44) = 10.03$, $p < .001$, $\eta_p^2 = .31$, indicating that for incompatible trials errors rate decreased much faster with increasing SOAs than for compatible trials.

In the $S_M S_O$ condition, in which responses were reversed in over 80 % of the trials, we observed a main effect of compatibility, too, $F(1,22) = 66.89$, $p < .001$, $\eta_p^2 = .75$, but there was neither a significant SOA effect, $F(2,44) = 1.13$, $p = .33$, nor a two-way interaction, $F(2,44) = 2.08$, $p = .14$. Overall, these results demonstrate that spatial between-task incompatibility represented a substantial source of interference. Its adverse impact on performance was to some extent reduced by increasing SOAs (but only in the $S_O S_M$ condition). This further corroborates the assumption that S_1 was held in working memory to allow for a comparison with S_2, which may have eventually caused confusion of the mapping of spatial codes to the appropriate response modalities.

A comparison across both stimulus order conditions showed that more errors occurred in the $S_M S_O$ condition (18.3 %) than in the $S_O S_M$ condition (12.1 %), $F(1,22) = 9.17$, $p = .006$, $\eta_p^2 = .29$. This may indicate that when both bottom-up and top-down factors suggest the same response order (i.e. as in the $S_O S_M$ condition), fewer overall cognitive demands are present when compared to a condition in which bottom-up factors (related to stimulus order) are in conflict with (and thus attenuating) the default top-down response order strategy based on effector system prioritisation.

5.3 Experiment 2

In Experiment 1, which did not involve specific instructions regarding response order, oculomotor responses were temporally prioritised over manual responses (i.e. executed first) with only a comparatively small impact of stimulus order information. One potentially important difference between Experiment 1 and typical PRP studies is that in the latter participants are often explicitly encouraged to respond in accordance with stimulus order. Thus, the lack of evidence for a strong role of stimulus order in Experiment 1 might be due to the absence of a corresponding instruction. In Experiment 2, we repeated the previous experiment but added the instruction to respond in accordance with stimulus order. This manipulation should be informative regarding the extent to which response scheduling strategies can be actively adjusted in a top-down manner while the remaining conditions are fully comparable (unlike in De Jong, 1995).

5.3.1 Method

Participants

Twenty-four new participants (6 male, 18 female) with a mean age of 24.9 years (range = 19–30) were recruited and received course credits or monetary reimbursement for participation. Before the experiment they gave informed consent.

Apparatus and Stimuli

The experimental hardware setup was exactly the same as in Experiment 1. However, an Eyelink 1000 (instead of an Eyelink II) eye tracker with a temporal resolution of 1000 Hz was used.

Procedure and Design

While the oculomotor and manual tasks were identical to Experiment 1, participants were now explicitly instructed to execute the responses in accordance with stimulus order. As in Experiment 1, they were not informed about the order of stimuli and did not receive any error feedback after each trial (see De Jong, 1995, for a different approach). Stimulus order (S_OS_M and S_MS_O), between-task compatibility (compatible and incompatible), and SOA (120 ms, 240 ms, and 360 ms) were manipulated within participants.

5.3.2 Results and Discussion

We applied the same data cleansing procedures as in Experiment 1. One participant was excluded from the analysis because of an unusual high amount of erroneous saccades in incompatible trials ($>$ 60 % incorrect). Valid data amounted to 95.2 %. The overall error rate was 11.9 % (see detailed analysis below). As in Experiment 1, the IRI distribution (see Figure 5.1) showed no signs of excessive response grouping.

Response order reversals

Figure 5.3 depicts the mean reversal rates as a function of stimulus order, compatibility, and SOA. The overall reversal rate amounted to 21.3 %, which significantly differed from 0, $t(22) = 7.17$, $p < .001$. Equivalently, in 76.5 % of the trials the oculomotor response was executed as the first response, which again is evidence for a strong oculomotor prioritisation effect. However, the frequency of oculomotor-first responses significantly differed between the two stimulus order conditions, $t(22) = 9.6$, $p < .001$ (two-sided), with 95 % oculomotor-first responses in the S_OS_M

order condition and 37.7 % oculomotor-first responses in the S_MS_O order condition. Thus, similar to Experiment 1 we observed a strong oculomotor prioritisation effect but also a significant influence of stimulus order, which was nominally greater than in the previous experiment (see Comparison Across Experiments for statistical analyses). To further analyse the effects of task compatibility and SOA on reversal rates, we calculated separate 2 $\times$ 3 ANOVAs for each stimulus order condition (S_OS_M and S_MS_O).

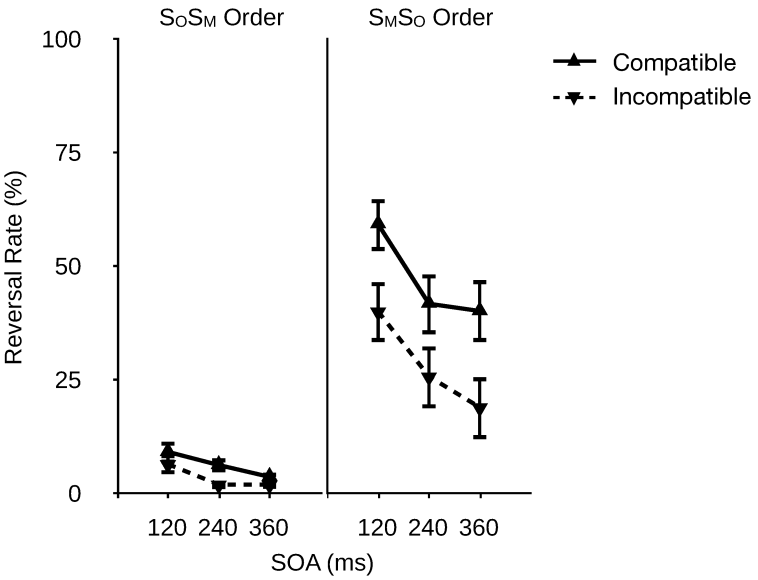


Figure 5.3. Reversal rate as a function of stimulus order (S_OS_M = stimulus for oculomotor response first, S_MS_O = stimulus for manual response first), spatial between-task compatibility (compatible and incompatible), and SOA in Experiment 2. Error bars represent standard errors.

Reversals in S_OS_M condition. The overall reversal rate was very low (5 %). However, unlike in Experiment 1 reversals here were significantly more frequent for compatible than for incompatible trials (6.4 % and 3.5 %), $F(1,22) = 4.87$, $p = .038$, $\eta_p^2 = .18$. There was also a main effect of SOA, $F(2,44) = 4.9$, $p = .012$, $\eta_p^2 = .18$, indicating a decrease of reversals with increasing SOA (7.9 %, 4.2 %, and 2.9 %). The interaction was not significant, $F < 1$.

Reversals in S_MS_O condition. The mean reversal rate amounted to 37.7 %, showing that despite explicit instructions participants failed to respond accordingly in more than one third of the trials. Reversals were more frequent in compatible trials than in incompatible trials (47.1 % and 28.3 %), $F(1,23) = 40.18$, $p < .001$, $\eta_p^2 = .65$, and the reversal rate decreased with increasing SOA (49.7 %, 33.8 %, and 29.6 %), $F(2,44) = 18.87$, $p < .001$, $\eta_p^2 = .46$. There was no two-way interaction, $F < 1$.

Taken together, participants were to some degree able to voluntarily execute responses in accordance with the stimulus order. Thus, they appear to be capable of attenuating their inherent prioritisation of the oculomotor task, which we referred to as a default response mode in Experiment 1. The SOA effect in both stimulus order conditions likely reflects that a larger temporal distance between stimuli generally helps to disambiguate response order, that is it facilitates to respond in accordance with the stimulus order. Nevertheless, oculomotor prioritisation still plays a major role in determining response order, since a notable amount of response reversals were still observed (e.g. 60 % for compatible trials in the 120 ms SOA condition in the S_MS_O order). This observation shows that mere instructions are not sufficient to fully overcome the effector system-based prioritisation. However, it is important to note that in Experiment 1 and 2 stimulus order changed unpredictably from trial to trial, a situation involving a degree of uncertainty that might have supported the overall influence of the default (oculomotor-first) response mode.

Interestingly, the results also suggest that the explicit response order instructions, which likely directed attention more towards stimulus order information, were more effective in incompatible than in compatible trials. Probably, greater resource mobilisation caused by the demand of spatial conflict resolution further increased the amount of attentional resources directed at the processing of stimuli, including their associated features like temporal order information. In contrast, the less demanding compatible trials may rather support keeping up the default prioritisation mode (based on effector systems irrespective of stimulus characteristics (for details see General Discussion).

The effect of SOA in the S_OS_M condition, which was not present in Experiment 1, can be explained by differences in salience of stimulus order affecting the likelihood of reversals in a similar way as in the S_MS_O condition. The lower reversal rate for incompatible trials in the S_OS_M condition may again indicate enhanced attention to stimulus features (including stimulus order information) during the presence of spatially incompatible stimuli.

However, unlike in Experiment 1 the compatibility effect in the S_MS_O condition (which was based on the analysis of correct trials only) disappeared when all trials (including error trials) were considered. Specifically, this analysis yielded 46.9 % reversals for compatible and 44.3 % reversals for incompatible trials, $F < 1$. This suggests that in Experiment 2, a trade-off might have occurred between two concurrent demands, namely responding with the correct (left/right) response and responding in the correct order (as specified by the response order instruction, which was only present in Experiment 2).

Error rates

Errors (see Table 5.2) were analysed in the same way as in Experiment 1. In the $\mathrm{S_OS_M}$ condition, compatible trials were less error-prone than incompatible trials (3.0 % vs. 11.8 %), $F(1,22) = 28.55$, $p < .001$, $\eta_p^2 = .57$, and errors decreased with increasing SOA (9.5 %, 6.2 %, and 6.6 %), $F(2,44) = 15.1$, $p < .001$, $\eta_p^2 = .41$. The interaction was also significant, $F(2,44) = 6.62$, $p = .003$, $\eta_p^2 = .23$, showing that the decrease of errors with increasing SOA was more pronounced in incompatible trials than in compatible trials.

In the $\mathrm{S_MS_O}$ condition, the main effect of compatibility was significant, too, $F(1,22) = 95.16$, $p < .001$, $\eta_p^2 = .81$, but there was no significant effect of SOA, $F(2,44) = 1.34$, $p = .272$, and no significant two-way interaction, $F(2,44) = 2.46$, $p = .097$. The substantial compatibility effect in the $\mathrm{S_MS_O}$ condition is similar to the corresponding effect observed in Experiment 1, most likely indicating that – despite the specific instructions highlighting stimulus order information – confusion regarding the mapping of spatial codes to effector modalities occurred in this particular condition.

A comparison of error rates between the two stimulus order conditions showed that similar to Experiment 1, significantly more errors occurred in the $\mathrm{S_MS_O}$ condition (15.7 %) than in the $\mathrm{S_OS_M}$ condition (7.4 %), $F(1,22) = 33.1$, $p < .001$, $\eta_p^2 = .60$.

Table 5.2

Percentage of error trials in Experiment 1 as a function of stimulus order (S_OS_M and S_MS_O), between-task compatibility, and SOA. Numbers in parentheses represent standard errors.

$\mathrm{S_OS_M}$						$\mathrm{S_MS_O}$					
Compatible			Incompatible			Compatible			Incompatible		
SOA (ms)			SOA (ms)			SOA (ms)			SOA (ms)		
120	240	360	120	240	360	120	240	360	120	240	360
4.7	2.8	3.1	28.7	18.7	14.3	2.4	2.6	3.6	35.9	35.7	29.4
(1.3)	(1.1)	(1.2)	(4.6)	(3.7)	(3.4)	(0.7)	(1.0)	(1.4)	(4.4)	(5.2)	(4.5)

Note. *S_OS_M = stimulus for oculomotor response presented first; S_MS_O = stimulus for manual response presented first.*

RTs and error rates of reversed vs. non-reversed responses

Compared to Experiment 1, reversals and non-reversals were more equally distributed in Experiment 2. This allows us to address the potential functional relevance of response reversals for overall performance within a trial with the specific question if response prioritisation (as reflected in response reversals) is associated with processing benefits. Although the present study was not specifically designed to examine effects of response order decisions on response times (RT) and error rates, a post hoc analysis might still be informative regarding processing efficiency. Specifically, two different scenarios are possible: Either, responses were reversed *strategically* in order to optimise processing efficiency, for instance in order to minimise total response time ($\text{TRT} = \text{RT}_1 + \text{RT}_2$) as suggested by Leonhard et al. (2011; see also Miller, Ulrich & Rolke, 2009). Alternatively, performance may have suffered in reversed response trials, suggesting that oculomotor prioritisation is a rather *generic* phenomenon that may be functionally relevant and thus beneficial in everyday life situations but not in the context of the specific laboratory setting in the present study.

In order to assess if there were significant performance differences between reversed and non-reversed responses, we conducted ANOVAs on RTs and error rates at $\text{SOA} = 120\,\text{ms}$ in the $S_M S_O$ order condition. This condition was especially suited for the comparison because 49.7 % of the trials were reversals. Since between-task compatibility manipulations in PRP studies are known to affect the two responses differently (see backward crosstalk effects, e.g. Miller, 2006), we subjected compatible and incompatible trials to separate analyses. Response order (reversed vs. non-reversed) and task (oculomotor vs. manual) served as independent factors. Note that the analysis included only a subsample of 15 participants, who contributed valid data to each of the conditions. Results are depicted in Figure 5.4.

In compatible trials, the main effect of task on RTs was significant with overall greater manual RTs (1207 ms) compared to oculomotor RTs (941 ms), $F(1,14) = 117.4$, $p < .001$, $\eta_p^2 = .89$, but there was no significant main effect of response order, $F(1,14) = 1.58$, $p = .23$. However, there was a significant two-way interaction, indicating that in the reversed response order (in which oculomotor responses were executed first), manual responses were slower while oculomotor responses were faster, $F(1,14) = 93.21$, $p < .001$, $\eta_p^2 = .87$, indicating prioritisation regarding both speed and order. For incompatible trials, the pattern was similar with a significant main effect of task, $F(1,14) = 98.82$, $p < .001$, $\eta_p^2 = .88$, no significant main effect of response order, $F = 3.09$, $p = .10$, and a significant two-way interaction, $F(1,14) = 115.31$, $p < .001$, $\eta_p^2 = .89$. The lack of a significant overall effect of response order on mean (equivalent to total) RTs, however, does not support an optimisation account according to which reversals aim at increased overall processing efficiency.

An analogous analysis of error rates in compatible trials revealed no significant main effects of task or response order, $F\text{s} < 1$, and only a marginally significant interaction, $F(1,14) = 4.42$, $p = .054$,

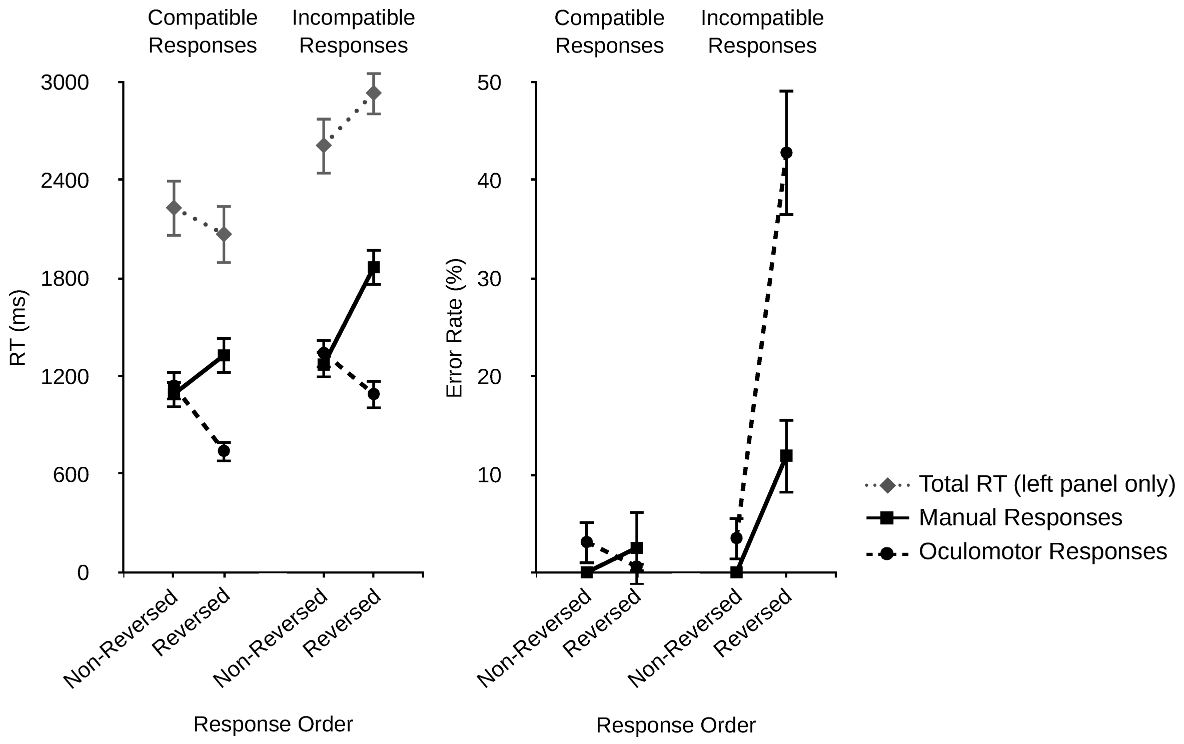


Figure 5.4. RTs and errors rates of oculomotor and manual responses in S_MS_O order at SOA = 120 ms as a function of response order (reversed and non-reversed) and spatial between-task compatibility (compatible and incompatible) in Experiment 2.

$\eta_p^2 = .24$, indicating that for both response orders the first executed response tended to be associated with fewer errors. For incompatible trials, however, there was a main effect of task, $F(1,14) = 47.88$, $p < .001$, $\eta_p^2 = .77$, indicating overall higher error rates for oculomotor responses (23.1 %) than for manual responses (5.9 %), and a significant main effect of response order, $F(1,14) = 24.84$, $p < .001$, $\eta_p^2 = .64$, indicating higher error rates in the reversed response order (27.3 %) than in non-reversed response order (1.7 %). The two-way interaction, $F(1,14) = 19.46$, $p = .001$, $\eta_p^2 = .58$, showed that the high error rates for reversed responses were mainly driven by errors in the oculomotor task.

Taken together, the present post hoc analysis showed no convincing evidence for a performance benefit associated with response reversals. Instead, reversing responses rather yielded lower accuracy in both tasks, and, interestingly, especially for the oculomotor response. Thus, we can exclude the possibility that the a priori prioritisation of the oculomotor system represents a successful *functional strategy* to increase overall performance. The present observations rather suggest that oculomotor prioritisation might represent a rather generic (instead of a strategic) bias, which is also consistent with the apparent difficulties of participants to comply with response order instructions.

