Effector System Prioritization in Multitasking

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Zusammenfassung (German Abstract)

Das gleichzeitige Bearbeiten von mehreren Aufgaben (Multitasking) führt in der Regel zu schlechterer Performanz, zum Beispiel bezüglich Geschwindigkeit und Genauigkeit der Aufgabenausführung. Diese sogenannten Doppelaufgaben- (oder Multitasking-) Kosten sind oft asymmetrisch auf die involvierten Aufgaben verteilt. Dies kann unter bestimmten Gegebenheiten als Priorisierung von jenen Aufgaben, die mit geringeren Kosten assoziiert sind über jene, die stärker durch die Doppelaufgabensituation leiden, interpretiert werden. Eine Quelle für solch eine Aufgabenpriorisierung sind unterschiedliche Effektorsysteme (z.B. Blickbewegungsapparat, Extremitäten, Vokaltrakt), mit denen die Aufgaben jeweils ausgeführt werden sollen. Die vorliegende Arbeit untersucht solche effektorsystembasierte Priorisierung, das heißt, inwiefern assoziierte Effektorsysteme determinieren, ob Aufgaben in Multitasking-Situationen priorisiert verarbeitet werden. Dazu wurden drei verschiedene experimentelle Paradigmen genutzt: a) das „Simultane Stimulus-Darbietungs-Paradigma“, b) das „Psychologische Refraktärperioden-Paradigma“ und c) das „Aufgabenwechsel-Paradigma“. Innerhalb dieser Paradigmen werden Reaktionen (Reaktionszeiten und Fehlerraten) gemessen und zwischen verschiedenen Effektorsystemen verglichen, die a) zum genau gleichen Zeitpunkt gestartet werden, b) mit einem kurzen, variierten zeitlichen Versatz gestartet werden, aber in ihrer Ausführung überlappen, oder c) zwischen denen in unvorhersehbarer Reihenfolge hin und her gewechselt werden soll. Entsprechend dieser drei Ansätze erlauben die Ergebnisse drei wichtige Schlussfolgerungen: 1. Unter simultanem Einsetzen der Aufgabenverarbeitung (und damit ohne extern suggerierte Reihenfolge) folgen Doppelaufgabenkontrollprozesse einem ordinalen Priorisierungsmuster auf Basis der mit den Aufgaben assoziierten Effektorsysteme in der Reihenfolge: okulomotorisch > pedal > vokal > manuell (im Sinne einer absteigenden Priorisierung). Dieses Muster ist nicht durch Bearbeitungsgeschwindigkeit im Sinne eines „wer zuerst kommt, mahlt zuerst“-Prinzips erklärbar. 2. Eine Aufgabenpriorisierung, die auf einer

externen Aufgabenreihenfolge basiert (gemessen im PRP-Effekt), kann durch die mit den Aufgaben assoziierten Effektorsysteme moduliert werden. 3. Systematische effektorsystembasierte Aufgabenpriorisierung ist nur dann konsistent zu beobachten, wenn Teile der Aufgabenverarbeitung zeitlich überlappen. Eine rein mentale Repräsentation einer Aufgabe, die in einem anderen Effektorsystem ausgeführt werden soll, reicht nicht dazu aus, um das oben beschriebene Priorisierungsmuster vollständig zu instanziieren. Alles in allem sprechen die Ergebnisse der vorliegenden Arbeit für parallele (und gegen ausschließlich serielle) Reaktionsauswahlprozesse und dafür, dass limitierte kognitive Ressourcen zwischen Aufgaben aufgeteilt werden. Außerdem zeigen die vorliegenden Ergebnisse den substantiellen Einfluss von Effektorsystemen auf Ressourcenzuweisungsprozesse in Mehrfachaufgabensituationen und legen nahe, entsprechende Gewichtungsparameter in bestehende Modelle zu Doppelaufgabenkontrolle zu integrieren.

Abstract

Multitasking, defined as performing more than one task at a time, typically yields performance decrements, for instance, in processing speed and accuracy. These performance costs are often distributed asymmetrically among the involved tasks. Under suitable conditions, this can be interpreted as a marker for prioritization of one task – the one that suffers less – over the other. One source of such task prioritization is based on the use of different effector systems (e.g., oculomotor system, vocal tract, limbs) and their characteristics. The present work explores such effector system-based task prioritization by examining to which extent associated effector systems determine which task is processed with higher priority in multitasking situations. Thus, three different paradigms are used, namely the simultaneous (stimulus) onset paradigm, the psychological refractory period (PRP) paradigm, and the task switching paradigm. These paradigms invoke situations in which two (in the present studies basic spatial decision) tasks are a) initiated at exactly the same time, b) initiated with a short varying temporal distance (but still temporally overlapping), or c) in which tasks alternate randomly (without temporal overlap). The results allow for three major conclusions: 1. The assumption of effector system-based task prioritization according to an ordinal pattern (oculomotor > pedal > vocal > manual, indicating decreasing prioritization) is supported by the observed data in the simultaneous onset paradigm. This data pattern cannot be explained by a rigid "first come, first served" task scheduling principle. 2. The data from the PRP paradigm confirmed the assumption of vocal-over-manual prioritization and showed that classic PRP effects (as a marker for task order-based prioritization) can be modulated by effector system characteristics. 3. The mere cognitive representation of task sets (that must be held active to switch between them) differing in effector systems without an actual temporal overlap in task processing, however, is not sufficient to elicit the same effector system prioritization phenomena observed for overlapping tasks. In summary, the insights obtained by the present work support the assumptions of parallel central

task processing and resource sharing among tasks, as opposed to exclusively serial processing of central processing stages. Moreover, they indicate that effector systems are a crucial factor in multitasking and suggest an integration of corresponding weighting parameters in existing dual-task control frameworks.