5.4 Experiment 3

Based on the results from Experiment 1 and 2 alone, it still remains possible that the general tendency to prioritise oculomotor responses only emerged because of the unpredictable stimulus order associated with a mixed stimulus order design. Thus, in Experiment 3 we analysed performance in a situation with a fixed ($S_M S_O$) stimulus order and without explicit response order instructions.

To selectively assess the impact of a fixed stimulus order on response scheduling decisions, we used a similar design as in Experiment 1 (i.e. without any explicit response order instructions). To further emphasise the overall salience of the fixed stimulus order, we additionally added more extreme SOA conditions (range: 120 ms − 1200 ms) but retained the SOA conditions from Experiment 1 (120 ms, 240 ms, and 360 ms), for comparison purposes. Note that the very large SOA conditions should strongly encourage performance patterns, in which the manual response is executed prior to the onset of the stimulus for the oculomotor response (i.e. non-overlapping task processing). If response reversals observed in the previous experiments were mainly resulting from a strategy to deal with changing stimulus order demands, we would expect much fewer reversal rates in Experiment 3, where task settings implicitly (opposed to the explicit instructions in Experiment 2) discourage an oculomotor-first strategy.

5.4.1 Method

Participants

Twenty-four new participants (23 female) with a mean age of 22.2 years (range = 18–28) were recruited and received course credits or monetary reimbursement for participation.

Apparatus, Stimuli, and Procedure

The experimental setup and instructions were identical to those in Experiment 1. Participants were neither explicitly informed about stimulus order nor instructed regarding response order.

Design

Between-task compatibility (compatible and incompatible) and SOA (120 ms, 240 ms, 360 ms, 480 ms, 720 ms, 960 ms, and 1200 ms) were manipulated within participants.

5.4.2 Results

97.7 % of the recorded data remained after the data cleansing procedures as described in Experiment 1. The overall error rate amounted to 5 % only. For response order analyses in correct trials, we applied a 2×7 ANOVA with the independent variables compatibility and SOA.

Response order reversals

The mean reversal rate amounted to 17.2 %, which differed significantly from 0 %, $t(23) = 3.86$, $p < .001$. Reversals were again more frequent in compatible than in incompatible trials, $F(1,23) = 18.09$, $p < .001$, $\eta_p^2 = .44$. Reversal rates also decreased with increasing SOAs, $F(6,138) = 28.03$, $p < .001$, $\eta_p^2 = .55$, (39.4 %, 25.6 %, 19.3 %, 12.7 %, 9.5 %, 7.4 %, 6.2 % for SOAs from 120 ms to 1200 ms). The interaction between compatibility and SOA was significant, too, $F(6,138) = 3.86$, $p = .001$, $\eta_p^2 = .14$, showing that the reversal rate dropped faster for incompatible than for compatible trials (specifically at short SOAs until SOA = 480 ms, see Figure 5.5).

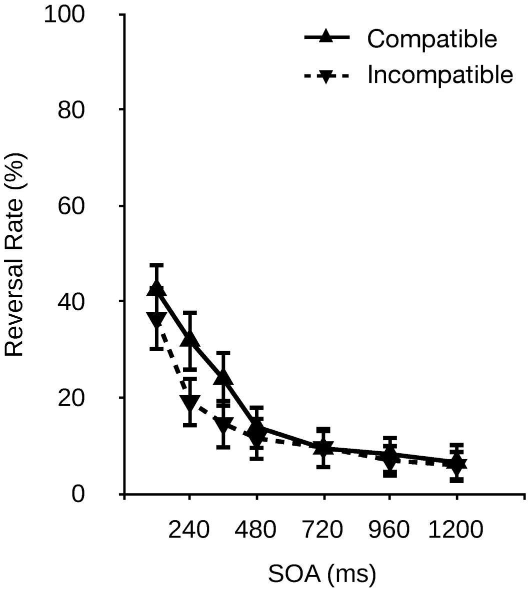


Figure 5.5. Reversal rate as a function of between-task compatibility (compatible and incompatible) and SOA in Experiment 3 with fixed stimulus order ($S_M S_O$) and without explicit response order instructions. Error bars represent standard errors.

Pairwise Bonferroni-corrected post hoc comparisons statistically corroborated that the reversal rate did not vary significantly for SOAs greater than 360 ms (i.e. all comparisons for data points at SOA = 480 ms against data points at larger SOA levels were non-significant, *p*s > .25).

The observation that overall reversal rate dropped to around 10 % above an SOA of 480 ms provides strong evidence that participants were able to overcome oculomotor prioritisation for substantial temporal stimulus distances, that is under conditions in which waiting for the second stimulus prior to manual response execution would be highly dysfunctional in terms of overall processing efficiency. Nevertheless, despite the fixed stimulus order in Experiment 3 reversals still occurred in approximately 40 % of the trials with SOA $=$ 120 ms . This observation shows that response modality characteristics and associated prioritisation mechanisms exert a strong influence even in conditions, in which the overall task settings strongly suggest a fixed processing order.

Unlike in Experiments 1 and 2, we here observed an SOA limit beyond which between-task compatibility was no longer relevant for response scheduling decisions. Apparently, beyond a certain stimulus distance participants did not apply a strategy to wait for (and compare) both stimuli in order to decide an appropriate response order. Instead, tasks were processed serially in accordance with the stimulus order.

Note that an analysis of reversal rates based on all trials (i.e. including error trials) yielded the same statistical pattern, including a significant compatibility effect. Similar to Experiment 1, this observation suggests that there was no substantial trade-off between response order control and accuracy.

Error rates

Error rates in Experiment 3 were significantly affected by compatibility (3 % in compatible trials and 8.6 % in incompatible trials), $F(1{,}23) = 27.4$, $p < .001$, $\eta_p^2 = .54$, and by SOA, $F(6{,}138) = 7.45$, $p < .001$, $\eta_p^2 = .25$ (see Table 5.3). The two-way interaction was significant, too, $F(6{,}138) = 12.51$, $p < .001$, $\eta_p^2 = .35$. Overall, this pattern reflects greater processing demands for processing incompatible spatial codes (likely due to code conflict), while this interference became weaker with greater temporal distance.

RTs and error rates of reversed vs. non-reversed responses

As in Experiment 2, we ran a post hoc analysis of the potential functional relevance of response reversals in terms of their overall behavioural consequences within a trial. A subsample of 16 participants contributed sufficient valid data in each relevant condition (see Figure 5.6 for results).

In compatible trials, there was a significant main effect of task with overall longer manual RTs (640 ms) compared to oculomotor RTs (506 ms), $F(1{,}15) = 96.49$, $p < .001$, $\eta_p^2 = .87$, and a

Table 5.3

Percentage of error trials in Experiment 3 as a function of between-task compatibility and SOA. Numbers in parentheses represent standard errors.

Compatible							Incompatible						
SOA (ms)							SOA (ms)						
120	240	360	480	720	960	1200	120	240	360	480	720	960	1200
1.0	3.2	3.1	4.1	3.9	2.9	3.0	18.5	11.3	8.9	10.1	4.5	3.5	3.5
(0.6)	(0.8)	(1.4)	(1.2)	(1.2)	(0.8)	(0.9)	(2.6)	(1.6)	(1.8)	(1.9)	(3.5)	(1.1)	(1.3)

significant main effect of response order, $F(1,15) = 14.56$, $p = .002$, $\eta_p^2 = .49$, indicating longer RTs on average (hence also longer total RTs) for reversed responses (616 ms) than for non-reversed responses (529 ms). The two-way interaction was also significant, $F(1,15) = 58.29$, $p < .001$, $\eta_p^2 = .80$, indicating that in the reversed (vs. non-reversed) response order manual responses were postponed while oculomotor responses were slightly prioritised (similar to Experiment 2). A similar pattern was observed for incompatible responses. Here, the analysis revealed a significant main effect of task, $F(1,15) = 25.74$, $p < .001$, $\eta_p^2 = .63$, indicating longer RTs for manual responses (1082 ms) than for oculomotor responses (959 ms), and a significant main effect of response order, $F(1,15) = 8.33$, $p = .011$, $\eta_p^2 = .36$, indicating longer RTs for reversed responses (1127 ms) than for non-reversed responses (914 ms). The two-way interaction was again significant, $F(1,15) = 50.93$, $p < .001$, $\eta_p^2 = .77$.

An analysis of error rates (0.1 % on average) in compatible trials revealed no significant effects. For incompatible trials, there was a significant main effect of task, $F(1,15) = 5.64$, $p = .031$, $\eta_p^2 = .27$, indicating overall higher error rates for oculomotor responses (15.9 %) than for manual responses (5.0 %), but no significant main effect of response order, $F(1,14) = 3.15$, $p = .096$, $\eta_p^2 = .17$. However, there was a nominal trend towards higher error rates for reversed responses (13.8 %) compared to non-reversed responses (7.0 %). The two-way interaction was not significant, $F(1,15) = 2.36$, $p = .145$.

Taken together, these analyses demonstrate that overall performance rather suffered from reversing responses, which supports the assumption that oculomotor prioritisation does not reflect an optimisation strategy but rather a generic bias.

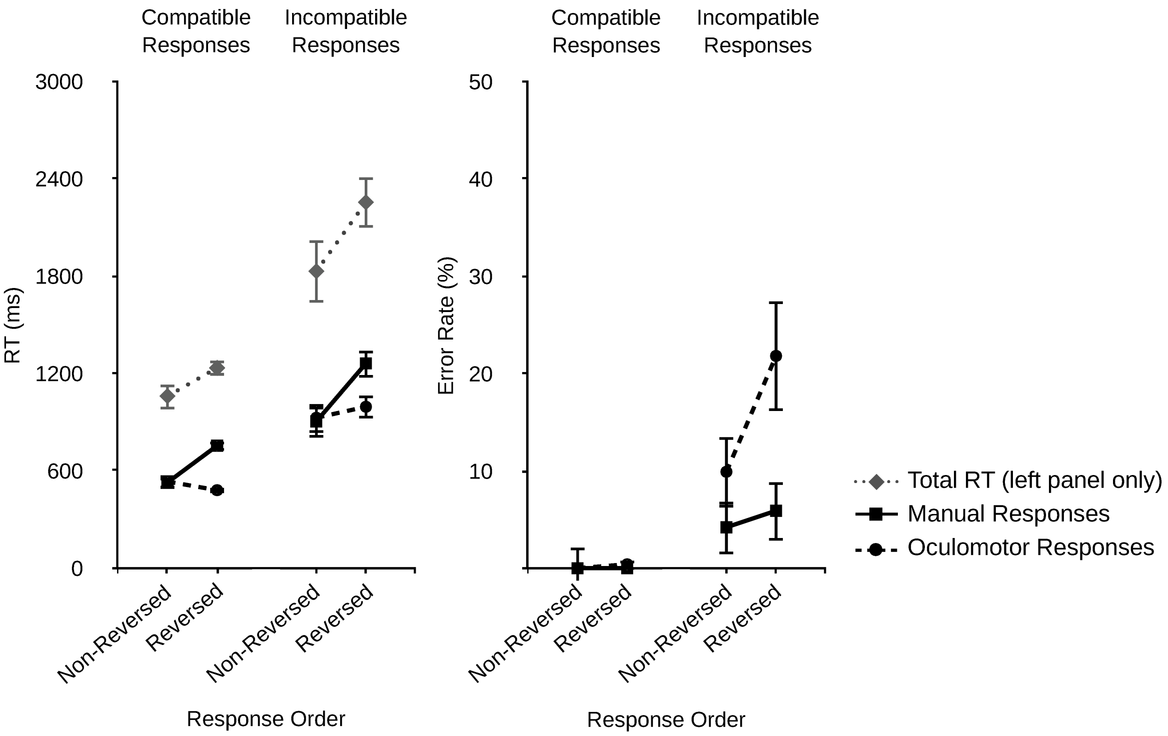


Figure 5.6. RTs and errors rates of oculomotor and manual responses in the $S_M S_O$ order condition at SOA = 120 ms as a function of response order (reversed and non-reversed) and spatial between-task compatibility (compatible and incompatible) in Experiment 3.

5.5 Comparison Across Experiments

Experiment 1 provided strong evidence that in a PRP setup with mixed stimulus order and without explicit response order instructions a strong oculomotor prioritisation occurred, which was only to a small degree affected by stimulus order. The identical setup under explicit instructions to respond in accordance with the stimulus order in Experiment 2 caused a decrease of response reversals. In contrast to the *explicit* instruction in Experiment 2, Experiment 3 *implicitly* encouraged participants to respond in accordance with the stimulus order by utilising a fixed stimulus order (i.e. by always triggering the dominant oculomotor response second). Taken together, Experiment 1 can thus be interpreted as a baseline against which the effectiveness of an explicit approach (instruction, Experiment 2) and an implicit approach (predictability of stimulus order, Experiment 3) to attenuate oculomotor dominance can be statistically compared.

5.5.1 Reversal rates across experiments

$\mathrm{S_O S_M}$ order

Response reversal rates did not differ significantly in $\mathrm{S_O S_M}$ conditions between Experiment 1 (3.6 %) and Experiment 2 (5.0 %), $F < 1$. Since in this condition the stimulus order corresponds to the effector system-based prioritised response order, these reversal rates likely represent the lower bound of unsystematic response order fluctuations. However, there was a marginal effect of SOA, $F(2,88) = 2.96$, $p = .066$, $\eta_p^2 = .06$, and a significant interaction between SOA and experiment, $F(2,88) = 3.53$, $p = .041$, $\eta_p^2 = .06$, reflecting that SOA only affected reversal rates in Experiment 2. Most probably, the explicit instruction encouraged participants to pay more attention to the stimulus order, and short SOAs might have rendered confusions regarding stimulus order processing slightly more likely.

$\mathrm{S_M S_O}$ order

To demonstrate the huge impact of instructions (Experiment 2) and trial context (Experiment 3) on performance in otherwise identical trials, we compared response reversal rates in the $\mathrm{S_M S_O}$ conditions for SOAs of 120 ms, 240 ms, and 360 ms, which were utilised in all three experiments (see Table 5.4). We conducted a mixed ANOVA with the within-subject factors compatibility and SOA and the between-subject factor experiment. Similar to the corresponding analyses in the individual experiments, there were significant main effects of between-task compatibility, $F(1,67) = 38.15$, $p < .001$, $\eta_p^2 = .36$, and SOA, $F(2,134) = 57.23$, $p < .001$, $\eta_p^2 = .46$. However, the analysis also revealed a significant main effect of experiment, $F(2,67) = 27.37$, $p < .001$, $\eta_p^2 = .45$, while there was no significant interaction between any of the factors, all ps $> .17$.

Post hoc (Bonferroni-corrected) comparisons showed that reversal rates in Experiment 2 and 3 differed from those in Experiment 1 (both ps $< .001$). However, reversal rates were not significantly different in Experiment 2 and 3, $p = .631$, although at least nominally reversal rates were lower in Experiment 3 throughout all experimental conditions, probably suggesting a lack of sufficient statistical power due to the between-subjects comparison. Taken together, the data show that both the explicit (Experiment 2) and the implicit (Experiment 3) approach were effective in order to decrease reversal rates. Specifically, the effectiveness of explicit instructions suggests that participants are able to control response order in a top-down manner. However, it appears interesting that the (implicit) effect of a fixed stimulus order is at least as strong as the instruction effect.

Table 5.4

Reversal rates (i.e. oculomotor-first responses in %) in $S_M S_O$ conditions as a function of experiment, compatibility, and SOA. Numbers in parentheses represent standard errors.

	Compatible			Incompatible		
	SOA (ms)			SOA (ms)		
Experiment	120	240	360	120	240	360
Experiment 1 (unspecific instructions, mixed stimulus order)	92.0 (5.1)	89.0 (5.8)	80.2 (6.3)	85.3 (6.1)	71.9 (6.6)	68.2 (6.8)
Experiment 2 (explicit instructions, mixed stimulus order)	59.3 (5.1)	41.8 (5.8)	40.2 (6.3)	40.1 (6.1)	25.8 (6.6)	19.0 (6.8)
Experiment 3 (unspecific instructions, fixed stimulus order)	42.4 (5.0)	37.9 (5.7)	23.9 (6.2)	36.5 (6.0)	19.2 (6.5)	14.6 (6.6)

Note. $S_M S_O$ *= stimulus for manual response presented first.*

5.5.2 Error rates across experiments

In order to test if response accuracy was affected by the manipulations across experiments, we conducted an ANOVA with the independent factors compatibility, SOA, and experiment. As in the individual experiments, there were significant main effects of between-task compatibility (25.1 % for incompatible and 2.6 % for compatible trials), $F(1{,}67) = 195.23$, $p < .001$, $\eta_p^2 = .74$, and SOA, $F(2{,}134) = 4.74$, $p = .013$, $\eta_p^2 = .07$, the latter reflecting a decrease of errors with longer SOA (15.3 %, 14.1 %, and 12.3 %). Importantly, there was a main effect of experiment, $F(2{,}67) = 11.14$, $p < .001$, $\eta_p^2 = .25$, demonstrating that a decrease of reversal rates across experiments was accompanied by an accuracy increase (18.3 %, 15.7 %, and 7.7 % in Experiment 1, 2, and 3, respectively). The interaction of compatibility and experiment was significant, too, $F(2{,}67) = 14.79$, $p < .001$, $\eta_p^2 = .31$, signifying that the compatibility effect became smaller with a decreasing reversal likelihood (compatibility effects of 30.8, 26.2, and 10.5 percentage points for Experiment 1, 2 and 3, respectively). Finally, there was a significant interaction of compatibility and SOA, $F(2{,}134) = 9.57$, $p < .001$, $\eta_p^2 = .13$, suggesting that spatial code conflict decreased with longer stimulus distance. There was neither an interaction between SOA and experiment, $F < 1$, nor a three-way interaction, $F(2{,}134) = 1.14$, $p = .34$.

Post hoc pairwise (Bonferroni-corrected) comparisons of the between-experiment manipulation showed no difference between error rates of the two experiments with mixed stimulus order (Experiment 1: 18.3 %, Experiment 2: 15.3 %), $p = .85$. However, error rates were lowest in Experiment 3 involving a fixed stimulus order compared to both Experiment 1, $p < .001$, and Experiment 2, $p = .003$. This strongly suggests that more predictable task settings (i.e. a fixed stimulus order) are eventually more effective (in terms of performance accuracy) in attenuating effector system-based prioritisation than explicit instructions.

Regarding the influence of between-task compatibility, we observed evidence for two distinct mechanisms. On the one hand, incompatible trials were more error-prone, probably due to a greater confusability potential regarding the mapping of spatial codes to response modalities. On the other hand, the presence of incompatible codes yielded a stronger focus of attention to bottom-up information within the task set (specifically, stimulus order information), eventually attenuating the occurrence of response order reversals.

Note that we did not run an experiment, in which we combined both factors that, in isolation, evidently lowered the frequency of response reversals, namely explicit instructions and fixed stimulus order. However, based on our results it seems relatively safe to assume that the occurrence of response reversals would be further attenuated – a result that would not provide substantial additional theoretical insight.