Contents

1. General Introduction

1.1 Multitasking in Cognitive Psychology

Performing more than one task at a time typically yields performance decrements, often referred to as multitasking costs. This phenomenon has a long-standing history and was used to gain insight into mechanisms of human cognition. By pushing the limits of cognitive resources, this line of research can test assumptions regarding prioritization in processing among different tasks. Over 50 years ago, multitasking studies were published that used continuous task paradigms, in which participants were trained to perform two or more tasks continuously over a longer time span (e.g., Peterson, 1969; Spelke, Hirst, & Neisser, 1976; see also Künstler et al., 2018). However, there are several methodological approaches to address cognitive mechanisms underlying dual-task control. Other currently more common research paradigms aimed at maximizing control over stimulus conditions and response execution by involving clearly defined sets of stimuli and responses. These are suited to better control for potential confounds compared to continuous task paradigms. The three most common approaches in multitasking research comprise dual tasking with simultaneous stimulus onset, the PRP paradigm, and task switching (see also Koch, Poljac, Müller, & Kiesel, 2018, for an integrative review about multitasking research in different paradigms). Thereby, this line of research was able to provide substantial empirical progress regarding underlying cognitive processes and to build up different theoretical ideas that explain the rules according to which limited cognitive resources can be allocated among tasks.

1.2 Parallel vs. Serial Processing in Dual-Task Control

Traditionally, dual-task interference (as shown in performance decrements) is assumed to indicate that cognitive resources for information processing are limited. During the 1950s, first theoretical models arose that assumed a processing bottleneck in a single channel model at the stage of stimulus identification (Broadbent, 1958) or at the stage of response selection (Welford, 1952). During such a bottleneck, only one task can be processed at once (strictly serial processing) while before and afterwards parallel processing is assumed to be possible. Also Pashler (1994) postulated such a bottleneck model to explain the crucial observation that in a paradigm involving a varying temporal stimulus onset delay performance in the secondly initiated task (Task 2) declined with decreasing stimulus onset asynchrony (SOA), while performance in the task associated with the firstly presented stimulus (Task 1) stayed mainly unaffected. This finding is called the PRP (*Psychological Refractory Period*) effect. Specifically, Pashler proposed a bottleneck model that consists of three processing stages (cf. also Sanders, 1980; Sternberg, 1969): stimulus processing, response selection, and response execution. Similar to Welford (1952), Pashler (1994) assumed a bottleneck at the stage of response selection (i.e., the process of selecting the correct response that corresponds to each stimulus), while stimulus processing and response execution of one task was assumed to be able to run in parallel to any stage of the other task (see Figure 1.1A). Thus, cognitive resources have been assumed to be allocated sequentially to the tasks. Such an account predicts that when two tasks are started within a relatively short temporal delay, Task 2 response selection would have to wait until response selection of Task 1 is finished, because until then the response selection bottleneck would be blocked. Such a delay of Task 2 processing (also referred to as slack time, cf. Schweickert, 1978) could nicely explain the PRP effect.

Importantly, the notion of a response selection bottleneck in Pashler's (1994) model is independent of the stimulus modality and effector system associated with the two tasks. That is, because it relies completely on a "first come, first served" principle based on the endpoint of stimulus processing duration (mainly determined by stimulus onset) in each task, assuming strictly sequential stage processing within each task.

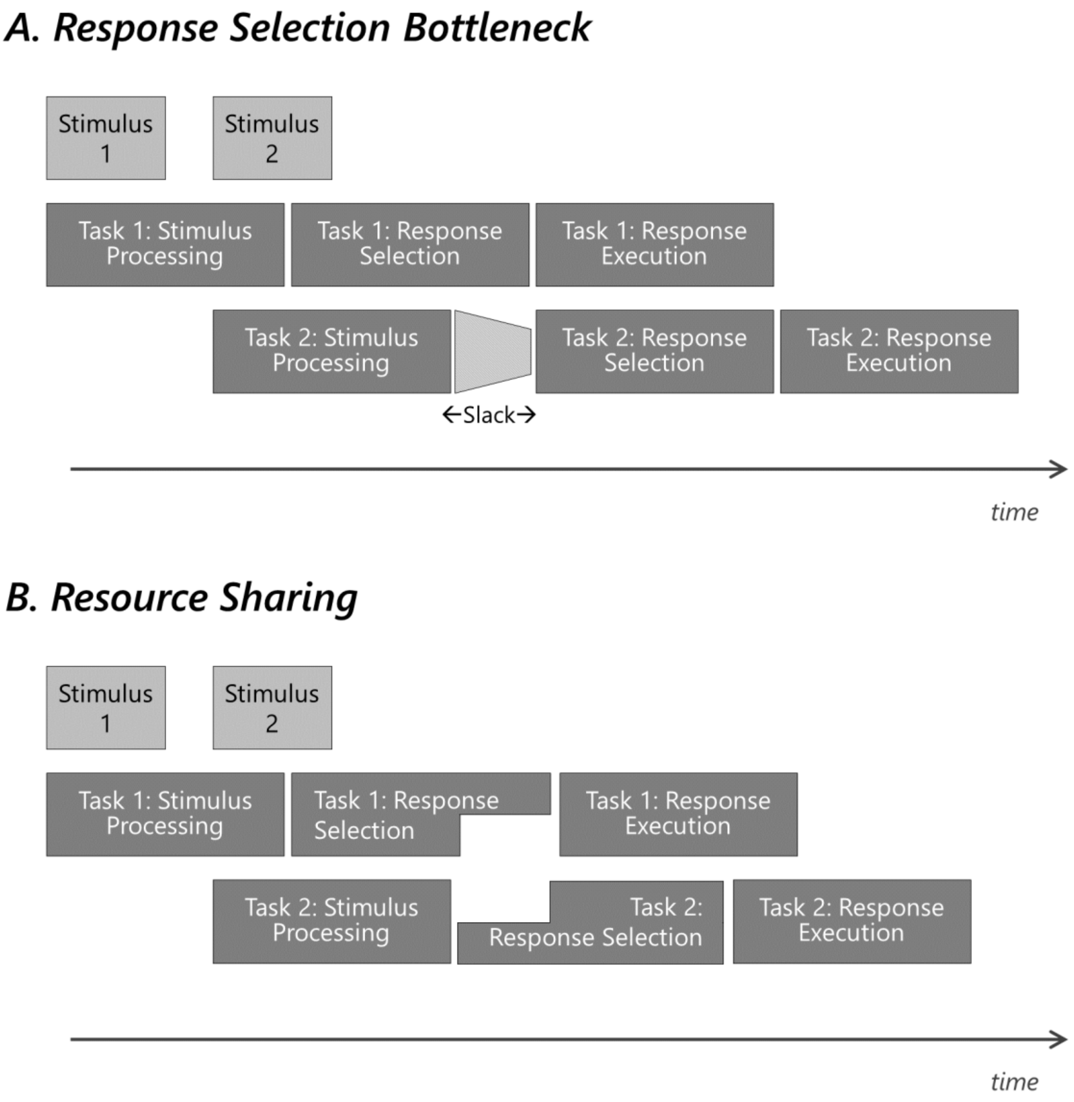

Figure 1.1. Response selection bottleneck and resource sharing as two contrasting theoretical models of resource allocation policies. (A) Schematic illustration of the response selection bottleneck (RSB) model (Pashler, 1994) indicating completely serial task processing at the stage of response selection. Task 2 response selection is assumed to be delayed until Task 1 response selection is finished (and therefore the bottleneck cleared). (B) Depiction of potential central resource sharing in parallel task processing. One exemplary resource allocation pattern based on Tombu and Jolicœur (2003) is illustrated.

However, over the years more and more data have been observed that speak against a strictly serial processing of response selection. Hommel (1998), for example, demonstrated a substantial influence of Task 2 related features on Task 1 performance in that the latter was influenced by the response-response compatibility/congruency relation between the two tasks (as well as by the compatibility/congruency between the secondary response and the primary stimulus). This finding is typically referred to as the backward crosstalk/compatibility effect (Hommel, 1998; see also Durst & Janczyk, 2018, 2019; Hommel & Eglau, 2002; Huestegge, Pieczykolan, & Janczyk, 2018; Janczyk & Huestegge, 2017; Janczyk, Pfister, Hommel, & Kunde, 2014; Janczyk, Renas, & Durst, 2018; Renas, Durst, & Janczyk, 2018). This observation suggested that at least some aspect of response-related central processing (e.g., response activation) can occur in parallel, a rationale that is incompatible with the original RSB model.

The tradition of bottleneck or single channel models was always challenged by a radically different assumption based on the metaphor of limited mental resources (e.g., Kahneman, 1973). Specifically, more and more evidence came to light that spoke against the assumption of strict seriality as proposed by Pashler (1994), so that the idea of parallel resource sharing among tasks became more popular in the early 2000s (see also Koch, 2008, for a review). Tombu and Jolicœur (2003), for instance, suggested the metaphor of a “central” processing resource that could be flexibly assigned to different processes (e.g., for strategic reasons). Within this framework, costs arise because limited cognitive resources must be divided between two parallel action demands and consequently shared continuously among (and differentially allocated to) tasks, instead of being deployed sequentially (see Figure 1.1B).

Such a resource limitation account could explain the empirical observations just as good as bottleneck models, as they can be easily employed for situations in which one of the two tasks gets a lion’s share of the available resources without neglecting the principal possibility of parallel processing. In fact, these models make predictions quite similar to a serial response selection account, for example, by assuming that a major portion of resources is allocated to Task 1 response selection first, until later resources are shifted (in either a gradual or step-wise manner) to complete Task 2 response selection. Thus, instead of an “inflexible”, all-or-nothing allocation mechanism based on subtask order, these more recent theories allow for flexible, graded resource sharing that can be modulated by particular task demands or instructions (see Fischer & Plessow, 2015, for an overview; Logan & Gordon, 2001, for a discussion). Thereby, they expand the assumptions of strict bottleneck models by postulating that such a bottleneck might be strategic and therefore potentially sensitive to cognitive influence (cf. also Meyer & Kieras, 1997a, 1997b; Navon & Miller, 2002). In line with this, Navon and Miller (2002) as well as Tombu and Jolicœur (2003) argued that consequently a structural all-or-none bottleneck model actually could be interpreted as a special case of an allocation policy of sharing cognitive resources. Generally, while models of shared resources typically interpret the PRP effect as an indication for a substantial influence of task order on allocation policies (i.e., as a prioritization of Task 1), this is assumed to potentially be modulated by other task characteristics.