5.6 General Discussion

The aim of the present study was to investigate the underlying mechanisms of the temporal organisation of behaviour, especially with respect to response order control in multitasking. We examined several sources of influences on response order decisions to achieve a comprehensive understanding of temporal action scheduling. Specifically, we utilised the rate of response reversals as an empirical marker for temporal performance scheduling in a dual-task situation involving two effector systems that are known to substantially differ in their characteristics regarding response execution stage duration and overall prioritisation (see Huestegge & Koch, 2013; Pieczykolan & Huestegge, 2014). This effector combination is also known to produce a substantial variability of response order decisions in the first place (see Pashler et al., 1993). This specific experimental setup allowed us to study the impact of characteristics of a relatively late processing stage on scheduling decisions that need to be made rather early in the processing chain. Within three PRP experiments, we systematically examined the influence of *stimulus order*, *response modalities*, *response order*, *instructions* (unspecific and explicit), *between-task compatibility*, and *stimulus order context* (fixed and mixed stimulus order) in a classic PRP paradigm involving a variable *temporal stimulus distance*. Note that the two tasks differed only with respect to their effector modality, since both required comparable left-or-right decisions.

5.6.1 Top-down and bottom-up determinants of response order control

A major finding was that response scheduling was not largely determined by a simple first-come, first-served mechanism driven by stimulus order. The plausibility of this bottom-up processing account follows from traditional stage logic within dual tasks, according to which the onset of the selection stage for the first response should be solely determined by the end of processing of the first stimulus (e.g. Pashler & Johnston, 1989). However, while some influence of stimulus order was clearly present in our current data, its overall impact was substantially smaller than one would probably expect from previous dual-task studies. The lack of a pronounced influence of bottom-up processing across the range of SOAs typical for PRP experiments is especially notable since previous dual-task studies that involved only a fairly limited number of effector systems usually treated response reversals as an abnormality and excluded them from further analyses (e.g. Bratzke et al., 2009; Hommel, 1998a; Logan & Delheimer, 2001; Pashler & Johnston, 1989; Tombu & Jolicœur, 2002). Nevertheless, it should be noted that the impact of stimulus order was to some extent amplified by another bottom-up factor, namely temporal stimulus distance, which became especially effective at long temporal distances ($> 240\,\text{ms}$).

In contrast to these bottom-up effects, our present data suggest a very strong overall influence of response characteristics (i.e. characteristics of late processing stages) on scheduling decisions. This is especially interesting since within a traditional processing stage logic, the scheduling decision should occur prior to the selection of the first response (if, according to the basic RSB framework, response selection is immediately followed by the corresponding response execution). Specifically, the results suggest a strong temporal prioritisation of oculomotor responses over manual responses, even when the stimulus for the manual task was presented first. This implies that, within the stage logic, stimulus processing of Task 1 was not immediately followed by selecting an appropriate response in Task 1. The present finding that processing characteristics of stages after stimulus processing affect response order decisions is in line with previous reports by Leonhard et al. (2011)

and Ruiz Fernández et al. (2011), who demonstrated the occurrence of more response reversals when the anticipated duration of response selection (i.e. response selection difficulty) in Task 2 was shorter (i.e. the task was easier) than in Task 1. Together with these findings, the present results seriously challenge any first-come, first-served account of response order control. In addition, the present data present novel evidence that even very late (response execution-related) characteristics affect response order decisions. Furthermore, the current data suggest that the underlying oculomotor response prioritisation is not rooted in a strategy to minimise slack time (Leonhard et al., 2011) but is rather originating from a more generic effector-specific bias.

Additionally, the present effects of oculomotor prioritisation regarding response order extend similar, previous findings where oculomotor prioritisation was reflected in dual-response cost asymmetries regarding RTs (Huestegge & Koch, 2013; Pieczykolan & Huestegge, 2014). Specifically, those previous studies showed that oculomotor responses (combined with manual responses) exhibit fewer dual-response costs than manual responses (combined with oculomotor responses), a finding that could not solely be explained through inherent differences in response execution durations between effector systems (Huestegge & Koch, 2013). This suggests that *effector-specific* characteristics (instead of mere execution stage duration) are responsible for oculomotor prioritisation. Interestingly, our analysis of the effects of reversed vs. non-reversed responses on RTs and error rates in Experiments 2 and 3 suggested that oculomotor prioritisation does not reflect a functional strategy in order to achieve performance benefits. Instead, oculomotor prioritisation rather appeared to be a generic, deeply rooted processing default that is comparatively difficult to overcome. While being dysfunctional in the present experimental (laboratory) setting, it may nevertheless represent a useful mechanism (looking before acting) in more natural situations.

At first sight, one potential explanation for both the high overall reversal rate and the decrease of reversals with longer SOA might refer to a potential confusion of stimuli or stimulus order already at a perceptual level. This is especially plausible since stimuli in both tasks were similar in terms of their (auditory) stimulus modality and their task-relevant (spatial left/right) stimulus dimension (set-level compatibility, see Kornblum, Hasbroucq, & Osman, 1990). A similar point was already raised by De Jong (1995), who showed that participants tended to encounter more difficulties in judging the correct stimulus order when the SOA was short (see also Hendrich, Strobach, Buss, Müller, & Schubert, 2012). However, two counter-arguments clearly speak against this assumption. If stimulus order uncertainty was mainly responsible for the high reversal rates, we should have observed a comparable amount of reversals for both stimulus order conditions (at the same SOAs) in Experiment 1 and 2, which was clearly not the case. Second, the low error rates in Experiment 3 prove that participants were principally able to accurately distinguish between the two stimuli. This rules out the potential objection that perceptual limitations regarding stimulus processing can account for the reported effects on response order scheduling (i.e. the occurrence of reversals). Nevertheless, it is still possible that a certain (small) amount of reversals has occurred due to processing errors at the perceptional stage.

5.6.2 Explicit and implicit determinants of scheduling and performance in multitasking

Experiment 2 revealed that explicit instructions can initiate a priority shift towards responding in accordance with the stimulus order. This finding shows that instructions alone can affect temporal response order (as suggested by De Jong, 1995, who reported an effect of the combination of instructions and feedback). However, despite this evidence for a top-down attenuation of effector system-based prioritisation it should be noted that at short SOAs oculomotor-first scheduling was still prevalent. Finally, Experiment 3 – in which the predictable stimulus order implicitly (i.e. without explicit response order instructions) suggested to respond accordingly – demonstrated that even in a condition involving constant stimulus order oculomotor prioritisation still occurred (at short SOAs). However, this experiment again showed that participants were able to overcome oculomotor prioritisation to some degree at short SOAs and quite effectively at longer SOAs. Taken together, Experiments 2 and 3 provide evidence that response order is at least partially under active, deliberate control of participants (see, De Jong, 1995, for similar results). However, at least in terms of overall response accuracy a change of task environment (Experiment 3) was a more effective approach to adjust performance (in terms of lowering reversal rates) than explicit instructions (Experiment 2), a finding that could probably be relevant for applied settings to improve multitasking performance.

5.6.3 Mechanisms of response control in dual tasks: Towards a multi-phase framework of temporal action scheduling

The finding that response order decisions were strongly affected by between-task compatibility in all three experiments is particularly informative regarding underlying mechanisms and dynamics of action scheduling. Usually, the resolution of spatial incompatibility in dual-task control is known to draw on cognitive resources thus yielding performance decrements in incompatible trials. However, here spatial incompatibility led to *fewer* response reversals, a finding that – at least in Experiment 2 – represents 'better' performance (i.e. performance that is more in line with the instructions). Thus, the present findings cannot be not simply attributed to known compatibility phenomena. In the following paragraph, we will thus develop a framework that is better in line with our present observations while integrating previous studies on response order control (see Figure 5.7).

Initially, we assume that each of the actions to be coordinated is associated with an attentional weight (e.g. based on effector-system based prioritisation), which determines a default response reversal probability for the specific effector combination at stake. By taking new incoming information into account (from the beginning of the experiment until the final response order decision in each trial), this probability can be continuously adjusted (either increased or attenuated) throughout several distinguishable phases. Experiment 1 strongly suggested a default mode of response order control, which is based on effector-system characteristics (i.e. oculomotor prioritisation). Since this default mode yielded very strong effects and was only to some extent modulated by factors such as temporal stimulus distance or compatibility, it seems reasonable to assume that it exerts its influence throughout the course of the experiment and is already set prior to the beginning of each experiment. This reasoning is in line with previous suggestions that response order as part of an overall task set is activated early (e.g. at the beginning of a trial, see De Jong, 1995; Leonhard et al., 2011; Luria & Meiran, 2003). Besides these generic attentional weights associated with actions, other factors can also contribute to adjustments of the reversal probability at a very early stage, for example, the anticipated response selection difficulty (e.g. Leonhard et al., 2011). While oculomotor responses might generally be prioritised over manual responses, the introduction of spatially incompatible S-R mappings (vs. compatible S-R mappings as implemented in the present study) might alter the strength of prioritisation (as shown for dual-response costs, Pieczykolan & Huestegge, 2014) and thus might also affect the reversal probability. Another factor that should be effective in adjusting the reversal probability at the beginning of an experiment are explicit response order instructions, as utilised in Experiment 2.

In a following phase, response order (i.e. reversal probability) can be adjusted immediately prior to the beginning of each trial by factors like the response order in the previous trial or stimulus order predictability (unpredictable in Experiments 1 and 2 vs. predictable in Experiment 3, see also De Jong, 1995). Furthermore, our data suggest that probability adjustments can still occur after the beginning

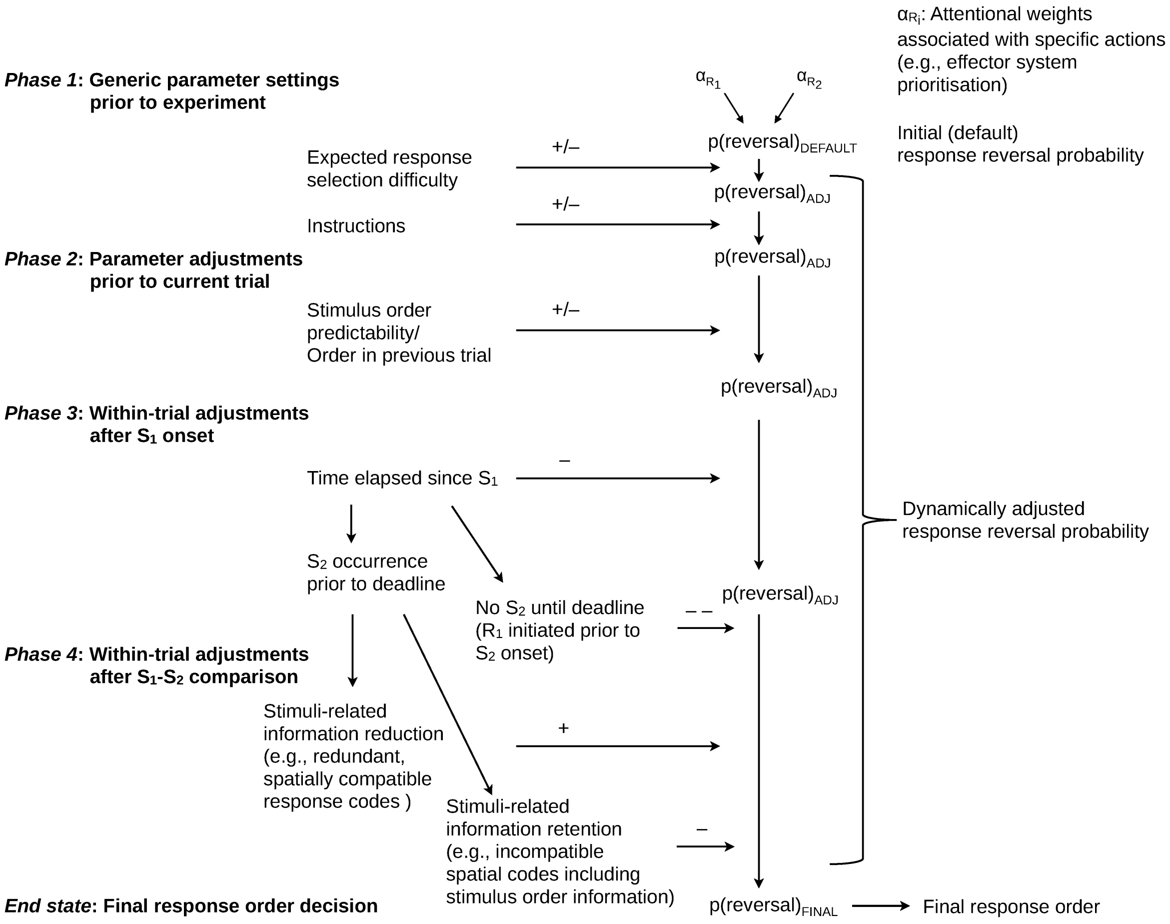


Figure 5.7. Schematic illustration of a multi-phase framework of temporal action scheduling: p(reversal) denotes the probability of a response reversal that is dynamically adjusted during the progress of processing phases. The default p(reversal)$_{\text{DEFAULT}}$ is determined by initial attentional weight parameters α_{R_i} associated with specific actions (or effector systems). After being continuously adjusted (p(reversal)$_{\text{ADJ}}$), a final p(reversal)$_{\text{FINAL}}$ is reached that eventually determines the realised response order.

of a trial. Importantly, a mechanism that accounts for the substantial portion of reversals in the present experiments needs to include an explanation why the response that corresponds to the first stimulus is withheld and what kind of processes occur between the end of stimulus processing and response selection. Also, it needs to explain why stimulus order exerted a stronger effect in incompatible than in compatible trials.

A plausible mechanism that can account for these observations involves the assumption that after the processing of both stimuli, a dedicated stimulus comparison process takes place, in which the two spatial codes (i.e. those coded by the stimuli of the two component tasks) are compared.

The assumption of such a comparison stage is crucial to account for the effects of compatibility on response scheduling decisions. In the case of *compatible spatial codes*, we assume that the outcome of the comparison process yields one common spatial code that can subsequently be utilised to specify both responses. This assumption has two implications: First, while relevant spatial information for both responses is still completely preserved, redundant information is discarded (parsimonious information reduction). Second, we assume that the generation of a common spatial code is accompanied by a loss of information associated with each of the two individual codes, including information about temporal stimulus order. This assumption would explain why participants are more likely to fall back on the default (oculomotor prioritisation) mode for determining the final response order instead of taking stimulus order into account.

Conversely, in the case of *incompatible spatial codes*, the comparison process will eventually retain both (conflicting) codes that are necessary to correctly map the two spatial codes to the two effector systems (i.e. to solve the dual-task binding problem, see Section 5.6.4). Thus, incompatible stimuli should launch a more deliberate processing strategy with a stronger attentional focus on stimulus characteristics, including stimulus order. Given that both spatial codes (based on the two stimuli) are retained, it appears reasonable to assume that specific information associated with the stimuli (especially stimulus order information) will not be discarded. In this way, response order decisions in incompatible trials are eventually more strongly affected by stimulus order (for instance by attenuating the default response order schedule (see Figure 5.7) than when redundant codes are processed on compatible trials, thus rendering the occurrence of reversals (i.e. the oculomotor-first regime) less likely. The assumption of more separate or distinct response processing in incompatible dual-task conditions is in line with previous assumptions that incompatible tasks generally involve more distinct response selection processes when compared to compatible tasks (Fagot & Pashler, 1992).

Note that the explicit instruction to focus on stimulus order (in Experiment 2) was effective in both compatible and incompatible conditions, whereas the compatibility effect was comparable in Experiment 1 and 2. This suggests that instructions no longer interfere once stimulus processing has started. Thus, instructions neither alter the specific probability of entering either of the two processing paths (information reduction vs. retention) referred to above nor do they reduce the information reduction process (i.e. the size of the compatibility effect). Instead, they rather appear to attenuate the overall strength of the default (oculomotor prioritisation) mode at the beginning of the experiment.

Finally, to explain the lower reversal rates for long SOAs, we additionally assume that there is only a limited temporal interval (ending with a final deadline) following the processing of the first stimulus, in which the reversal probability can be continuously adjusted. However, after the deadline any further waiting for the second stimulus for initiating the stimulus comparison process would be too costly. In this case, participants should initiate response selection in Task 1 without any dedicated code comparison process, which is especially likely at long SOAs (that are more likely associated with non-overlapping task processing), because it would be highly dysfunctional to withhold R_1 until the occurrence of S_2 (at long SOAs in Experiment 3). This case can also be regarded as equivalent to a very strong attenuation of the default reversal probability settings.

Taken together, the this framework of multi-phase adjustments of response reversal probability integrates the major findings of the present study as well as previously reported effects. As such, it represents a more realistic approach to response order scheduling than a simple first-come, first-served account, which can be clearly rejected.

5.6.4 Implications for current theoretical frameworks of dual-task control

In this section, we will discuss how response order control is related to current theoretical frameworks of dual tasking. Since the concurrent processing of two actions necessarily requires temporal scheduling, it seems surprising that this issue did not yet receive much attention in current theories on dual-task control. Apparently, the typical procedures associated with the PRP paradigm, namely sequential stimulus presentation, serial processing instructions, and the utilisation of response modalities that are rather similar regarding their overall characteristics yielded only few response reversals. As a result, there was not much to be explained, and the focus of research rather shifted towards processes that occur after a certain response order has been established. Therefore, it is possible that the absence of a dedicated research focus on response order control to date is the result of the prevalence of certain research paradigms (associated with low response order variability), but not the result of a lack of theoretical interest per se. As a consequence, the view that stimulus order should mainly determine response order is reflected in many of the current dual-task frameworks.

As outlined in the Introduction, the standard RSB model does not include any additional control mechanisms regarding task order. Instead, it assumes that the task in which stimulus processing is finished first will be the first to immediately enter the response selection stage. As outlined above, our present results clearly do not correspond with this first-come, first-served principle. Instead, the present results suggest that participants usually waited for both stimuli prior to the occurrence of any response selection. Thus, response selection for Task 1 was deferred until S_2 processing was finished. The idea of strategic deferment in dual-task control has already been proposed by Meyer and Kieras (1997a, 1997b), who assumed that processing strategies play a greater role in dual-task control than previously assumed. However, within their Executive-Process Interactive Control (EPIC) framework strategic deferment rather refers to the assumption that response selection in the second task (i.e. based on S_2) is strategically deferred until response selection in the first task is finished. Thus, their model does not explicitly consider the possibility of processing deferment (e.g. in terms of effector-based task prioritisation mechanisms) as a potential account of response reversals, but instead focuses on strategic processes *after* response order has been already determined.

Another class of theories that principally allow for parallel central processing is built on the assumption of central capacity sharing (e.g. Navon & Miller, 2002; Tombu & Jolicœur, 2003). These theories assume that resources can be allocated in a temporally flexible way to two simultaneous tasks. Interestingly, these accounts do not explicitly discuss the issue of response order control, although response reversals could probably be explained by assuming that resources (specifically those relevant for response selection) are primarily allocated to Task 2 once S_2 has been presented. However, these models (e.g. Navon & Miller, 2002) typically start from the premise that Task 1 is processed with the majority of available resources (and is therefore prioritised), so that Task 2 processing receives fewer resources until Task 1 processing has been finished. For example, Navon and Miller (2002, p.232) explicitly stated that for reasons of ‘simplicity [they] exclude the possibility that selection of R_2 finishes before selection of R_1 because this possibility is remote with the particular tasks typically used in studies with the overlapping tasks paradigm’.

Finally, another successful computational approach to dual-task control is the Executive Control Theory of Visual Attention (ECTVA) by Logan and Gordon (2001), which is characterised by the interplay of control parameters related to bottom-up and top-down processing. Basically, this theory also assumes that processing priorities result from stimulus presentation order. Nevertheless, it principally allows for the occurrence of response reversals as a result of parallel processing. Specifically, ECTVA conceptualises serial stimulus processing by allocating priority to S_1 and S_2 in succession. This serial mechanism is assumed to solve the *dual-task binding problem* associated with ‘knowing which response goes with which stimulus’ (p. 402). However, while our present results regarding incompatible trials (and the associated mechanism of information retention) as well as the strong influence of stimulus order to some extent agree with this assumption, the high reversal rates for compatible trials are rather difficult to explain within this framework. At least in these trials participants are unlikely to have solved this problem by resorting to serial processing as envisioned in ECTVA. Thus, we strongly believe that a dedicated, more complex mechanism (as developed in Section 5.6.3) is necessary to account for such response order phenomena. However, these limitations of the current version of ECTVA (which was not designed to account for response order) do not rule out the possibility that a more extended version can be considered feasible in the future (e.g. one that incorporates features of the framework developed in Section 5.6.3).

Finally, two potential limitations regarding the generalisability of the present data should be discussed. First, one might argue that the amount of oculomotor prioritisation in the present setup might have been amplified by differences in the ease of mapping responses to stimuli between the two tasks. Specifically, it is possible that auditory input is more difficult to be translated into a manual response than into an oculomotor response (e.g. see input output modality compatibility (IOMC) effect, e.g. Hazeltine et al., 2006; Stephan, Koch, Hendler, & Huestegge, 2013). However, recent research has shown that the specific perceptual system plays a much smaller role for IOMC effects than the type of the task-relevant stimulus code (e.g. verbal vs. spatial), suggesting that our spatially defined (auditory) input for the manual response should in fact be easily transferable into a respective response (Göthe, Oberauer, & Kliegl, 2016). Furthermore, both tasks in the present study were largely comparable in that both require a spatial transformation (i.e. of auditory signals on the left or right ear into distinct key press movements or eye movements to lateralised saccade targets), ensuring the involvement of central processes during S-R mapping requirements for both tasks (see Nieuwenstein & Wyble, 2014). Second, one might argue that the present study utilises a quite unique task combination, especially when compared to those studies which provide the database for current dual-task frameworks and which seldom yield notable amounts of response reversals (see Navon & Miller, 2002). Thus, the proposed mechanisms reported in the present study might not be generalisable to other, more conventional settings. However, while dual-task studies combining oculomotor and manual responses are indeed rare, a mandatory precondition to comprehensively study determinants of response order control is to establish a situation involving a reasonable amount of response order variability in the first place (to avoid floor effects). Therefore, the lack of a substantial research focus on response order control, which – in our view – actually represents a very relevant control process in everyday multitasking situations, may be largely the result of the usage of rather conventional task combinations in previous dual-task research, which, however, appear to be insufficient for the present research purpose.

5.6.5 Conclusions

The present study demonstrated that temporal action scheduling in multitasking is not largely determined by the order in which external events call for their corresponding actions. Instead, the temporal organisation of behaviour (in terms of order decisions) greatly depends on a priori characteristics of the particular tasks involved, especially with reference to the associated effector systems. However, these effector-based prioritisations were even rather dysfunctional in that they were associated with lower general performance. While explicit instructions as a measure to adjust performance (Experiment 2) were shown to effectively attenuate effector-based prioritisation, a change of environmental settings (i.e. providing temporally predictive input in terms of stimulus order in Experiment 3) was even more successful in that it also improved multitasking performance accuracy. Regarding the dynamics of response order decisions, the present study expands previous research suggesting that response order is to some extent already determined prior to each individual experimental trial. While our present study is in line with this general assumption, it additionally implies that response order settings can nonetheless be adjusted after a dedicated code comparison process that occurs after stimulus processing in both tasks. Together, this shows how mental processing priorities can be flexibly adjusted by dynamic task sets that adapt sensitively to particular task requirements. In this context, the present study precisely demonstrates the impact of specific task characteristics (including response modalities) on processing dynamics and shows that the human cognitive architecture works in a much more flexible manner than previously assumed.

6 | General Discussion

6.1 Summary: Theoretical contribution of the present studies

In order to advance our understanding of multiple-action processing, the present work aimed at two major aspects across four studies (based on eight experiments) related to underlying mechanisms of cross-modal action control.

1. Since a-modal processing is at the core of the majority of current dual-task theories, the potential role of *response modalities* has been largely neglected in the literature. Although by now, several studies have demonstrated that effector systems matter in cognitive processes, in that the specific choice of response modality affects the amount of dual-task interference (e.g. Hazeltine, Ruthruff, & Remington, 2006; or dual-response interference, e.g. Huestegge & Hazeltine, 2011; Huestegge & Koch, 2013), it is rare to see current theories integrating modality influences. The present studies attempt to fill in such blank areas on the theoretical map of dual-response interference mechanisms with regard to the influence of response modalities.

2. In contrast to concepts that assume a purely structural origin for dual-task interference mechanisms, such as resources or bottleneck models, *crosstalk* has been found to be a widely accepted concept for explaining dual-task interference by taking the semantic interrelation between the tasks into account. In particular, it has been quite useful in explaining why dual-task processing is influenced by the specific combination of sensory and response modality configurations of two tasks (Hazeltine et al., 2006; see also Stephan & Koch, 2010, for a similar application in the context of task switching), and during the selection of conflicting cross-modal responses (Huestegge & Koch, 2009, 2010). However, specifying the mechanisms underlying crosstalk has seldom been attempted, hence crosstalk has continued to remain a rather vague explanatory concept since its introduction into theories of dual-task interference (Navon & Miller, 1987). For example, the

observation of SOA effects on RT_1 (i.e. when two responses are, e.g. spatially, incompatible than when they are compatible) in PRP studies is regarded as an empirical marker for the occurrence of *backward crosstalk*. However, what actually ‘talks’ in backward crosstalk has only recently begun to be studied in more detail (e.g. Janczyk, Pfister, Hommel, & Kunde, 2014, by utilising two manual responses).

Therefore, the present studies were intended to add to this line of research by specifying crosstalk mechanisms in the case of cross-modal action control. It must be noted that the notion of crosstalk logically presupposes the assumption of parallel processing, hence the ideas of crosstalk and parallel processing are closely linked. In the following, I will discuss the present findings by proposing how they can be integrated into existing frameworks of dual-task control grouped by four major aspects, that is *effector-based prioritisation mechanisms* in Section 6.1.1, their *modulation by crosstalk* in Section 6.1.2, *serial and parallel processing* in Section 6.1.3, and the *interrelation of response selection and crosstalk* in Section 6.1.4.

6.1.1 Effector-based prioritisation mechanisms

First of all, the present work yielded insights into phenomena that are based on response characteristics – that is to say, those which occur due to the specific usage of certain response modalities. For example, we found evidence for oculomotor prioritisation over concurrent manual and vocal response demands both in terms of less dual-task interference for oculomotor responses than for context responses (Study C) and in terms of a temporal task order prioritisation (Study D), in that oculomotor responses were executed prior to manual responses although such a behaviour was not instructed nor suggested by task rules. In contrast, this was not the case for manual responses. Interestingly, such an asymmetry in terms of effector prioritisation (see also Huestegge & Koch, 2013) has not been integrated into current dual-task frameworks to date although some of them explicitly include weighting mechanisms (however not in terms of response prioritisation).

For instance, the ‘Executive Control of Theory of Visual Attention’ framework (ECTVA, Logan & Gordon, 2001, a computational model based on a set of parameters) principally contains the idea that the cognitive system allocates resources by prioritising, however, not in terms of allocating resources directly to R_1 or R_2, but to their associated stimuli by assigning a priority parameter π to each stimulus. Response order, hence task prioritisation, in this framework follows from stimulus priorities.

ECTVA is based on the *Theory of Visual Attention* (TVA, Bundesen, 1990) representing the stimulus selection process (based on attentional parameters including a priority parameter π for the relevant stimulus) and the exemplar-based random walk (EBRW, Nosofsky & Palmeri, 1997) representing the response selection process by assuming an evidence accumulation process. Importantly, in ECTVA the dual-task situation is represented by running TVA twice (i.e. once per task), in which normally during Task 1 processing S_1 (associated with the first response) receives a priority of $\pi = 1$ and S_2 (associated with the second response) a priority of $\pi = 0.1$. During the successive Task 2 processing, reversed stimulus priorities are assigned. Importantly, by assigning either stimulus a much higher priority than the other in two successive attentional processes, it is ensured that the correct response is chosen for the respective stimulus. Hence, this procedure represents the solution to the *dual-task binding problem* in form of serial processing. Consequently, this implicates that serial processing is the result of a large prioritisation gradient between stimuli, while more similar π values lead to more parallel processing and a higher probability of a reversed response order (see Logan & Gordon, 2001).

In order to accommodate response prioritisation effects into ECTVA one could assume, for example, that there is an a priori gradient between effector priorities, represented by a parameter ξ that denotes the relative priority of one effector over the other (depending on the specific effector combination). In the case of a sequential stimulus presentation, once the S-R association is instantiated (via arbitrary S-R rules or previously learned associations) the stimulus associated with the prioritised effector is no longer prioritised by π but by $\pi \times \xi$ with ξ ranging from 1 to a maximum (e.g. 20). With the appearance of S_1 a representation of the effector prioritisation gradient is activated, so that, for example, the oculomotor effector systems is prioritised, e.g. by $\xi = 5$, over the manual effector system. As a result, S_2 would receive a total weight of $\pi = 0.5$. Based on ECTVA‘s assumption that processing modes are determined by stimulus priorities, such an additional effector gradient weighting would elevate the chance of parallel processing and thus amplify the probability for a reversed response order.

Interestingly, such an additional weighting adjustment mechanism would also predict that for a reversed response order, processing should occur in parallel rather than serially, because the final stimulus priority values are more similar than in the initial, serial processing version that assumes a relative weight of 10 ($= \frac{\pi_{S_1}}{\pi_{S_2}}$) for S_1 over S_2. Such a prediction is plausible, because for a reversed response order the time frame between S_2 and the associated R_1 (i.e. the reversal) – that is prioritised –

would need to occur in between any processes of Task 1 (i.e. between onset of stimulus classification until response execution), which consequently would increase the opportunity for parallel processing.

In the case of only one stimulus for both tasks – as in the setup of the present Study C – a similar weighting mechanism can be assumed. Due to only one stimulus, initial stimulus priorities are equal for both tasks, and the weighting parameter ξ amplifies the priority for one response as in the previous example. Consequently, dual-response costs for the prioritised response are smaller because the *relative* increase of processing time (compared to single-task RTs) is smaller for the response with the higher priority. However, in order to ensure that the prioritised response is not executed prior to the context response (e.g. as in the case of prioritised vocal responses in the context of manual responses) parallel processing would be a prerequisite.

Alternatively, at first glance one would expect that effector prioritisation should be easily integrable into another (also computational) model of dual-task processing – the Strategic Response Deferment (SRD) model within the *executive-process interactive control* (EPIC) framework (Meyer & Kieras, 1997a, 1997b) – that explicitly takes sensory and response modalities into account. In contrast to ECTVA, SRD consists of a set of ‘if-then’ procedures instead of parameters, thus both rely on relatively different structural concepts. The SRD model is based on the premise that any stages within both tasks can always be processed in parallel, while an executive supervisory system actively chooses to defer the response with the lower priority in order to ensure that the prioritised response receives sufficient processing time. Interestingly, it is argued that strategic deferment especially prevents the cognitive system of accessing the same motor processor at the same time (e.g. in the case of two manual responses) and that task prioritisation is instantiated by instructions.

However, the SRD model runs into difficulties in explaining how prioritisation can occur if not encouraged via explicit instructions, specifically, since in our present study participants were instructed to prioritise S_1 but still responded earlier to S_2. In addition, the deferment of one response in SRD should highly depend on the similarity of the two responses in terms of their motor processors. However, based on human neurophysiology, there is no reason why, for example, oculomotor and vocal responses should be more or less similar than manual and vocal responses (see also Huestegge, Pieczykolan, & Koch, 2014). Here, the fact that manual and oculomotor responses are inherently spatial in contrast to vocal responses would be in line with the prioritisation scheme found in Study C (see also Huestegge & Koch, 2013). However, one should note that in the EPIC framework the oculomotor effector system should be included as an additional response modality in the first place complementing the existing manual and vocal effector system.

Apart from the difficulties associated with integrating response priorities into EPIC, a general problem with this framework relates to the assumption of unlimited resources. From a point of view that leans towards cognitively plausible assumptions, the SRD model's basis of an unlimited capacity that strategically choses to delay certain parts of processing is not very convincing (see also conclusion by Hazeltine et al., 2006, who pointed out the problem of assuming an unlimited capacity). In addition, since parallel processing is regarded as possible and assumed to occur, but at the same time the withholding of one response is assumed, this model actually cannot be tested for the occurrence of parallel processing. Therefore, it rather qualifies as a process description than as a theory from which new hypotheses can be derived. In sum, response prioritisation can be integrated into existing dual-task theories, but an integration into ECTVA appears more convincing then into SRD.

6.1.2 Modulation of prioritisation by crosstalk

Secondly, we found that the prioritisation effects as outlined in the previous section are influenced by between-task compatibility. In Study D, a completely novel multi-phase framework enclosing several different influences on response order scheduling was proposed, which is also able to account for the observation that reversed responses occurred less often (i.e. oculomotor prioritisation was attenuated) when tasks were incompatible to each other. The compatibility effect suggested that when there is between-task conflict to resolve, processing appears to be driven more strongly by bottom-up factors. Specifically, we suggested that at relatively short SOAs a stimulus code comparison process occurs. In the case of compatible responses, this process discards redundant information when both responses are mapped to the same common spatial code (parsimonious information reduction), so order information associated with the two stimulus codes is more likely to get erased. In the case of incompatible responses, this process retains order information because responses need to be mapped to their corresponding spatial codes (in order to solve the dual-task binding problem, see Logan & Gordon, 2001).

Interestingly, such an assumption of mapping response codes to spatial codes might bear strong similarities to the common mapping selection process suggested in Study A, even though a different experimental setting utilising one common stimulus (single-onset paradigm) was employed in the latter. Importantly, this mapping selection assumption also suggests that for compatible responses, a reduction of response codes occurs compared to incompatible responses. However, in the single-onset setting there was no bottom-up factor inducing a response order bias (e.g. equivalent to the SOA in the PRP paradigm), and response order was not instructed, thus making it difficult to draw conclusions regarding response order mechanisms in this paradigm. Therefore, it would be theoretically (and methodologically) rewarding to study if response order instructions and between-task compatibility would have a similar effect on response order in a single-onset paradigm. If that would be the case, the observed response order should more frequently conform with the instructed response order under incompatible response conditions. Additionally, the temporal oculomotor prioritisation should manifest in significantly fewer correct order responses in instructed manual-first conditions than in instructed oculomotor-first conditions. If we assumed such an outcome, then together with the present results, previous backward crosstalk mechanisms and the response-based crosstalk mechanism in form of a conjoint mapping selection (as proposed in Study A, see also Huestegge & Koch, 2010) would turn out to have more in common than previously assumed. However, at this point one can only draw conclusion for the specific case of dimensionally overlapping responses (as implemented in each of the four present studies, in which we utilised stimuli and responses with relevant spatial information). More specifically, the code comparison and generation process as suggested in the present PRP studies (see also Study B) and the conjoint mapping selection might both be a possible specification of the existing idea of parallel response activation stages within the RSB framework (Hommel, 1998a; Watter & Logan, 2006; Schubert, Fischer, & Stelzel, 2008; Thomson, Watter, & Finkelshtein, 2010).

Another instance of crosstalk influence on prioritisation was found in Study C, in which response distance was varied by introducing spatially asymmetric S-R mappings between responses in terms of compatibility in two groups (i.e. the crossed incompatibility paradigm employing one common stimulus). Interestingly, between-task compatibility shifted priorities towards the a priori ‘difficult’ response, which already had to resolve an S-R conflict proper, at the cost of the ‘easy’ compatible response. This suggests that there might be a strategic component (similar to a supervisory executive processor Meyer & Kieras, 1997a), which during parallel processing prevents the more difficult task of becoming even more impaired (because it already requires relatively many processing resources in the first place). However, any framework that might integrate the assessment of S-R rules or task difficulty before or during the course of a dual-task performance would have to take task content into account. Therefore, frameworks based on pure scheduling decisions (such as the SRD or RSB) are limited in providing connecting points for the integration of crosstalk phenomena.

6.1.3 Parallel and serial processing in cross-modal action

Although the concept of content-based interference (i.e. crosstalk) and the concept of a structural limitation conceptually differ, previous research suggested a potential interplay. More specifically, it has been proposed that serial processing may represent an elegant strategy to prevent adverse effects of crosstalk that emerge during parallel processing (e.g. Logan & Gordon, 2001; Meyer & Kieras, 1997b; Navon & Miller, 2002; Tombu & Jolicœur, 2002). For example, Lehle and Hübner (2009) presented evidence that participants can be instructed with respect to the extent of processing two tasks in parallel. However, parallel processing came at a substantial cost in performance, so that serial processing (in accordance with an RSB) appeared to be effective in preventing strong performance decrements based on crosstalk (see also Paucke, Oppermann, Koch, & Jescheniak, 2015, for a similar observation during lexical processing; see Plessow, Schade, Kirschbaum, & Fischer, 2012; Fischer & Hommel, 2012, for the related concept of task shielding).

In Study B, we indeed found evidence for both serial and parallel processing modes during cross-modal action in a PRP paradigm utilising oculomotor and manual responses. This is a novel finding although a PRP study 23 years ago already investigated dual-task interference for oculomotor responses (in form of saccades) as Task 2. However, at that time they concluded that oculomotor responses are special in that they do not occupy the central bottleneck or only very briefly (Pashler, Carrier, & Hoffman, 1993). Notably, their results were only discussed on the backdrop of a purely serial RSB. While their conclusions have certainly been drawn on reasonable grounds, the present study extended the theoretical background for adding the possibility that crosstalk during a parallel central processing stage might occur. Interestingly, we found that depending on between-task compatibility participants either processed both task in a rather parallel mode (for compatible responses) or in a more serial mode (for incompatible) responses. However, even in incompatible conditions we still found evidence for backward crosstalk for Task 1, suggesting that at least a certain amount of parallel processing occurred in each condition. Hence, the present data from Study B nicely fit the idea that both types of processing might exist and that they are strategically adaptable to the demands of the particular task.