In order to decide how to allocate limited resources among tasks some kind of supervisory authority in form of an executive function becomes necessary. However, corresponding models do not fully specify *why* a certain task or action receives more resources and is therefore prioritized. Occasionally, it has been assumed that task prioritization might rely on stimulus characteristics (e.g., the temporal sequence of two stimuli; see Logan & Gordon, 2001), but such a mechanism cannot account for task prioritization in situations with only one stimulus or simultaneous stimulus presentation. In addition, the concrete mechanisms of strategic reasons discussed as a factor influencing allocation are not fully specified to date. One example for evidence supporting the idea of flexible strategy-related resource scheduling comes from a study by Miller, Ulrich, and Rolke (2009), in which a clear indication of more parallel processing in conditions with particularly frequent SOAs were observed. Interestingly, this was concurrently associated with increased overall dual-task processing efficiency (Miller et al., 2009).

1.3 The Role of Effector Systems in Multitasking

1.3.1 First Indication for Systematic Effector System Prioritization

A relatively new line of research suggests that the effector system in which a task is executed might be an additional factor influencing task processing. While in typical multitasking research the impact of effector systems on performance is mostly disregarded as most studies use a rather restricted range of effector systems (mostly manual key presses; see e.g., Pashler, 1994), in everyday life we are often confronted with *cross-modal* task demands (see e.g., Huestegge & Hazeltine, 2011; Pieczykolan & Huestegge, 2017). That is, we usually have to coordinate motor execution in different effector systems simultaneously. In these situations, it can be vitally important to prioritize one of these systems. For example, imagine the driver of a car who is speaking to a co-passenger while navigating through traffic. In a potentially hazardous situation, it would be wise to prioritize a driving-relevant effector system (e.g., a pedal braking response) over vocal tract control (speaking) to avoid a car crash. Thus, in such dual-task situations one action should be prioritized over the other in that it receives the larger proportion of available cognitive resources.

This observation highlights the theoretical and practical importance of examining the role of effector systems and their specific combinations in dual-task research. The most important preliminary research here was a study of Huestegge and Koch (2013). In this study, Huestegge and Koch compared dual-task performance when two responses towards one and the same (auditory) stimulus should be executed by different effector systems.

Specifically, Huestegge and Koch (2013) asked participants to execute oculomotor, vocal, and manual responses in pairwise combinations. In a blocked design, participants should react either with only one or with both effector systems (always spatially congruent with the presented stimulus). By calculating dual-task costs (referred to in the paper as dual-response costs) as the difference in response latencies between the dual-task and the single-task condition for each effector system Huestegge and Koch (2013) demonstrated that interference was distributed asymmetrically among the involved tasks. More precisely, they observed that oculomotor responses were generally prioritized, that is, they were associated with smaller dual-task costs than vocal responses (in oculomotor-vocal response compounds) and manual responses (in oculomotor-manual response compounds). At first sight, this finding appears to be in line with the assumption of a “first come, first served” principle assuming that the selection of oculomotor responses was usually carried out first, in line with the observation that oculomotor responses were usually executed first.

However, when vocal responses were combined with manual responses the former exhibited no significant dual-task costs although they were usually executed as the second response. Nevertheless, manual responses, that were usually executed as first response and overall faster, were associated with substantial dual-task costs. This observation was theoretically meaningful, because it showed that in constant stimulus processing conditions it is possible that the overall slower response is prioritized in that it is associated with fewer dual-task interference (relatively to the overall faster response). This observation cannot be explained by effects of task order as indicated by the different reaction time (RT) levels, but ruled out any explanation based on a classic response selection bottleneck approach as well as based on any modification of this classic approach that refers to overall processing speed. Instead, this cost pattern was interpreted as a marker for task prioritization that has to be guided by specific effector system characteristics. Further, the observation of substantial vocal dual-task costs when combined with oculomotor responses (but not when combined with manual responses) indicates an overall flexible allocation of resources among tasks that, besides the executing effector system of one response, also takes the specific combination of effector systems into account.

Based on these observations, Huestegge and Koch (2013) introduced the idea of an ordinal prioritization pattern based on effector system characteristics in the form of a dominance of oculomotor over vocal over manual responses, similar to previously reported prioritization effects among perceptual processing systems (visual dominance, cf. Colavita, 1974; for a review see Spence, Parise, & Chen, 2012). This suggestion of an effector system-based ordinal prioritization could be strengthened by a replication of the proposed differences among effector systems in cross-modal action control with spatial S-R incongruent vs. congruent responses in a study by Pieczykolan and Huestegge (2014).