However, it must also be noted that we cannot definitively determine if the amount of serial processing we observed in Study B actually stemmed from a generic RSB and not from the result of strategically allocating all resources first to Task 1 and then to Task 2, although parallel processing might principally have been possible. The claim that serial processing (in the PRP paradigm) might represent a strategy rather than a structural limitation has been proposed, for example, by Israel and Cohen (2011), who demonstrated that participants, who were trained to perform a dual task without significant costs in conditions with an $\text{SOA} = 0\,\text{ms}$, showed signs of serial processing (i.e. a PRP effect in Task 2) when this condition was embedded in conditions with an $\text{SOA} \neq 0\,\text{ms}$ (see also Hazeltine, Teague, & Ivry, 2002; Schumacher et al., 2001; Strobach, Liepelt, Pashler, Frensch, & Schubert, 2013). Hence, it was argued that performing dual tasks without costs is only possible under certain conditions, for example when the bottleneck stages of the utilised tasks are too short to be tapped by the experimental manipulations (i.e. a *latent* bottleneck was still present, e.g. Ruthruff, Johnston, Van Selst, Whitsell, & Remington, 2003a) or when stimulus and response are ideo-motor compatible (e.g. Halvorson, Ebner, & Hazeltine, 2013; Lien, McCann, Ruthruff, & Proctor, 2005, for instance when uttering a word after hearing it spoken).

From a parsimonious point of view, one could argue that if parallel processing is possible in principle, then why should there be a specific processing step that requires the necessity of serial processing, especially when it was shown that under certain circumstances dual-task costs can be abolished? Perhaps, the question of strategic vs. generic serial processing can never be resolved empirically because the introduction of the additional assumption that bottleneck stages for a task can vary in length (e.g. depending on training) decreases the probability of empirical falsification. Therefore, this issue might be of a rather analytical nature and will still remain a subject to theoretical debate.

6.1.4 The interplay of crosstalk and response selection

Finally, the present data from Study A can also be interpreted as strong evidence for the occurrence of parallel processing during oculomotor and manual responses since we found dual-task costs for both responses (at least for incompatible responses) when utilising a single-onset paradigm. In particular, this study specified the predictions of the previously suggested framework by Huestegge and Koch (2010). In this framework, a conjoint mapping selection of spatial to modality response code bindings is assumed. In addition, other potential mappings from previous or future demands impinge on that of the current demand. By manipulating the presence and absence of response selection and between-response compatibility in Study A, the data allowed us to differentiate between *online crosstalk* (i.e. conflict between incompatible response codes in the current trial) and *memory-based crosstalk* (i.e. activation of alternative mapping selections in previous or future trials). We found that memory-based crosstalk is only effective in the presence of online crosstalk, meaning that only when there is a conflict to solve between response codes in the current trial, it matters that there is a choice (i.e. more than one response possibility). When spatial response codes are not conflicting, then the presence of response alternatives is not amplifying dual-response interference.

According to the classic conceptualisations of crosstalk and response selection outlined in the General Introduction, both are independent concepts in that the former refers to content-based interference whereas the latter rather refers to a structural limitation irrespective of any processing content. In line with this understanding, one might argue that the response selection manipulation (presence or absence) in Study A mainly influenced content-*independent* mechanisms of response control. Specifically, that dual-response cost differed between the two response selection conditions could be explained by the presence or absence of a time-consuming (a-modal) response (compound) selection process irrespective of the particular processing content. However, if this interpretation were correct we should have observed a substantial difference in dual-response costs between the compatibility conditions, which was not the case. Therefore, the assumption of an abstract, time-consuming selection process alone does not provide a satisfying explanation of the whole result pattern.

Instead – within the present model – response selection can principally also be conceptualised in terms of competition between potentially relevant code binding patterns (i.e. mapping selections) and thus as a variant of content-based interference. Consequently, online crosstalk would represent the activation of conflicting spatial response codes during one mapping selection in a given trial (instead of two separate response selection processes). Response selection essentially could be regarded as the resolution of conflict between the currently relevant task demands, i.e. the mapping selection in the current trial, and alternative currently irrelevant task demands, i.e. mapping selections from previous or future trials. We refer to the resolution of between-trial conflicts as memory-based crosstalk.

Taken together, the present work along with the considerations regarding the underlying mechanisms of crosstalk and response selection suggest that both concepts may have more in common than previously assumed. Specifically, it is conceivable that response selection may be re-conceptualised in terms of content-based interference (a characterisation yet reserved to define crosstalk). In conclusion, it appears that crosstalk is a very potent overarching theoretical concept of content-based interference in cognition and may serve as a complement to a-modal, structural accounts to explain dual-response control (e.g. to the RSB framework). Therefore, the next section contains a proposal of a four-dimensional taxonomy that integrates present findings as well as previous findings from the literature.

6.2 Towards a taxonomy of crosstalk

In the following, I will outline a substantially enriched taxonomy of crosstalk which is based on the initial groundwork introduced by Navon and Miller (1987). Crosstalk in terms of outcome conflict in dual tasks has been systematically investigated by these authors, who essentially proposed a three-stage model of crosstalk (see General Introduction). Note that the term ‘outcome’ here can refer to the output of each of the typical three stages of information processing. Specifically, they differentiated between crosstalk at the perceptual level (i.e. between stimuli or aspects of stimuli), at the level of stimulus-response translation, and at the response level. Navon and Miller (1987) provided experimental data supporting the existence of conflict on each of these levels (see General Introduction). Surprisingly, further empirical research on crosstalk seldom explicitly referred to this conceptualisation but nevertheless can be classified within this three-stage model. While some studies focused on boundary conditions of perceptual crosstalk (Hommel, 1998a; Logan & Schulkind, 2000), or on variants of crosstalk on the level of S-R mappings (e.g. Logan & Gordon, 2001; Stephan & Koch, 2010), most studies examined response-based crosstalk that may either occur on the level of S-R mapping (response activation/selection) or at the final level of response processing (e.g. Hommel, 1998a; Hommel & Eglau, 2002; Huestegge & Koch, 2009, 2010; Janczyk, 2016; Koch & Prinz, 2002; Lehle & Hübner, 2009; Lien & Proctor, 2000; Logan & Gordon, 2001; Logan & Schulkind, 2000; Miller, 2006; Navon & Miller, 1987). Importantly, these studies and theories did not address the critical issue of contextual effects. Instead, they often focused on spatial compatibility issues, and were mainly concerned with adverse effects of crosstalk on performance (as opposed to potential benefits). These limitations call for a new taxonomy of crosstalk.

A four-dimensional taxonomy of crosstalk

While the original three-stage model of crosstalk by Navon and Miller (1987) characterised crosstalk along one dimension, namely processing stage, I will introduce a four-dimensional conceptualisation of crosstalk. In addition to the processing stage dimension, this taxonomy adds a time dimension (see Figure 6.1) capturing the memory-based crosstalk effects reported in Study A, a level dimension, which contrasts different types of content-based relatedness, and finally a valence dimension (see Figure 6.2), which addresses the idea that crosstalk may not only result in adverse effects on performance, but may also produce beneficial (priming) effects under certain conditions (e.g. repetition benefits, see Bertelson, 1965). This four-dimensional framework results in a variety of types of crosstalk, each having a specific empirical signature and also an underlying cognitive mechanism that can be specified. In the following, I will explain these individual dimensions briefly and relate them to corresponding empirical findings.

The processing stage dimension specifies the level of information processing at which conflict between cognitive representations occurs (e.g. see Navon & Miller, 1987, for a thorough introduction and empirical examples). Firstly, content-based conflict may occur on the stimulus stage between cognitive representations of two stimuli (see introduction for an empirical example), or between two different aspects of the same stimulus (e.g. in Stroop-like stimuli, see MacLeod, 1991). Secondly, crosstalk may occur at the S-R mapping stage. For example, in a previous study (Huestegge & Koch, 2009) participants responded to single lateralised tones with S-R incompatible saccades and S-R incompatible manual responses. While the overall dual-response costs were lower than in conditions with an incompatible S-R mapping for only one response modality, they were still much greater compared to conditions in which both responses were S-R compatible. This result is probably due to crosstalk between the residual activation of (highly trained) S-R compatible responses and the currently task-appropriate S-R incompatible response demands (see Navon & Miller, 1987; Logan & Gordon, 2001, for other empirical examples of crosstalk on the level of S-R mapping). Another well-known crosstalk phenomenon on the level of S-R mapping processes in dual-task control is the input-output modality compatibility (IOMC) effect. The IOMC effect refers to the phenomenon that in a dual-task context, it is easier to simultaneously perform a task with visual input and manual output (VM task) and a task with auditory input and vocal output (AV task) than to perform two tasks with reversed modality mappings (i.e. combining a VV task and an AM task). This effect appears to be an example of online crosstalk at the S-R mapping stage with particular regard to S-

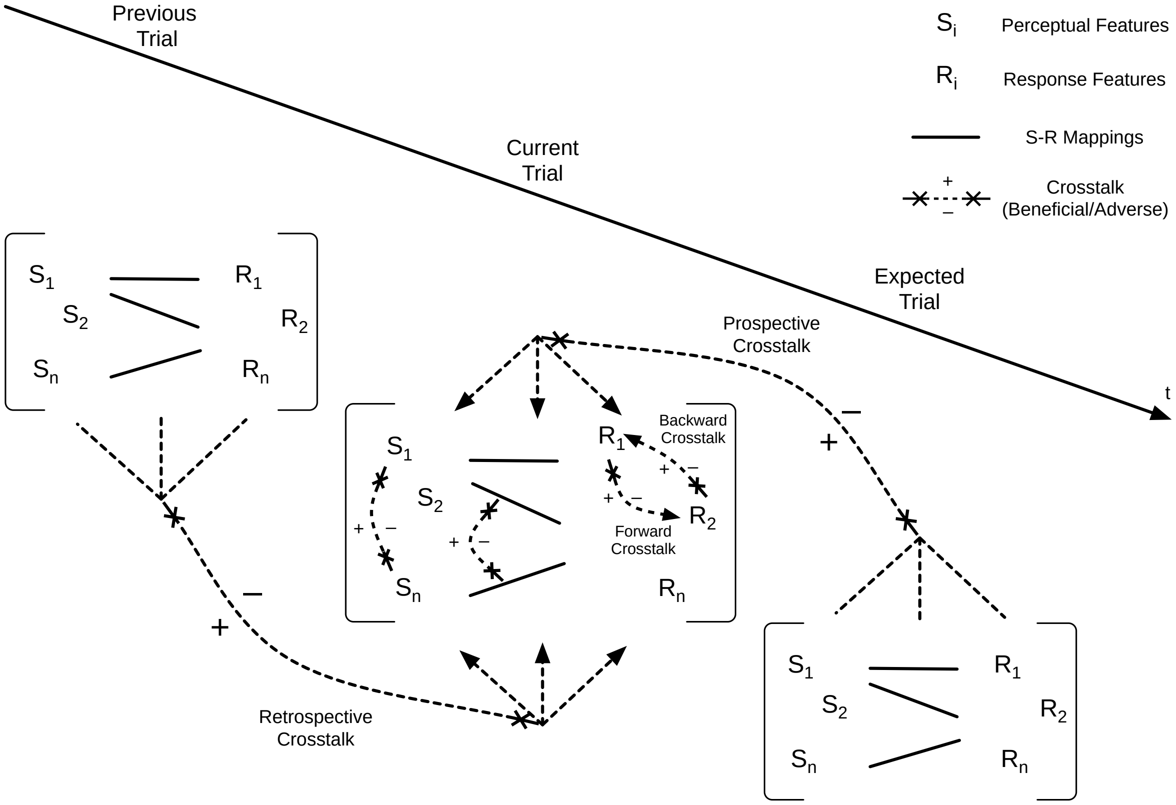


Figure 6.1. Taxonomy of crosstalk as a comprehensive concept of content-based interference in cognition. This framework comprises crosstalk based on conflict resolution within features of processing stage dimensions in each trial, i.e. between stimulus features, between S-R feature mappings, and between response feature. It also adds a temporal dimension within a trial (forward/backward crosstalk) and covers phenomena of memory-based crosstalk (prospective/retrospective crosstalk) across previous, current, and expected trials. Note that S_i and R_i can related to features within as well as across stimuli and responses.

R modality combinations (e.g. Hazeltine et al., 2006; Stephan & Koch, 2010). Finally, probably the most frequently studied type of crosstalk is response-related crosstalk, which occurs when two responses involve incompatible content, and is assumed to originate either at the level of response selection (or response activation) during S-R translation (e.g. Hommel, 1998a) or at the response stage (e.g. Miller & Alderton, 2006).

It should be noted that studies involving an ideo-motor approach to cognition (e.g. Greenwald, 1970; Hommel, Müsseler, Aschersleben, & Prinz, 2001; James, 1890) extended the processing stage framework by adding a final stage referring to the perception of response effects. By manipulating the compatibility between stimuli and learned behavioural effects (hence, by inducing crosstalk between

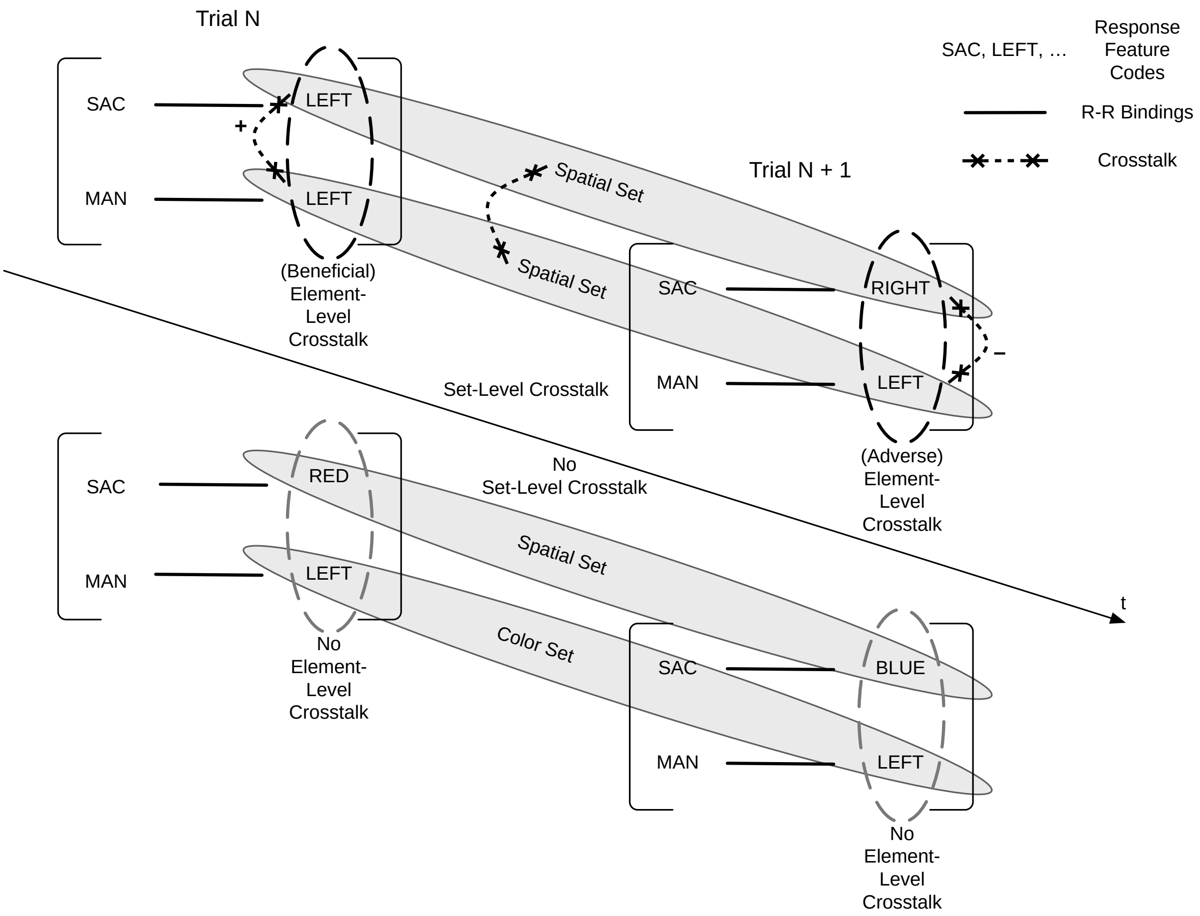


Figure 6.2. Dimensional overlap during response code binding: The valence dimension represents the possibility of both beneficial and adverse effects of crosstalk by element-level crosstalk among response codes (see the ‘R’s in Figure 6.1) during set-level (i.e. dimensional) overlap. In the upper panel, set-level crosstalk (beneficial or adverse) can occur because both tasks involve a spatial set of response codes. The lower panel depicts two tasks that do not share an overlapping set of response codes (colour set vs. spatial set), eliminating the potential for occurrence of element-level crosstalk.

stimuli and anticipated action effects), they demonstrated that the anticipation of action effects plays a crucial role in behavioural control. Thus, the present model might certainly be extended by adding the perception (and/or anticipation) of response effects as an additional processing stage, which might be relevant for the occurrence of crosstalk (see, e.g. Janczyk et al., 2014).

The second dimension of the taxonomy is the temporal dimension. It consists of three components related to the present (i.e. conflict during current task demands yielding *online crosstalk*), to the future (i.e. to expectations/anticipations regarding upcoming response demands yielding *prospective crosstalk*), and to the past (i.e. to content based on previously encountered information yielding *retrospective crosstalk*). Online crosstalk based on present task demands can, for example, relate to conflict that occurs within a single experimental trial, and can be further dissociated into forward and backward online crosstalk. Within a certain stage of information processing (e.g. on the response level), either the characteristics of the first executed response can affect performance of the second response (forward crosstalk), or vice versa (backward crosstalk, e.g. Ellenbogen & Meiran, 2010; Hommel, 1998a; Hommel & Eglau, 2002; Koch & Prinz, 2005; Logan & Delheimer, 2001; Logan & Schulkind, 2000; Miller, 2006; Miller & Alderton, 2006).

The mechanisms underlying memory-based (prospective and retrospective) crosstalk may essentially be similar to those underlying switch costs in the task switching literature. In typical task switching experiments, different tasks are defined by different S-R mapping rules, while the identity of stimuli and responses is often the same across tasks (see Kiesel et al., 2010; Monsell, 2003, for comprehensive reviews). Consequently, performance costs associated with a task switch can be explained by assuming conflict between currently relevant S-R bindings and previously activated S-R bindings. In this sense, memory-based crosstalk on the S-R mapping stage would also underlie switch costs (and mixing costs) observed in typical task switching studies.

Note that each type of crosstalk on the temporal dimension is accompanied by a typical empirical marker and a corresponding potential cognitive mechanism. Within-trial incompatibility costs are an empirical marker of online crosstalk (as observed in Study A and Study B), and the corresponding cognitive mechanism may lie in the activation of two conflicting (response) codes that need to be bound to other codes or features to fully specify a response. An empirical marker for retrospective crosstalk are costs associated with switching between several dual-response demands, and the corresponding mechanism could be based on competition or priming between residual and online binding pattern activation (see Experiment 2 in Study A). Finally, an empirical marker for prospective crosstalk are costs associated with mixing dual-response demands. Prospective crosstalk might be based on conflict between the activation of currently needed code bindings and the activation of alternative binding patterns in order to improve overall response readiness for potentially upcoming task demands (see Experiment 1 in Study A).

The third dimension (albeit not explicitly investigated in the present work) within this taxonomy of crosstalk refers to the semantic level of crosstalk. Kornblum, Hasbroucq, and Osman (1990) differentiated between two levels of compatibility, namely set-level compatibility, which refers to the degree of dimensional overlap between task set features (e.g. colour and orientation are independent task dimension features), and element-level compatibility, which is based on feature-based conflict within a specific dimension (e.g. left/right within the spatial dimension, see Figure 6.2, lower panel). This represents the type of interference that was considered in most of the previous empirical crosstalk studies described above. I will refer to this phenomenon as element-level crosstalk. However, crosstalk may also arise based just on the dimensional overlap alone, and thus even in the absence of element-level conflict (dimensional or set-level crosstalk). For example, evidence for such set-level crosstalk was revealed by comparing dual-task performance of conditions with weak dimensional overlap to conditions with strong dimensional overlap (including the variation of element-level compatibility by utilising compatible and incompatible responses, e.g. Koch, 2009; Koch & Rumiati, 2006; see also General Introduction). The results showed that performance in compatible trials in strong dimensional overlap conditions was still worse than performance in weak dimensional overlap conditions, suggesting the relevance of such set-level crosstalk. By integrating the notion of dimensional (set-level) overlap into crosstalk theory, multiple-resource frameworks of dual-task control would then be rendered a special case of set-level crosstalk, since they also predict that shared dimensions across tasks (e.g. when two tasks involve auditory processing) may impair performance (e.g. Hirst, Neisser, & Spelke, 1978; Navon & Gopher, 1979; Spelke, Hirst, & Neisser, 1976; Wickens, 2002, 2008).

Finally, the fourth crosstalk dimension refers to crosstalk valence. Essentially, all existing studies on crosstalk focused on performance decrements (i.e. adverse crosstalk). However, in their seminal work Navon and Gopher (1979) theoretically discussed the possibility of (beneficial) priming effects in dual-task control (beneficial crosstalk). While mechanisms like response priming have a long tradition in the related field of task switching (e.g. Altmann, 2005), there has been no clear attempt to explicitly study beneficial crosstalk effects in the dual-task literature. In a recent study (Huestegge et al., 2014), we found evidence for beneficial effects of crosstalk on performance in a dual-response paradigm involving the simultaneous execution of saccades and vocal responses (see also the Section 1.2.4 on crosstalk in cross-modal action in the General Introduction). Crucially, conditions without spatial overlap led to increased dual-response costs compared to conditions with set-level and element-level overlap, indicating that participants can benefit from shared response codes across responses via response-code priming mechanisms. Thus, these data together with the large amount of literature on priming effects in general represent instances of beneficial crosstalk.

Taken together, the proposed taxonomy of crosstalk may serve as a comprehensive theoretical framework of content-based interference in cognition. It is supported by empirical evidence that dissociates several components of interference in dual-task control, and specifically focuses on contextual, memory-based crosstalk phenomena that were largely ignored in previous empirical studies and theories on multiple-response control. It is hoped that the present framework will foster new research in order to shed further light on the underlying mechanisms of the many varieties of crosstalk.

6.3 Outlook: Open issues and an agenda for future research

During analyses and interpretations of the results of the present studies, several open issues emerged. In the next sections, I will therefore address issues related to the *specifications of crosstalk mechanisms* in Section 6.3.1, *flexibility of processing* in Section 6.3.2, *generalisability* in Section 6.3.3, and *response order* in Section 6.3.4 by presenting potential research questions for the future including possible approaches to those issues.

6.3.1 Specifications of crosstalk dimensions and mechanisms

Although the results in Study A provide indisputable evidence that contextual effects (i.e. memory-based crosstalk) are only effective when there is a (e.g. spatial) conflict within current binding demands (i.e. online crosstalk), there is still a possible confound that needs to be eradicated. Specifically, in conditions with two potentially relevant mapping selections, a currently relevant compatible R-R mapping selection was always preceded or followed by an R-R compatible mapping selection, and the equivalent holds for trials involving R-R incompatible bindings, respectively. Therefore, we cannot definitively tell if memory-based crosstalk is occurring due to conflicting response codes in the current or in alternative trials. It might be possible, for example, that a current R-R incompatible mapping is less (or not at all) affected by the presence of R-R compatible mapping selections than a R-R compatible mapping in the presence of R-R incompatible mappings. Therefore, in a subsequent study it would be informative to examine if there is an influence of the specific compatibility relation of current and alternative mappings by comparing dual-response costs in blocks including both compatible and incompatible mappings. An overall difference in dual-response costs would suggest that the number of alternatives does indeed matter for the occurrence of memory-based crosstalk, and an asymmetry between transitions from compatible to incompatible and vice versa (by comparing local switch and repetition demands) would provide details about the underlying causes.

Furthermore, regarding the specification of crosstalk mechanisms, an open question relates to the role of dimensional overlap in crosstalk. While between-task crosstalk in dual tasks has been typically (and also in the present work) studied either by manipulating compatibility between responses (e.g. by combining a ‘left’ response in Task 1 and a ‘right’ response in the concurrent Task 2), Miller (2006) suggested that backward crosstalk can also occur based on Task 2 difficulty alone. By manipulating the number of response alternatives in Task 2, he demonstrated effects in Task 1 without any between-task relatedness within one semantic dimension. His findings suggest that not only the R-R relation between tasks but also the S-R relation within Task 2 represents an important source of backward crosstalk. Hence, a study explicitly manipulating both potential sources of influence based on the taxonomy of dimension overlap by Kornblum et al. (1990) would provide insight into the relative scales of S-R mapping (of Task 2) influences and R-R influences yielding backward crosstalk. In particular, these potential sources could be dissociated within one experiment by implementing four different conditions with a) R-R overlap without S_2-R_2 overlap, b) R-R overlap with S_2-R_2 overlap, c) S_2-R_2 overlap without R-R overlap, and d) neither S_2-R_2 nor R-R overlap. Based on the results, it could also be discussed whether both instances of interference should be summarised under the common term ‘crosstalk’ in the first place.

Finally, based on the four-dimensional taxonomy of crosstalk, several blank spots are evident. For example, there is still a lack of research on how exactly information processing stages that are represented in working memory interact with currently task-relevant representations along the timeline of information processing. Additionally, the role of strategic pre-activation of binding patterns in prospective crosstalk may be further studied by using cues to manipulate the certainty with which specific response demands may be relevant in an upcoming trial. Furthermore, there appears to be a lack of research on crosstalk benefits in dual-task research. While in the field of task switching – as another instance of multitasking (see General Introduction) – researchers studied priming effects in terms of influences of specific stimulus features, S-R mappings, and response features and their interplay (e.g. Bertelson, 1965; Campbell & Proctor, 1993; Hübner & Druey, 2006; Kleinsorge, 1999; Koch, Schuch, Vu, & Proctor, 2011; Lien & Ruthruff, 2004; Pashler & Baylis, 1991; Remington, 1969), this issue is relatively underrepresented in dual-task research (e.g. Schuch & Koch, 2004). Notably – from a parsimonious point of view – it could be discussed if priming effects in sequential tasks might represent the case of beneficial crosstalk, so that eventually these mechanisms could also be subsumed under the general term ‘crosstalk’. These examples show that the proposed taxonomy may provide fruitful suggestions for future research.

6.3.2 Flexibility of processing modes

The results from Study B, which examined dual-task interference between oculomotor responses and manual responses in the PRP paradigm, suggested that participants adopted processing modes based on the crosstalk potential inflicted by between-task compatibility in each trial. Specifically, it appeared that participants always started each trial with a moderate amount of parallel processing and then – depending on the result of the stimulus code comparison – continued either in parallel mode or switched to more serial processing. However, since in the present study only averaged RTs of compatibility conditions were compared, a detailed analysis of trial-by-trial effects would be necessary in order to determine the temporal dynamics of switching between processing modes. Specifically, by manipulating transition probabilities between compatible and incompatible trials one could investigate if participants were indeed in a default state at the beginning of each trial – prepared for rather parallel processing. This would also reveal if (or to which extent) this initial state depends on the previous trial and/or the fact that there are several task demands that require different kinds of (efficient) processing modes (c.f. rationale of switch and mixing costs in Study A).

In addition, one could test the hypothesis raised in Section 6.1 if reversing responses indeed leads to rather parallel processing as predicted by ECTVA. For example, one could manipulate between-task compatibility and instruct participants to respond with a specific response order (reversed vs. non reversed) while stimulus order would be held constant. If reversing responses is more likely to cause parallel processing, then backward crosstalk effects on Task 1 should be larger in reversed responses trials compared to non-reversed responses trials.

6.3.3 Generalisability

While in Study A an extension to Huestegge & Koch’s framework (2010) of response-based crosstalk was presented, it should be further studied if this crosstalk mechanism also generalises to other effector modalities and, importantly, if cross-modal action crosstalk underlies similar mechanisms as intra-modal action crosstalk. One should, for instance, examine if the representation of a dual task utilising two manual responses (e.g. operationalised by two hands, each for one task, with the assignment of one of two fingers for each response alternative) as employed in the majority of dual-task research is similar to the representation of a cross-modal dual task. This should be particularly interesting since major dual-task frameworks (especially, the multiple resources model by Wickens, 2002, 2008; see also executive processor characteristics within the EPIC framework by Meyer & Kieras, 1997a) assume that performing two tasks that share characteristics at one of the three main processing stages regarding sensory modality, S-R mapping dimension (e.g. spatial, verbal), or response modality, results in larger dual-task interference than when the tasks do not share dimensions. In this framework, it is assumed that the combination of, for instance, one task with visual input requiring a decision based on a spatial properties performed manually and another task with auditory input requiring a decision based on verbal properties performed vocally should lead to fewer dual-task costs for both responses than two task that, for example, are both triggered by visual stimuli, or are both performed manually. Especially, the latter aspect has not received much attention, yet.

Since the multiple resource framework (as any other framework) does not regard the oculomotor system as an effector system, one could test if the benefit of cross-modal processing does also hold for oculomotor responses and a context response modality. Therefore, one could utilise the single-onset paradigm (as in Study A) and contrast a dual response consisting of two manual responses (intra-modal condition) with a dual response consisting of a saccade and a manual response (cross-modal condition) under identical input conditions (i.e. one common stimulus). According to the multiple resources model, dual response costs should be larger for the intra-modal condition than for the cross-modal condition. By additionally manipulating between-response compatibility, one could further investigate if two hands are rather represented as two different response modalities that need to be bound to (e.g. spatial) response codes or rather as one integral response modality (system). In the latter case, dual-response costs for intra-modal responses should be different than for cross-modal responses depending on between-response compatibility because of a different number of overall response codes that need to be bound to spatial codes (i.e. one manual code opposed to two separate, e.g. left and right, manual codes).

6.3.4 Mechanisms of prioritisation and response order

Study D on response order control demonstrated that despite instructions or a predictable task order, participants still reversed responses at short SOAs when they should have performed the manual response first. Since our post hoc analyses showed that this was not due to a functional strategy to optimise overall reaction time, the question of the underlying cause of such a behaviour remains. It does not seem plausible that participants would willingly choose not to comply with task instructions, especially since this should be associated with additional mental effort. Therefore, it should be empirically addressed if participants were indeed aware of their reversed responses. Evidence for diverging introspective and objective RTs comes from PRP studies that showed that participants have difficulties to correctly report their own RTs and are not aware of the PRP effect, i.e. the slowing of RT_2 at short SOAs, so that they underestimated their own RTs (e.g. Bratzke, Bryce, & Seifried-Dübon, 2014; Bryce & Bratzke, 2014; Corallo, Sackur, Dehaene, & Sigman, 2008; Marti, Sackur, Sigman, & Dehaene, 2010). Hence, it is possible that in trials in which responses were reversed, participants may not have noticed a reversal because they underestimated the RT of the second (manual) RT. Since we did not provide feedback on the correctness of response order, participants might have constantly misjudged the correct temporal distances. Therefore, a future study could explore if providing feedback on the correctness of response order would help participants to adapt and to further attenuate the probability of reversals. If that would be the case, then the oculomotor-first bias might be less generic than assumed, but would rather be based on problems associated with the temporal perception of cross-modal actions.

Since Study D represents a first attempt to model the influence of several factors on response order decisions, there is still room for improvement and specifications. Particularly, since the present study utilised a cross-modal response setting, it would be interesting to study if the effects of temporal response prioritisation are generalisable to task combinations that exhibit an a priori prioritisation gradient based on other task characteristics (i.e. other than the identity of the effector system). For example, one could combine a task with an relatively ‘automatic’ S-R translation (e.g. an ideo-motor compatible task) with a task involving arbitrary S-R rules.

And finally, another question (that is related albeit not immediately resulting from the present work) is how the timing of cross-modal actions are actually perceived. It is known that during a saccade a temporal and spatial compression is perceived (Morrone, Ross, & Burr, 2005; Yarrow, Haggard, Heal, Brown, & Rothwell, 2001) in that participants predate the temporal landing point of a saccade to the point in time before the saccade actually starts. This effect could have strong implications for response order control. Specifically, it would be interesting to study which point in time (i.e. start or end of a saccade) is perceived as temporally coinciding with a manual key press –

such as one that is utilised as response in the majority of cognitive research questions. Since a manual response and a saccade differ in the amount of control that can be exerted during the movement – a manual response can be monitored to some extent while a saccade is a ballistic movement that cannot be stopped once programmed – it could be tested to which extend such generic differences affect cross-modal action control.

Taken together, the present work intended to contribute a cross-modal action perspective on the research of multiple-action control. It is to wish that based on the results of the present work (and perhaps by including suggestions from this final section), future research on multiple-action control will further continue to include a broad variety of cross-modal action demands.

References

Adam, J. J., Hommel, B., & Umiltà, C. (2003). Preparing for perception and action (I): The role of grouping in the response-cuing paradigm. *Cognitive Psychology*, *46*, 302–358. doi:10.1016/s0010-0285(02)00516-9

Alexander, G. E., & Crutcher, M. D. (1990). Functional architecture of basal ganglia circuits: Neural substrates of parallel processing. *Trends in Neurosciences*, *13*, 266–271. doi:10.1016/0166-2236(90)90107-l

Allport, A. (1987). Selection for action: Some behavioral and neurophysiological considerations of attention and action. In H. H. A. F. Sanders (Ed.), *Perspectives on Perception and Action* (pp. 395–419). Hillsdale, NJ, US: Lawrence Erlbaum Associates.

Allport, A., Styles, E. A., & Hsieh, S. (1994). Shifting intentional set: Exploring the dynamic control of tasks. In C. Umilta, & M. Moscovitch (Eds.), *Conscious and nonconscious information processing* (15, pp. 421–452). Attention and Performance. Cambridge, MA, US: The MIT Press.

Altmann, E. M. (2005). Repetition priming in task switching: Do the benefits dissipate? *Psychonomic Bulletin & Review*, *12*, 535–540. doi:10.1037/a0020557

Anderson, J. R., Taatgen, N. A., & Byrne, M. D. (2005, August). Learning to achieve perfect timesharing: Architectural implications of Hazeltine, Teague, and Ivry (2002). *Journal of Experimental Psychology: Human Perception and Performance*, *31*, 749–61. doi:10.1037/0096-1523.31.4.749

Baumeister, R. F., Vohs, K. D., & Funder, D. C. (2007). Psychology as the science of self-reports and finger movements: Whatever happened to actual behavior? *Perspectives on Psychological Science*, *2*, 396–403. doi:10.1111/j.1745-6916.2007.00051.x

Bayliss, W. M. (1916). ‘‘Neurone” or “Neuron”. *British Medical Journal*, *1*, 888–888. doi:10.1136/bmj.1.2895.888

Bekkering, H., Adam, J. J., Kingma, H., Huson, A., & Whiting, H. T. (1994). Reaction time latencies of eye and hand movements in single- and dual-task conditions. *Experimental Brain Research*, *97*, 471–476. doi:10.1007/bf00241541

Belliveau, J., Kennedy, D., McKinstry, R., Buchbinder, B., Weisskoff, R., Cohen, M., … Rosen, B. (1991). Functional mapping of the human visual cortex by magnetic resonance imaging. *Science*, *254*, 716–719. doi:10.1126/science.1948051

Berlyne, D. E. (1957). Uncertainty and conflict: A point of contact between information-theory and behavior-theory concepts. *Psychological Review*, *64*, 329–339. doi:10.1037/h0041135

Bertelson, P. (1965). Serial choice reaction-time as a function of response versus signal-and-response repetition. *Nature*, *206*, 217–218. doi:10.1038/206217a0

Botvinick, M., Nystrom, L. E., Fissell, K., Carter, C. S., & Cohen, J. D. (1999). Conflict monitoring versus selection-for-action in anterior cingulate cortex. *Nature*, *402*, 179–181. doi:10.1038/46035

Bratzke, D., Bryce, D., & Seifried-Dübon, T. (2014). Distorted subjective reports of stimulus onsets under dual-task conditions: Delayed conscious perception or estimation bias? *Consciousness and Cognition*, *30*, 36–47. doi:10.1016/j.concog.2014.07.016

Bratzke, D., Rolke, B., & Ulrich, R. (2009). The source of execution-related dual-task interference: Motor bottleneck or response monitoring? *Journal of Experimental Psychology: Human Perception and Performance*, *35*, 1413–1426. doi:10.1037/a0015874

Bratzke, D., Ulrich, R., Rolke, B., Schröter, H., Jentzsch, I., & Leuthold, H. (2008). Motor limitation in dual-task processing with different effectors. *The Quarterly Journal of Experimental Psychology*, *61*, 1385–1399. doi:10.1080/17470210701536856

Broadbent, D. E., & Gregory, M. (1967). Psychological refractory period and the length of time required to make a decision. *Proceedings of the Royal Society of London B: Biological Sciences*, *168*, 181–193. doi:10.1098/rspb.1967.0059

Bryce, D., & Bratzke, D. (2014). Introspective reports of reaction times in dual-tasks reflect experienced difficulty rather than timing of cognitive processes. *Consciousness and Cognition*, *27*, 254–267. doi:10.1016/j.concog.2014.05.011

Bundesen, C. (1990). A theory of visual attention. *Psychological Review*, *97*, 523–547. doi:10.1037/0033-295x.97.4.523

Callan, J., Klisz, D., & Parsons, O. A. (1974). Strength of auditory stimulus-response compatability as a function of task complexity. *Journal of Experimental Psychology*, *102*, 1039–1045. doi:10.1037/h0036329

Campbell, K. C., & Proctor, R. W. (1993). Repetition effects with categorizable stimulus and response sets. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *19*, 1345–1362. doi:10.1037/0278-7393.19.6.1345

Christina, R. W., Fischman, M. G., Vercruyssen, M. J. P., & Anson, J. G. (1982). Simple reaction time as a function of response complexity. *Journal of Motor Behavior*, *14*, 301–321. doi:10.1080/00222895.1982.10735282

Colavita, F. B. (1974). Human sensory dominance. *Perception & Psychophysics*, *16*, 409–412. doi:10.3758/bf03203962

Corallo, G., Sackur, J., Dehaene, S., & Sigman, M. (2008). Limits on introspection distorted subjective time during the dual-task bottleneck. *Psychological Science*, *19*, 1110–1117. doi:10.1111/j.1467-9280.2008.02211.x

Danek, R. H., & Mordkoff, J. T. (2011). Unequal motor durations under simple-, go/no-go, and choice-RT tasks: Extension of Miller and Low (2001). *Journal of Experimental Psychology: Human Perception and Performance*, *37*, 1323–1329. doi:10.1037/a0023092

De Jong, R. (1993). Multiple bottlenecks in overlapping task performance. *Journal of Experimental Psychology: Human Perception and Performance*, *19*, 965–980. doi:10.1037/0096-1523.19.5.965

De Jong, R. (1995). The role of preparation in overlapping-task performance. *The Quarterly Journal of Experimental Psychology*, *48*, 2–25. doi:10.1080/14640749508401372

Deichkind. (2015). Selber machen lassen. In *Niveau Weshalb Warum (Deluxe)*. Sultan Günther Music (Universal Music).