However, while these results clearly emphasize the importance of taking effector system characteristics into consideration when studying multiple action control, there are still important limitations that prevent generalizability to more typical dual-task control situations and theories. First, the single-onset paradigm employed in Huestegge and Koch (2013) as well as Pieczykolan and Huestegge (2014) is a special kind of dual-task paradigm in that both responses are triggered by a common aspect of one stimulus, thus yielding dual-response compounds (Fagot & Pashler, 1992). Such compound responses differ from two individually selected responses in a more typical dual-task situation involving distinct stimuli in each of the two tasks (that is, when each response is triggered independently based on a separate stimulus; cf. Pieczykolan & Huestegge, 2017; for a more detailed discussion see Pieczykolan & Huestegge, 2018). Despite the observation that results were similar regardless of whether participants should react spatially congruent to this single stimulus with both responses or spatially incongruent with one and congruent with the other response, we cannot completely be sure if two independent response selection processes took place. Fagot and Pashler (1992), for example, argued that when participants respond to only one attribute of a single stimulus, only one response selection occurs, as they found only a very slight slowing of responses by adding a second response to the same stimulus. This could, however, be crucial when we aim to understand underlying mechanisms of task prioritization, as limitations regarding the execution of two response selections in parallel are a major claim in most theoretical multitasking frameworks (e.g., Tombu & Jolicœur, 2003). Therefore, this constraint delimitates the generalization of the idea of a general ordinal prioritization pattern among effector systems in dual-task control.

Second, Huestegge and Koch (2013) found evidence for an ordinal prioritization pattern by studying pairwise combinations among three effector systems (oculomotor, vocal, and manual). However, relying on only three effector systems yielded a high a priori probability of finding a consistent ordinal prioritization pattern (e.g., a pattern without circular triads like A > B, B > C, but C > A). Much stronger evidence for the existence of a consistent effector system prioritization structure would be a pattern without circular triads based on more than three effector systems. Furthermore, given evidence for oculomotor dominance over manual and vocal responses (cf. Huestegge & Koch, 2013; Pieczykolan & Huestegge, 2014; see also Huestegge & Koch, 2009, 2010; Huestegge, Pieczykolan, & Koch, 2014) every outcome of a manual-vocal combination would have yielded an ordinal structure (either oculomotor > vocal > manual or oculomotor > manual > vocal, without the possibility of a circular triad as long as oculomotor responses are prioritized over both other effector systems).

Third, by using exclusively auditory stimuli in the previous studies, it was not possible to pinpoint the influence of the stimulus modality on resource allocation in these observations. In the next section, a detailed explanation will follow why it indeed appears crucial to control for a potential influence of stimulus modality and the specific relation of stimulus to response modality to generalize any observation of effector system prioritization.

1.3.2 The Interplay of Effector System and Stimulus Modality

Besides the limitations regarding generalizability of the ordinal prioritization pattern proposed by Huestegge and Koch (2013) described above, one important constraint that so far has not yet been investigated sufficiently concerns the influence of stimulus modality on potential effector system prioritization. Crucially, by using only one stimulus and therefore only one stimulus modality, namely auditory lateral sine tones (Huestegge & Koch, 2013; Pieczykolan & Huestegge, 2014), the potential influence of stimulus modality as well as the specific combination of stimulus and response modalities remained elusive. However, this appears relevant given previous reports, for instance, regarding input system prioritization (e.g., Spence et al., 2012).

Moreover, numerous studies have shown that the combination of stimulus and response modalities affects performance in dual-task control (input-output modality compatibility [IOMC] effect, Göthe, Oberauer, & Kliegl, 2016; Halvorson, Ebner, & Hazeltine, 2013; Hazeltine, Ruthruff, & Remington, 2006; Stelzel & Schubert, 2011; Stelzel, Schumacher, Schubert, & D'Esposito, 2006; see also Stephan & Koch, 2010, 2011; Stephan, Koch, Hendler, & Huestegge, 2013, for an approach to IOMC effects in task switching). That is, responses in some stimulus response (S-R) modality pairings typically suffer from less dual-task interference than other pairings. Specifically, performance costs in manual-vocal dual tasking have been observed to be overall smaller when manual responses were mapped to visual stimuli and vocal responses to auditory stimuli than when the S-R modality assignment was reversed (e.g., Hazeltine et al., 2006; Stelzel et al., 2006). This has been demonstrated several times, for example, by showing better overall performance regarding dual-task costs (Göthe et al., 2016; Hazeltine et al., 2006), but also regarding shift costs in task switching (e.g., Stephan et al., 2013; Stephan & Koch, 2010, 2011).

As an explanatory approach to understand the mechanisms causing this difference in dual-task performance, the assumption has been discussed that specific effector system characteristics (especially typical perceptual after-effects of responses in a certain modality) affect how easily specific stimulus-response modality combinations can be associated (Stephan et al., 2013; Stephan & Koch, 2010). For example, vocal utterances normally result in a sound that is also perceived by the person who produced it. Manual actions, in contrast, often produce effects that can be perceived visually. Congruently, S-R modality bindings are assumed to be stronger in those mappings in which stimulus modality and sensory effects of a response resemble each other (compared to a reversed assignment).

While IOMC effects have been repeatedly shown in dual-task settings combining manual and vocal responses (triggered by visual and auditory stimuli), there is first evidence from the related research field of task switching that no equivalent IOMC effect is observed when the oculomotor effector system is involved (Stephan et al., 2013). This is probably due to specific characteristics of the oculomotor system. Taken together, the hitherto existing observations demonstrate the importance of examining the role of S-R modality mappings in effector system prioritization.

1.4 Overview of the Present Work

1.4.1 General Methodological Approach and Paradigms

The present work intends to fill the gap identified above by systematically addressing effector system prioritization in the field of multitasking. To be more precise, in situations in which typical dual-task paradigms are involved, one might now also refer to such effects as effector system-based task prioritization. In the present work effector system-based task prioritization is compared using different markers of multitasking decrements. The role of stimulus modality and the combination of stimulus and response modalities in effector system prioritization processes will be examined, too.

Moreover, in the first study of this work, Study A, also pedal responses are included, a response modality that to date is utilized seldom in dual-task research (but see Liepelt, Fischer, Frensch, & Schubert, 2011; Naefgen, Caissie, & Janczyk, 2017; Sangals, Wilwer, & Sommer, 2007, for notable exceptions). The fact that so far relatively little is known about the role of the pedal system in dual-task control can be considered as somewhat surprising, as cross-modal situations involving pedal movements are frequent in everyday life due to the high relevance of pedal control in standing, walking, or driving. As foreshadowed above, there are three common dual-task paradigms that will be addressed separately in the present work, as each can provide us with different insights regarding task prioritization processes.

The first approach is the *simultaneous (stimulus) onset paradigm*, in which dual-task performance is compared to single task performance (e.g., Schumacher et al., 2001; Stelzel et al., 2006). The difference in performance parameters between these two conditions results in dual-task costs that represent dual-task interference. In this paradigm, two stimuli are presented at exactly the same time, and participants are instructed to fulfil either one or two independent tasks in accordance to the two stimuli. There is no externally suggested task order and, consequently, no resource allocation policies that could be rooted in task order-based prioritization (as, in contrast, e.g., in the PRP paradigm). Nevertheless, such dual-task costs can still be distributed asymmetrically among tasks, a phenomenon that in the present work will be used as a marker for effector system prioritization.

Second, in the *PRP (psychological refractory period) paradigm* (Kahneman, 1973; Pashler, 1984, 1994; Telford, 1931; Welford, 1952), two tasks triggered by two different stimuli have to be processed while overlapping in time. However, in contrast to the simultaneous onset paradigm, in the PRP paradigm these two stimuli are presented with a varying short temporal delay, the so-called stimulus onset asynchrony (SOA). Usually, participants are instructed to respond to the two stimuli in the same order as presented. Thus, there is already an externally suggested (and often explicitly instructed) order of task processing. This leads to a typical result pattern that is referred to as PRP effect. Specifically, a decrease in SOA leads to an increase in Task 2 RTs, while Task 1 RTs remain largely unaffected by SOA. This has often been interpreted as evidence for a prioritization of Task 1 over Task 2 based on externally determined task order in an all-or-none fashion (response selection bottleneck; cf. Pashler, 1994; see Section 1.2).

Lastly, also in the *task switching paradigm* requirements of more than one task have to be coordinated. However, in this case tasks do not actually overlap temporally. Rather, participants have to rapidly switch between two (or more) tasks, while the representation of both task sets has to be kept active throughout (e.g., Allport, Styles, & Hsieh, 1994; Philipp & Koch, 2005, 2011; Rogers & Monsell, 1995; Stephan et al., 2013; Stephan & Koch, 2010, 2011, 2016). Note that a task set is typically defined as the cognitive representation of task requirements including intentions, stimuli, potential responses, and the mappings of stimuli to responses (cf. e.g., Monsell, 1996, 2003; Vandierendonck, Christiaens, & Liefooghe, 2008). Emanating performance costs have been observed repeatedly. Typically, performance is impaired in repetition trials within mixing blocks compared to performance in mere repetition (i.e., single task) blocks (*mixing costs*), as well as in switch trials compared to repetition trials within mixing blocks (*switch costs*). Again, these kinds of multitasking costs are often distributed unevenly among tasks.

Taken together, the present work systematically compares the influence of different effector systems on performance in the most relevant multitasking paradigms typically used in cognitive psychology. It comprises the presentation of four studies that systematically address the role of effector system characteristics as well as their relation to the associated stimulus modalities in multitasking control.

Study A compares dual-task costs among tasks involving the oculomotor, pedal, vocal, and manual effector system in six pairwise combinations when simultaneously triggered by an auditory and a visual stimulus with varied stimulus to response (S-R) modality mappings. This approach is similar to previous work of Huestegge and Koch (2013) and Pieczykolan and Huestegge (2014), apart from the crucial distinction that in these previous studies only one single (auditory) stimulus and therefore no distinct stimuli for each response was used, and the pedal system was neglected. Based on this prior work, we hypothesized to observe an ordinal pattern among effector systems without any circular triads. Specifically, we expected smaller dual-task costs associated with oculomotor compared to vocal or manual tasks, and smaller dual-task costs for vocal than for manual tasks. Beyond that, it should be possible to readily integrate the pedal effector system in the suggested effector system prioritization pattern without violating its ordinal structure. Note that the design presented here is the first to compile a systematic pairwise comparison of oculomotor, vocal, manual, but also pedal responses within a typical dual-task setting using two types of input modalities.

Because the combination of the vocal and the manual effector system and especially the role of the stimulus modality for vocal prioritization yielded ambiguous results in Study A (and also in former research), Study B addresses this specific combination in a typical dual-task situation (and without externally suggested task order) using intra-modal (either only visual or only auditory) stimulation. We expected to observe a prioritization of vocal over manual responses throughout. Nevertheless, the extent of prioritization might be modulated by stimulus modality. Thereby, we can rule out any alternative explanation for vocal-over-manual prioritization observed in previous studies in terms of input-output modality compatibility (cf. e.g., Greenwald, 1972, 2003; Hazeltine et al., 2006; Stephan & Koch, 2010, 2011). Note that we control for IOMC effects by using both possible stimulus to response modality mappings in one study (Study A), while we explicitly address the issue of whether effector system prioritization differs when using either only visual or only auditory (intra-modal) stimulation conditions in another study (Study B), both using the simultaneous onset paradigm.