Desimone, R., & Duncan, J. (1995). Neural mechanisms of selective visual attention. *Annual Review of Neuroscience*, *18*, 193–222. doi:10.1146/annurev.ne.18.030195.001205

Donders, F. C. (1969). On the speed of mental processes. *Acta Psychologica*, *30*, 412–431. doi:10.1016/0001-6918(69)90065-1

Dreisbach, G., & Wenke, D. (2011). The shielding function of task sets and its relaxation during task switching. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *37*, 1540–1546. doi:10.1037/a0024077

Duncan, J. (1979). Divided attention: The whole is more than the sum of its parts. *Journal of Experimental Psychology: Human Perception and Performance*, *5*, 216–228. doi:10.1037/0096-1523.5.2.216

Duncan, J. (1980). The locus of interference in the perception of simultaneous stimuli. *Psychological Review*, *87*, 272–300. doi:10.1037/0033-295x.87.3.272

Eidels, A., Townsend, J. T., & Algom, D. (2010, February). Comparing perception of stroop stimuli in focused versus divided attention paradigms: Evidence for dramatic processing differences. *Cognition*, *114*, 129–150. doi:10.1016/j.cognition.2009.08.008

Ellenbogen, R., & Meiran, N. (2008). Working memory involvement in dual-task performance: Evidence from the backward compatibility effect. *Memory & Cognition*, *36*, 968–978. doi:10.3758/mc.36.5.968

Ellenbogen, R., & Meiran, N. (2010). Objects and events as determinants of parallel processing in dual tasks: Evidence from the backward compatibility effect. *Journal of Experimental Psychology: Human Perception and Performance*, *37*, 152–167. doi:10.1037/a0019958

Engbert, R., Nuthmann, A., Richter, E. M., & Kliegl, R. (2005). SWIFT: A dynamical model of saccade generation during reading. *Psychological Review*, *112*, 777–813. doi:10.1037/0033-295x.112.4.777

Eriksen, B. A., & Eriksen, C. W. (1974). Effects of noise letters upon the identification of a target letter in a nonsearch task. *Perception & Psychophysics*, *16*, 143–149. doi:10.3758/bf03203267

Fagot, C., & Pashler, H. (1992). Making two responses to a single object: Implications for the central attentional bottleneck. *Journal of Experimental Psychology: Human Perception and Performance*, *18*, 1058–1079. doi:10.1037/0096-1523.18.4.1058

Feng, S. F., Schwemmer, M., Gershman, S. J., & Cohen, J. D. (2014). Multitasking vs. multiplexing: Toward a normative account of limitations in the simultaneous execution of control-demanding behaviors. *Cognitive, Affective & Behavioral Neuroscience*, *14*, 129–146. doi:10.3758/s13415-013-0236-9

Findlay, J. M., & Gilchrist, I. D. (2003). *Active vision: The psychology of looking and seeing*. New York, US: Oxford University Press.

Findlay, J. M., & Walker, R. (1999). A model of saccade generation based on parallel processing and competitive inhibition. *Behavioral and Brain Sciences*, *22*(4), 661–674.

Fischer, R., Gottschalk, C., & Dreisbach, G. (2014). Context-sensitive adjustment of cognitive control in dual-task performance. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *40*, 399–416. doi:10.1037/a0034310

Fischer, R., & Hommel, B. (2012). Deep thinking increases task-set shielding and reduces shifting flexibility in dual-task performance. *Cognition*, *123*, 303–307. doi:10.1016/j.cognition.2011.11.015

Fischer, R., & Plessow, F. (2015). Efficient multitasking: Parallel versus serial processing of multiple tasks. *Frontiers in Psychology*, *6*, 1–11. doi:10.3389/fpsyg.2015.01366

Fischer, R., Plessow, F., Kunde, W., & Kiesel, A. (2010). Trial-to-trial modulations of the Simon effect in conditions of attentional limitations: Evidence from dual tasks. *Journal of Experimental Psychology: Human Perception and Performance*, *36*, 1576–1594. doi:10.1037/a0019326

Fodor, J. A. (1983). *The modularity of mind: An essay on faculty psychology*. Cambridge, MA, US: MIT press.

Garry, I. M., & Franks, M. I. (2000). Reaction time differences in spatially constrained bilateral and unilateral movements. *Experimental Brain Research*, *131*, 236–243. doi:10.1007/s002219900299

Göthe, K., Oberauer, K., & Kliegl, R. (2016). Eliminating dual-task costs by minimizing crosstalk between tasks: The role of modality and feature pairings. *Cognition*, *150*, 92–108. doi:10.1016/j.cognition.2016.02.003

Gottsdanker, R. (1980). The ubiquitous role of preparation. In G. E. Stelmach, & J. Requim (Eds.), *Tutorials in motor behavior* (Vol. 3, pp. 355–370). Amsterdam: North-Holland.

Gottsdanker, R., Broadbent, L., & Sant, C. V. (1963). Reaction time to single and to first signals. *Journal of Experimental Psychology*, *66*, 163–167. doi:10.1037/h0044920

Greenwald, A. G. (1970). Sensory feedback mechanisms in performance control: With special reference to the ideo-motor mechanism. *Psychological Review*, *77*, 73–99. doi:10.1037/h0028689

Hallett, P. E. (1978). Primary and secondary saccades to goals defined by instructions. *Vision Research*, *18*, 1279–1296. doi:10.1016/0042-6989(78)90218-3

Halvorson, K. M., Ebner, H., & Hazeltine, E. (2013). Investigating perfect timesharing: The relationship between IM-compatible tasks and dual-task performance. *Journal of Experimental Psychology: Human Perception and Performance*, *39*, 413–432. doi:10.1037/a0029475

Hämäläinen, M., Hari, R., Ilmoniemi, R. J., Knuutila, J., & Lounasmaa, O. V. (1993). Magneto-encephalography—theory, instrumentation, and applications to noninvasive studies of the working human brain. *Reviews of Modern Physics*, *65*, 413–497. doi:10.1103/revmodphys.65.413

Hazeltine, E., Ruthruff, E., & Remington, R. W. (2006). The role of input and output modality pairings in dual-task performance: Evidence for content-dependent central interference. *Cognitive Psychology*, *52*, 291–345. doi:10.1016/j.cogpsych.2005.11.001

Hazeltine, E., Teague, D., & Ivry, R. B. (2002). Simultaneous dual-task performance reveals parallel response selection after practice. *Journal of Experimental Psychology: Human Perception and Performance*, *28*, 517–545. doi:10.1037/0096-1523.28.3.527

Hendrich, E., Strobach, T., Buss, M., Müller, H. J., & Schubert, T. (2012). Temporal-order judgment of visual and auditory stimuli: Modulations in situations with and without stimulus discrimination. *Frontiers in Integrative Neuroscience*, *6*, 1–9. doi:10.3389/fnint.2012.00063

Herman, L. M., & Kantowitz, B. H. (1970). The psychological refractory period effect: Only half the double-stimulation story? *Psychological Bulletin*, *73*, 74–88. doi:10.1037/h0028357

Hick, W. E. (1952). On the rate of gain of information. *Quarterly Journal of Experimental Psychology*, *4*, 11–26. doi:10.1080/17470215208416600

Hirst, W., Neisser, U., & Spelke, E. S. (1978). Divided attention. *Human Nature*, *1*, 54–61.

Hirst, W., & Kalmar, D. (1987). Characterizing attentional resources. *Journal of Experimental Psychology: General*, *116*, 68–81. doi:10.1037/0096-3445.116.1.68

Holender, D. (1980). Interference between a vocal and a manual response to the same stimulus. In G. E. Stelmach, & J. Requin (Eds.), *Tutorials in motor behavior* (Vol. 1, pp. 421–431). Advances in Psychology. Amsterdam: North-Holland. doi:10.1016/s0166-4115(08)61959-7

Hommel, B. (1998a). Automatic stimulus-response translation in dual-task performance. *Journal of Experimental Psychology: Human Perception and Performance*, *24*, 1368–1384. doi:10.1037/0096-1523.24.5.1368

Hommel, B. (1998b). Event files: Evidence for automatic integration of stimulus-response episodes. *Visual Cognition*, *5*, 183–216. doi:10.1080/713756773

Hommel, B., & Eglau, B. (2002). Control of stimulus-response translation in dual-task performance. *Psychological Research, 66*, 260–273. doi:10.1007/s00426-002-0100-y

Hommel, B., Müsseler, J., Aschersleben, G., & Prinz, W. (2001). The theory of event coding (TEC): A framework for perception and action planning. *Behavioral and Brain Sciences*, *24*, 849–937. doi:10.1017/s0140525x01520105

Horn, A., & Leigh, R. (2011). The anatomy and physiology of the ocular motor system. *Handbook of Clinical Neurology*, *102*, 21–69. doi:10.1016/b978-0-444-52903-9.00008-x

Hübner, R., & Druey, M. D. (2006). Response execution, selection, or activation: What is sufficient for response-related repetition effects under task shifting? *Psychological Research*, *70*, 245–261. doi:10.1007/s00426-005-0219-8

Huestegge, L. (2011). The role of saccades in multitasking: Towards an output-related view of eye movements. *Psychological Research*, *75*, 452–465. doi:10.1007/s00426-011-0352-5

Huestegge, L., & Hazeltine, E. (2011). Crossmodal action: Modality matters. *Psychological Research*, *75*, 445–451. doi:10.1007/s00426-011-0373-0

Huestegge, L., & Koch, I. (2009). Dual-task crosstalk between saccades and manual responses. *Journal of Experimental Psychology: Human Perception and Performance*, *35*, 352–562. doi:10.1037/a0013897

Huestegge, L., & Koch, I. (2010). Crossmodal action selection: Evidence from dual-task compatibility. *Memory & Cognition*, *38*, 493–501. doi:10.3758/mc.38.4.493

Huestegge, L., & Koch, I. (2013). Constraints in task-set control: Modality dominance patterns among effector systems. *Journal of Experimental Psychology: General*, *142*, 633–637. doi:10.1037/a0030156

Huestegge, L., & Koch, I. (2014). When two actions are easier than one: How inhibitory control demands affect response processing. *Acta Psychologica*, *151*, 230–236. doi:10.1016/j.actpsy.2014.07.001

Huestegge, L., Pieczykolan, A., & Koch, I. (2014). Talking while looking: On the encapsulation of output system representations. *Cognitive Psychology*, *73*, 72–91. doi:10.1016/j.cogpsych.2014.06.001

Israel, M., & Cohen, A. (2011). Involuntary strategy-dependent dual task performance. *Psychological Research*, *75*, 513–524. doi:10.1007/s00426-011-0359-y

Issen, L. A., & Knill, D. C. (2012). Decoupling eye and hand movement control: Visual short-term memory influences reach planning more than saccade planning. *Journal of Vision*, *12*, 1–13. doi:10.1167/12.1.3

Jaeggi, S. M., Seewer, R., Nirkko, A. C., Eckstein, D., Schroth, G., Groner, R., & Gutbrod, K. (2003). Does excessive memory load attenuate activation in the prefrontal cortex? Load-dependent processing in single and dual tasks: Functional magnetic resonance imaging study. *NeuroImage*, *19*, 210–225. doi:10.1016/s1053-8119(03)00098-3

James, W. (1890). *The principles of psychology*. Boston: Harvard University Press.

Janczyk, M. (2016). Sequential modulation of backward crosstalk and task-shielding in dual-tasking. *Journal of Experimental Psychology: Human Perception and Performance*, *42*, 631–647. doi:10.1037/xhp0000170

Janczyk, M., Pfister, R., Hommel, B., & Kunde, W. (2014). Who is talking in backward crosstalk? How action goals influence dual-task performance. *Cognition*, *132*, 30–43. doi:10.1016/j.cognition.2014.03.001

Jentzsch, I., & Leuthold, H. (2005). Response conflict determines sequential effects in serial response time tasks with short response-stimulus intervals. *Journal of Experimental Psychology: Human Perception and Performance*, *31*, 731–748. doi:10.1037/0096-1523.31.4.731

Jentzsch, I., & Sommer, W. (2002). Functional localization and mechanisms of sequential effects in serial reaction time tasks. *Perception & Psychophysics*, *64*, 1169–1188. doi:10.3758/bf03194765

Jolicœur, P., & Dell'Acqua, R. (1998). The demonstration of short-term consolidation. *Cognitive Psychology*, *36*, 138–202. doi:10.1006/cogp.1998.0684

Kahneman, D. (1973). *Attention and effort*. New York, US: Prentice-Hall.

Kamienkowski, J. E., Pashler, H., Dehaene, S., & Sigman, M. (2011). Effects of practice on task architecture: Combined evidence from interference experiments and random-walk models of decision making. *Cognition*, *119*, 81–95. doi:10.1016/j.cognition.2010.12.010

Karlin, L., & Kestenbaum, R. (1968). Effects of number of alternatives on the psychological refractory period. *The Quarterly Journal of Experimental Psychology*, *20*, 167–178. doi:10.1080/14640746808400145

Kee, D. W., Bathurst, K., & Hellige, J. B. (1983). Lateralized interference of repetitive finger tapping: Influence of familial handedness, cognitive load and verbal production. *Neuropsychologia*, *21*, 617–624. doi:10.1016/0028-3932(83)90059-3

Keele, S. W. (1968). Movement control in skilled motor performance. *Psychological Bulletin*, *70*, 387–403. doi:10.1037/h0026739

Kiesel, A., Steinhauser, M., Wendt, M., Falkenstein, M., Jost, K., Philipp, A. M., & Koch, I. (2010). Control and interference in task switching-a review. *Psychological Bulletin*, *136*, 849–874. doi:10.1037/a0019842

Kinsbourne, M. (1981). Single channel theory. In D. H. Holding (Ed.), *Human Skills*. Chichester, Sussex: Wiley.

Kleinsorge, T. (1999). Response repetition benefits and costs. *Acta Psychologica*, *103*, 295–310. doi:10.1016/s0001-6918(99)00047-5

Kliegl, R., Nuthmann, A., & Engbert, R. (2006). Tracking the mind during reading: The influence of past, present, and future words on fixation durations. *Journal of Experimental Psychology: General*, *135*, 12–35. doi:10.1037/0096-3445.135.1.12

Koch, I. (2009). The role of crosstalk in dual-task performance: Evidence from manipulating response-code overlap. *Psychological Research*, *73*, 417–424. doi:10.1007/s00426-008-0152-8

Koch, I., & Prinz, W. (2002). Process interference and code overlap in dual-task performance. *Journal of Experimental Psychology: Human Perception and Performance*, *28*, 192–201. doi:10.1037/0096-1523.28.1.192

Koch, I., & Prinz, W. (2005). Response preparation and code overlap in dual tasks. *Memory & Cognition*, *33*, 1085–1095. doi:10.3758/bf03193215

Koch, I., & Rumiati, R. I. (2006). Task-set inertia and memory-consolidation bottleneck in dual tasks. *Psychological Research*, *70*, 448–458. doi:10.1007/s00426-005-0020-8

Koch, I., Schuch, S., Vu, K.-P. L., & Proctor, R. W. (2011). Response-repetition effects in task switching—dissociating effects of anatomical and spatial response discriminability. *Acta Psychologica*, *136*, 399–404. doi:10.1016/j.actpsy.2011.01.006

Kornblum, S., Hasbroucq, T., & Osman, A. (1990). Dimensional overlap: Cognitive basis for stimulus-response compatibility—a model and taxonomy. *Psychological Review*, *97*, 253–270. doi:10.1037/0033-295x.97.2.253

Kowler, E. (2011). Eye movements: The past 25 years. *Vision Research*, *51*, 1457–1483. doi:10.1016/j.visres.2010.12.014

Kveraga, K., Boucher, L., & Hughes, H. C. (2002). Saccades operate in violation of Hick’s law. *Experimental Brain Research*, *146*, 307–314. doi:10.1007/s00221-002-1168-8

Land, M. F., & Hayhoe, M. (2001). In what ways do eye movements contribute to everyday activities? *Vision Research*, *41*, 3559–3565. doi:10.1016/S0042-6989(01)00102-X

Lawrence, B. M., St. John, A. S., Abrams, R. A., & Snyder, L. H. (2008). An anti-Hick’s effect in monkey and human saccade reaction times. *Journal of Vision*, *8*, 1–7. doi:10.1167/8.3.26

Lehle, C., & Hübner, R. (2009). Strategic capacity sharing between two tasks: Evidence from tasks with the same and with different task sets. *Psychological Research*, *73*, 707–726. doi:10.1007/s00426-008-0162-6

Lehle, C., Steinhauser, M., & Hübner, R. (2009). Serial or parallel processing in dual tasks: What is more effortful? *Psychophysiology*, *46*, 502–509. doi:10.1111/j.1469-8986.2009.00806.x

Leonhard, T., Ruiz Fernández, S., Ulrich, R., & Miller, J. (2011). Dual-task processing when task 1 is hard and task 2 is easy: Reversed central processing order? *Journal of Experimental Psychology: Human Perception and Performance*, *37*, 115–136. doi:10.1037/a0019238

Lien, M.-C., McCann, R. S., Ruthruff, E., & Proctor, R. W. (2005). Dual-task performance with ideomotor-compatible tasks: Is the central processing bottleneck intact, bypassed, or shifted in locus? *Journal of Experimental Psychology: Human Perception and Performance*, *31*, 122–144. doi:10.1037/0096-1523.31.1.122

Lien, M.-C., & Proctor, R. W. (2000). Multiple spatial correspondence effects on dual-task performance. *Journal of Experimental Psychology: Human Perception and Performance*, *26*, 1260–1280. doi:10.1037/0096-1523.26.4.1260

Lien, M.-C., & Proctor, R. W. (2002). Stimulus-response compatibility and psychological refractory period effects: Implications for response selection. *Psychonomic Bulletin & Review*, *9*, 212–238. doi:10.3758/bf03196277

Lien, M.-C., & Ruthruff, E. (2004). Task switching in a hierarchical task structure: Evidence for the fragility of the task repetition benefit. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *30*, 697–713. doi:10.1037/0278-7393.30.3.697

Liversedge, S., Gilchrist, I., & Everling, S. (2011). *The Oxford handbook of eye movements*. New York, US: Oxford University Press.