Study C deals with the issue of the relation of two sources of task prioritization, the well investigated effects of externally suggested task order (elicited by SOA) on the one hand and effector system prioritization on the other hand. To do so, PRP effects associated with oculomotor, vocal, and manual responses (under otherwise controlled conditions) are compared in the context of the PRP paradigm. We hypothesized that effector system prioritization is not fully cancelled out by effects of task prioritization based on externally determined task order. Rather, effector systems might affect the size of PRP effects.

Lastly, Study D examines potential effector system-based differences in mixing costs and switch costs in the task switching paradigm. This paradigm provides especially interesting theoretical insight when combining two tasks differing only in the associated effector systems, as this is a factor in a task set that is typically assumed to mainly influence processes of response execution (i.e., late processes). By examining whether or not we observe systematic differences in switch costs based on different effector systems, we aim to answer whether the mere cognitive representation of an effector-specific task can evoke effector system prioritization. Moreover, these performance cost asymmetries should be in line with the prioritization pattern found in the previous studies. Taken together, the results of these four studies give a detailed insight in how multitasking processes are influenced by the specific effector systems and their combination.

1.4.2 Synopsis of Studies

1.4.2.1 Summary of Study A

Performing two actions at once (vs. one in isolation) usually leads to performance costs. Typically, such costs are distributed asymmetrically whenever different effector systems are involved. Under suitable conditions, this asymmetry can be interpreted as a marker for effector system prioritization, that is, the effector associated with relatively smaller dual-task costs is prioritized over the other. Based on this rationale, an ordinal prioritization pattern among effector systems has been suggested, in which oculomotor responses are prioritized over vocal and manual responses while vocal responses are prioritized over manual responses. However, previous studies were limited in that they involved only a small set of effector systems, never focused on typical dual-task situations (in which two distinct tasks need to be processed simultaneously), and never considered the role of stimulus-response (S-R) modality mapping. In Study A, we comprehensively investigate dual-task cost asymmetries in pairwise combinations of tasks requiring oculomotor, manual, vocal, and pedal responses triggered by visual and auditory stimuli. Overall, the pattern of observed dual-task cost asymmetries was in line with the assumption of an ordinal prioritization pattern among effector systems (oculomotor > pedal > vocal > manual). While the S-R modality mapping affected dual-task cost patterns in some task combinations, it did not substantially change the prioritization scheme in general, suggesting a substantial influence of output (compared to input) systems on dual-task resource scheduling. The present results call for including a distinct effector system weighting mechanism in dual-task control models and highlight the impact of (peripheral) effector systems on (central) resource scheduling. Note that based on these data a paper has been published in a peer-reviewed journal (Hoffmann, Pieczykolan, Koch, and Huestegge, Journal of Experimental Psychology: Human Perception and Performance, 2019). Thus, Study A represents a modified version and supplementary considerations of this published paper.

1.4.2.2 Summary of Study B

Executing two responses at once typically leads to impaired reaction speed and accuracy in comparison to single-task situations. However, these performance costs are often distributed asymmetrically among responses, reflecting differences in resource allocation among tasks. Huestegge and Koch (2013) found first evidence for the influence of effector systems on allocation processing priorities to the particular responses by showing prioritized processing of vocal over manual responses when using one common auditory stimulus. This finding is especially interesting considering that manual responses were overall executed faster than vocal responses. This indicated that the distribution of limited resources between two tasks cannot sufficiently be explained by a "first come, first served" account. However, it remains an open issue whether the observed prioritization was indeed mainly driven by effector system characteristics, or rather by the particular case of modality compatibility for vocal responses with auditory stimulation, which is known to improve dual-task performance (input-output modality compatibility; see Hazeltine et al., 2006). It also remained unresolved whether prioritizing vocal over manual responses is restricted to the special case of interdependent dual responses based on a common stimulus or whether vocal-over-manual effector system prioritization generalizes to more typical dual-task settings with separate stimulation for the two responses. In Study B, we studied prioritization patterns for dual-task settings involving manual and vocal responses triggered by two independent aspects of a single stimulus. Specifically, we compared dual-task costs associated with the two effector systems with separate, either visual or auditory stimulus modality conditions. As a result, we observed prioritized processing of vocal over manual responses in both stimulus modality conditions. This effector system prioritization was even more pronounced under auditory stimulation conditions. Consequently, our results extend the validity of previous findings of hierarchical prioritization and resource allocation among effector systems by demonstrating vocal-over-manual prioritization for dual tasks with independent component task demands that cannot be explained by specific input-output modality combinations. On the other hand, we showed that the extent of effector system prioritization was indeed dependent on the particular sensory modality, while the effector system hierarchy itself was not. Note that based on these data a paper is currently under consideration in a peer-reviewed journal (Hoffmann, Westermann, Pieczykolan, & Huestegge, under review). Consequently, reports regarding Study B also represent a modified version of the existing submitted manuscript.