Logan, G. D., & Delheimer, J. A. (2001). Parallel memory retrieval in dual-task situations: II. Episodic memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *27*, 668–685. doi:10.1037/0278-7393.27.3.668

Logan, G. D., & Gordon, R. D. (2001). Executive control of visual attention in dual-task situations. *Psychological Review*, *108*, 393–434. doi:10.1037/0033-295x.108.2.393

Logan, G. D., & Schulkind, M. D. (2000). Parallel memory retrieval in dual-task situations: I. Semantic memory. *Journal of Experimental Psychology: Human Perception and Performance*, *26*, 1072–1090. doi:10.1037/0096-1523.26.3.1072

Luria, R., & Meiran, N. (2003). Online order control in the psychological refractory period paradigm. *Journal of Experimental Psychology: Human Perception and Performance*, *29*, 556–574. doi:10.1037/0096-1523.29.3.556

MacLeod, C. M. (1991). Half a century of research on the Stroop effect: An integrative review. *Psychological Bulletin*, *109*, 163–203. doi:10.1037/0033-2909.109.2.163

Marti, S., Sackur, J., Sigman, M., & Dehaene, S. (2010). Mapping introspection’s blind spot: Reconstruction of dual-task phenomenology using quantified introspection. *Cognition*, *115*, 303–313. doi:10.1016/j.cognition.2010.01.003

Meyer, D. E., & Kieras, D. E. (1997a). A computational theory of executive cognitive processes and multiple-task performance: Part 1. Basic mechanisms. *Psychological Review*, *104*, 3–65. doi:10.1037/0033-295x.104.1.3

Meyer, D. E., & Kieras, D. E. (1997b). A computational theory of executive cognitive processes and multiple-task performance: Part 2. Accounts of psychological refractory-period phenomena. *Psychological Review*, *104*, 749–791. doi:10.1037//0033-295x.104.4.749

Miller, J. (2006). Backward crosstalk effects in psychological refractory period paradigms: Effects of second-task response types on first-task response latencies. *Psychological Research*, *70*, 484–493. doi:10.1007/s00426-005-0011-9

Miller, J., & Alderton, M. (2006). Backward response-level crosstalk in the psychological refractory period paradigm. *Journal of Experimental Psychology: Human Perception and Performance*, *32*, 149–165. doi:10.1037/0096-1523.32.1.149

Miller, J., & Durst, M. (2014). ‘‘Just do it when you get a chance”: The effects of a background task on primary task performance. *Attention, Perception, & Psychophysics*, *76*, 2560–2574. doi:10.3758/s13414-014-0730-3

Miller, J., & Durst, M. (2015). A comparison of the psychological refractory period and prioritized processing paradigms: Can the response-selection bottleneck model explain them both? *Journal of Experimental Psychology: Human Perception and Performance*, *41*, 1420–1441. doi:10.1037/xhp0000103

Miller, J., Ulrich, R., & Rolke, B. (2009). On the optimality of serial and parallel processing in the psychological refractory period paradigm: Effects of the distribution of stimulus onset asynchronies. *Cognitive Psychology*, *58*, 273–310. doi:10.1016/j.cogpsych.2006.08.003

Monsell, S. (2003). Task switching. *Trends in cognitive sciences*, *7*, 134–140. doi:10.1016/s1364-6613(03)00028-7

Morrone, M. C., Ross, J., & Burr, D. (2005). Saccadic eye movements cause compression of time as well as space. *Nature Neuroscience*, *8*, 950–954. doi:10.1038/nn1488

Nakayama, K., & Silverman, G. H. (1986). Serial and parallel processing of visual feature conjunctions. *Nature*, *320*, 264–265. doi:10.1038/320264a0

Navon, D. (1985). Attention division or attention sharing. In *Attention and Performance* (Vol. 11, pp. 133–146). Hillsdale, NJ, US: Lawrence Erlbaum Associates.

Navon, D., & Gopher, D. (1979). On the economy of the human-processing system. *Psychological Review*, *86*, 214–255. doi:10.1037/0033-295x.86.3.214

Navon, D., & Miller, J. (1987). Role of outcome conflict in dual-task interference. *Journal of Experimental Psychology: Human Perception and Performance*, *13*, 435–448. doi:10.1037/0096-1523.13.3.435

Navon, D., & Miller, J. (2002). Queuing or sharing? A critical evaluation of the single-bottleneck notion. *Cognitive Psychology*, *44*, 193–251. doi:10.1006/cogp.2001.0767

Neys, W. D. (2006). Automatic–heuristic and executive–analytic processing during reasoning: Chronometric and dual-task considerations. *The Quarterly Journal of Experimental Psychology*, *59*, 1070–1100. doi:10.1080/02724980543000123

Nieuwenstein, M., & Wyble, B. (2014). Beyond a mask and against the bottleneck: Retroactive dual-task interference during working memory consolidation of a masked visual target. *Journal of Experimental Psychology: General*, *143*, 1409–1427. doi:10.1037/a0035257

Norman, D. A., & Bobrow, D. G. (1975). On data-limited and resource-limited processes. *Cognitive Psychology*, *7*, 44–64. doi:10.1016/0010-0285(75)90004-3

Nosofsky, R. M., & Palmeri, T. J. (1997). An exemplar-based random walk model of speeded classification. *Psychological Review*, *104*, 266–300. doi:10.1037/0033-295x.104.2.266

Notebaert, W., & Soetens, E. (2003). The influence of irrelevant stimulus changes on stimulus and response repetition effects. *Acta Psychologica*, *112*, 143–156. doi:10.1016/s0001-6918(02)00080-x

Osman, A., & Moore, C. M. (1993). The locus of dual-task interference: Psychological refractory effects on movement-related brain potentials. *Journal of Experimental Psychology: Human Perception and Performance*, *19*, 1292–1312. doi:10.1037/0096-1523.19.6.1292

Pashler, H. (1984). Processing stages in overlapping tasks: Evidence for a central bottleneck. *Journal of Experimental Psychology: Human Perception and Performance*, *10*, 358–377. doi:10.1037/0096-1523.10.3.358

Pashler, H. (1990). Do response modality effects support multiprocessor models of divided attention? *Journal of Experimental Psychology: Human Perception and Performance*, *16*, 826–842. doi:10.1037/0096-1523.16.4.826

Pashler, H. (1994). Dual-task interference in simple tasks: Data and theory. *Psychological Bulletin*, *116*, 220–244. doi:10.1037/0033-2909.116.2.220

Pashler, H., & Baylis, G. C. (1991). Procedural learning: II. Intertrial repetition effects in speeded-choice tasks. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *17*, 33–48. doi:10.1037/0278-7393.17.1.33

Pashler, H., Carrier, M., & Hoffman, J. (1993). Saccadic eye movements and dual-task interference. *The Quarterly Journal of Experimental Psychology*, *46 A*, 51–82. doi:10.1080/14640749308401067

Pashler, H., & Christian, C. L. (1994). *Bottlenecks in planning and producing vocal, manual, and foot responses*. University of California, San Diego, Center for Human Information Processing. La Jolla, CA.

Pashler, H., & Johnston, J. C. (1989). Chronometric evidence for central postponement in temporally overlapping tasks. *The Quarterly Journal of Experimental Psychology*, *41A*, 19–45. doi:10.1080/14640748908402351

Paucke, M., Oppermann, F., Koch, I., & Jescheniak, J. D. (2015). On the costs of parallel processing in dual-task performance: The case of lexical processing in word production.

Journal of Experimental Psychology: Human Perception and Performance, *41*, 1539–1552. doi:10.1037/a0039583

Pieczykolan, A., & Huestegge, L. (2014). Oculomotor dominance in multitasking: Mechanisms of conflict resolution in cross-modal action. *Journal of Vision*, *14*, 1–17. doi:10.1167/14.13.18

Plessow, F., Schade, S., Kirschbaum, C., & Fischer, R. (2012). Better not to deal with two tasks at the same time when stressed? Acute psychosocial stress reduces task shielding in dual-task performance. *Cognitive Affective Behavioral Neuroscience*, *12*, 557–570. doi:10.3758/s13415-012-0098-6

Posner, M. I., Nissen, M. J., & Klein, R. M. (1976). Visual dominance: An information-processing account of its origins and significance. *Psychological Review*, *83*, 157–171. doi:10.1037/0033-295x.83.2.157

Proctor, R. W. (2011). Playing the Simon game: Use of the Simon task for investigating human information processing. *Acta Psychologica*, *136*, 182–188. doi:10.1016/j.actpsy.2010.06.010

Proctor, R. W., & Reeve, T. G. (1990). *Stimulus-response compatibility: An integrated perspective*. Oxford, England: North-Holland.

Rayner, K. (1998). Eye movements in reading and information processing: 20 years of research. *Psychological Bulletin*, *124*, 372–422. doi:10.1037/0033-2909.124.3.372

Rayner, K. (2009). Eye movements and attention in reading, scene perception, and visual search. *The Quarterly Journal of Experimental Psychology*, *62*, 1457–1506. doi:10.1080/17470210902816461

Reichle, E. D., Rayner, K., & Pollatsek, A. (2003). The EZ reader model of eye-movement control in reading: Comparisons to other models. *Behavioral and Brain Sciences*, *26*, 445–476. doi:10.1017/s0140525x03000104

Remington, R. J. (1969). Analysis of sequential effects on choice reaction times. *Journal of Experimental Psychology*, *82*, 250–257. doi:10.1037/h0028122

Reynolds, D. (1966). Time and event uncertainty in unisensory reaction time. *Journal of Experimental Psychology*, *71*, 286–293. doi:10.1037/h0022837

Rogers, R. D., & Monsell, S. (1995). Costs of a predictible switch between simple cognitive tasks. *Journal of Experimental Psychology: General*, *124*, 207–231. doi:10.1037/0096-3445.124.2.207

Ruiz Fernández, S., Leonhard, T., Rolke, B., & Ulrich, R. (2011). Processing two tasks with varying task order: Central stage duration influences central processing order. *Acta Psychologica, 137,* 10–17. doi:10.1016/j.actpsy.2011.01.016

Ruthruff, E., Johnston, J. C., & Van Selst, M. (2001). Why practice reduces dual-task interference. *Journal of Experimental Psychology: Human Perception and Performance*, *27,* 3–21. doi:10.1037/0096-1523.27.1.3

Ruthruff, E., Johnston, J. C., Van Selst, M., Whitsell, S., & Remington, R. (2003a). Vanishing dual-task interference after practice: Has the bottleneck been eliminated or is it merely latent? *Journal of Experimental Psychology: Human Perception and Performance, 29,* 280–289. doi:10.1037/0096-1523.29.2.280

Ruthruff, E., Pashler, H., & Hazeltine, E. (2003b). Dual-task interference with equal task emphasis: Graded capacity sharing or central postponement? *Perception & Psychophysics*, *65*, 801–816. doi:10.3758/bf03194816

Salvucci, D. D., & Taatgen, N. A. (2008). Threaded cognition: An integrated theory of concurrent multitasking. *Psychological Review*, *115*, 101–130. doi:10.1037/0033-295x.115.1.101

Schubert, T. (1999). Processing differences between simple and choice reactions affect bottleneck localization in overlapping tasks. *Journal of Experimental Psychology: Human Perception and Performance*, *25*, 408–425. doi:10.1037/0096-1523.25.2.408

Schubert, T., Fischer, R., & Stelzel, C. (2008). Response activation in overlapping tasks and the response-selection bottleneck. *Journal of Experimental Psychology: Human Perception and Performance*, *34*, 376–397. doi:10.1037/0096-1523.34.2.376

Schuch, S., & Koch, I. (2004). The costs of changing the representation of action: Response repetition and response-response compatibility in dual tasks. *Journal of Experimental Psychology: Human Perception and Performance*, *30*, 566–582. doi:10.1037/0096-1523.30.3.566

Schumacher, E. H., Seymour, T. L., Glass, J. M., Fencsik, D. E., Lauber, E. J., Kieras, D. E., & Meyer, D. E. (2001). Virtually perfect time sharing in dual-task performance: Uncorking the central cognitive bottleneck. *Psychological Science*, *12*, 101–108. doi:10.1111/1467-9280.00318

Schütz, A. C., Braun, D. I., & Gegenfurtner, K. R. (2011). Eye movements and perception: A selective review. *Journal of Vision*, *11*, 1–30. doi:10.1167/11.5.9

Sigman, M., & Dehaene, S. (2008). Brain mechanisms of serial and parallel processing during dual-task performance. *The Journal of Neuroscience, 28,* 7585–7598. doi:10.1523/jneurosci-0948-08.2008

Simon, J. R. (1969). Reactions toward the source of stimulation. *Journal of Experimental Psychology, 81,* 174–176. doi:10.1037/h0027448

Simonyan, K., & Horwitz, B. (2011). Laryngeal motor cortex and control of speech in humans. *The Neuroscientist, 17,* 197–208. doi:10.1177/1073858410386727

Smith, M. C. (1969). The effect of varying information on the psychological refractory period. *Acta Psychologica, 30,* 220–231. doi:10.1016/0001-6918(69)90052-3

Solomons, L. M., & Stein, G. (1896). Normal motor automatism. *Psychological Review, 3,* 492–512. doi:10.1037/h0066163

Sommer, W., Leuthold, H., & Schubert, T. (2001). Multiple bottlenecks in information processing? An electrophysiological examination. *Psychonomic Bulletin & Review, 8,* 81–88. doi:10.3758/bf03196142

Spelke, E., Hirst, W., & Neisser, U. (1976). Skills of divided attention. *Cognition, 4,* 215–230. doi:10.1016/0010-0277(76)90018-4

Spence, C. (2009). Explaining the colavita visual dominance effect. *Progress in Brain Research, 176,* 245–258. doi:10.1016/s0079-6123(09)17615-x

Stephan, D. N., & Koch, I. (2010). Central cross-talk in task switching: Evidence from manipulating input-output modality compatibility. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 36,* 1075–1081. doi:10.1037/a0019695

Stephan, D. N., Koch, I., Hendler, J., & Huestegge, L. (2013). Task switching, modality compatibility, and the supra-modal function of eye movements. *Experimental Psychology, 60,* 90–99. doi:10.1027/1618-3169/a000175

Strayer, D. L., & Johnston, W. A. (2001). Driven to distraction: Dual-task studies of simulated driving and conversing on a cellular telephone. *Psychological Science, 12,* 462–466. doi:10.1111/1467-9280.00386

Strobach, T., Liepelt, R., Pashler, H., Frensch, P. A., & Schubert, T. (2013). Effects of extensive dual-task practice on processing stages in simultaneous choice tasks. *Attention, Perception, & Psychophysics, 75,* 900–920. doi:10.3758/s13414-013-0451-z

Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology*, *18*, 643–662. doi:10.1037/0096-3445.121.1.15

Szameitat, A. J., Lepsien, J., von Cramon, D. Y., Sterr, A., & Schubert, T. (2006). Task-order coordination in dual-task performance and the lateral prefrontal cortex: An event-related fMRI study. *Psychological Research*, *70*, 541–552. doi:10.1007/s00426-005-0015-5

Telford, C. W. (1931). The refractory phase of voluntary and associative responses. *Journal of Experimental Psychology*, *14*, 1–36. doi:10.1037/h0073262

Thomson, S. J., Watter, S., & Finkelshtein, A. (2010). Parallel response selection in dual-task situations via automatic category-to-response translation. *Attention, Perception, & Psychophysics*, *72*, 1791–1802. doi:10.3758/app.72.7.1791

Thornton, T. L., & Gilden, D. L. (2007). Parallel and serial processes in visual search. *Psychological Review*, *114*, 71–103. doi:10.1037/0033-295x.114.1.71

Tombu, M., & Jolicœur, P. (2002). All-or-none bottleneck versus capacity sharing accounts of the psychological refractory period phenomenon. *Psychological Research*, *66*, 274–286. doi:10.1007/s00426-002-0101-x

Tombu, M., & Jolicœur, P. (2003). A central capacity sharing model of dual-task performance. *Journal of Experimental Psychology: Human Perception and Performance*, *29*, 3–18. doi:10.1037/0096-1523.29.1.3

Ulrich, R., Fernández, S. R., Jentzsch, I., Rolke, B., Schröter, H., & Leuthold, H. (2006). Motor limitation in dual-task processing under ballistic movement conditions. *Psychological Science*, *17*, 788–793. doi:10.1111/j.1467-9280.2006.01783.x

Ulrich, R., & Miller, J. (2008). Response grouping in the psychological refractory period (PRP) paradigm: Models and contamination effects. *Cognitive Psychology*, *57*, 75–121. doi:10.1016/j.cogpsych.2007.06.004

Watter, S., & Logan, G. D. (2006). Parallel response selection in dual-task situations. *Attention, Perception, & Psychophysics*, *68*, 254–277. doi:10.3758/bf03193674

Welford, A. T. (1952). The psychological refractory period and the timing of high-speed performance—a review and a theory. *British Journal of Psychology. General Section*, *43*, 2–19. doi:10.1111/j.2044-8295.1952.tb00322.x

Welford, A. T. (1967). Single-channel operation in the brain. *Acta Psychologica*, *27*, 5–22. doi:10.1016/0001-6918(67)90040-6

Wickens, C. D. (2002). Multiple resources and performance prediction. *Theoretical Issues in Ergonomics Science*, *3*, 159–177. doi:10.1080/14639220210123806

Wickens, C. D. (2008). Multiple resources and mental workload. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *50*, 449–455. doi:10.1518/001872008x288394

Wilson, M. (2002). Six views of embodied cognition. *Psychonomic Bulletin & Review*, *9*, 625–636. doi:10.3758/bf03196322

Wu, C., & Liu, Y. (2008). Queuing network modeling of the psychological refractory period (PRP). *Psychological Review*, *115*, 913–954. doi:10.1037/a0013123

Yarrow, K., Haggard, P., Heal, R., Brown, P., & Rothwell, J. C. (2001). Illusory perceptions of space and time preserve cross-saccadic perceptual continuity. *Nature*, *414*, 302–305. doi:10.1038/35104551

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Epilog

…and finally, another proposition for solving the dual-task binding problem:

> ‘*Je wenijer du selber machst, desto wenijer machste och falsch.*
> *Denk mal darüber nach, Alter. Jar nich so schwer.*’
>
> (Deichkind, 2015)