1.4.2.3 Summary of Study C

In the PRP paradigm two tasks are triggered by two sequentially presented stimuli and therefore with a short temporal delay, the so-called stimulus onset asynchrony (SOA). A decrease in SOA typically leads to an impairment of performance primarily in form of longer response latencies for the task associated with the second stimulus (Task 2). Interestingly, performance of Task 1 (the task associated with the firstly presented stimulus) remains mainly unaffected by SOA. This pattern is usually referred to as the PRP effect and has often been interpreted in terms of an allocation of limited central resources in an all-or-none fashion (cf. response selection bottleneck; see Section 1.2). Specifically, it has been assumed that response selection in Task 1 is prioritized in that response selection of Task 2 is delayed until the former has been completed. Recently, another important factor determining task prioritization (indexed by asymmetrical dual-task costs) has been proposed, namely the particular effector systems associated with tasks. In Study C, we aim at studying both sources of task prioritization simultaneously by systematically combining three different effector systems (pairwise combinations of oculomotor, vocal, and manual responses) with sequential stimulus presentation. Specifically, we examine whether task prioritization based on externally suggested task order (reflected in PRP effects) is modulated as a function of the effector system associated with Task 2. The results indicate a modulation of the PRP effect when the same (oculomotor) Task 1 is combined with either a vocal or a manual Task 2. These observations are incompatible with the assumption that the PRP effect is solely determined by Task 1 response selection duration. Instead, they support the view that dual-task processing bottlenecks are resolved by establishing a resource allocation scheme, which additionally takes the particular utilized effector systems into account. A third paper has recently been submitted for publication in a peer-reviewed journal based on the data and considerations presented in Study C (Hoffmann, Pieczykolan, Koch, & Huestegge, under review).

1.4.2.4 Summary of Study D

In the task switching paradigm participants switch between two (or more) tasks in an often unpredictable sequence of trials. As a consequence, performance is typically worse in task alternation trials than in task repetition trials. These switch costs are often distributed asymmetrically among tasks, which is usually explained by referring to processes related to task set configuration or inhibitory mechanisms. Previous studies indicated that effector systems associated with two tasks might be considered an integral component for defining a task set. Study D systematically compares switch costs when combining tasks that differ in their associated effector systems. In Experiment 1, participants switched (in unpredictable sequence) between oculomotor and vocal tasks. In Experiment 2, participants switched among oculomotor, vocal, and manual tasks (in pairwise combinations). Crucially, although we observed systematic differences in switch costs between tasks executed in the vocal vs. the manual system (i.e., switch costs were greater when switching to the vocal task compared to switching to the manual task), the results did not reflect a prioritization of the oculomotor system in task switching. This observation appears to be at odds with previous observations of oculomotor effector system prioritization in dual-task paradigms requiring simultaneous actions in different effector systems. Overall, the results demonstrate the importance of temporally overlapping task demands for observing typical effector system-based prioritization effects. A fourth paper based on data and considerations presented in Study D is currently in preparation and close to submission to a peer-reviewed journal.

2. Study A: Flexible Resource Scheduling in Dual-Task Control

2.1 Introduction

Former research regarding cognitive processing of actions in multitasking usually made use of only a very restricted range of effector systems (i.e., mostly of manual key presses). However, in daily life we are often confronted with situations that require cross-modal actions, that is, actions across multiple effector systems. Interestingly, while most studies in multitasking research concentrated on studying negative effects of dual tasking on performance, the role of effector system prioritization has barely been addressed. Therefore, the purpose of the present study is to investigate underlying mechanisms of effector system prioritization in dual-task control.

Due to a limitation of cognitive resources in order to process tasks efficiently, performing two actions simultaneously usually leads to higher error rates and longer reaction times (RTs) than when performed separately (e.g., Kahneman, 1973; Koch et al., 2018; Navon & Miller, 1987; Pashler, 1994). Such performance decrements yielded by dual tasking (i.e., dual-task costs) can be analysed for each component task. Interestingly, dual-task costs are often distributed unevenly among tasks. That is, one task exhibits greater dual-task costs than the other, especially whenever two different effector systems are involved (Fagot & Pashler, 1992; Holender, 1980; Huestegge & Koch, 2009, 2010; Schumacher et al., 2001; Stelzel et al., 2006). Such asymmetries can be interpreted as a marker for task prioritization in that the task with smaller dual-task costs is prioritized over the one associated with greater costs (Huestegge & Koch, 2013).

One classic experimental approach that can be used to study underlying mechanisms behind dual-task costs is the psychological refractory period (PRP) paradigm (Kahneman, 1973; Navon & Miller, 2002; Pashler, 1984, 1994; Telford, 1931; Welford, 1952). In the PRP paradigm, two stimuli are presented sequentially: the second stimulus follows the first stimulus after the so-called stimulus onset asynchrony (SOA), a short variable temporal delay. This typically leads to the finding of dual-task costs in RTs in the second response, while the first response stays mainly unaffected by the temporal interval between the two tasks. This can be interpreted as indicating a prioritization of processing the first task. An often discussed explanatory approach for this observation is the assumption of a central cognitive bottleneck within a three-stage framework (stimulus processing, response selection, response execution) of task processing (Pashler, 1994; see also Section 1.2). The response selection bottleneck model assumes that response selection in the second task has to be delayed until response selection in the first task is completed, since prior to that all cognitive resources are absorbed by the latter. Thus, Task 2 RTs are prolonged for short SOAs. A consequence of this framework is that, by definition, the first response is always prioritized over the second response, which is eventually reflected in both response order and dual-task cost asymmetry. In such a model, this should be independent of effector systems, but instead rely completely on the endpoint of stimulus processing, thereby following a "first come, first served" principle.

Indeed, empirical evidence has been observed that sometimes also the second of two simultaneously triggered responses can be relatively prioritized. Specifically, Huestegge and Koch (2013) studied dual-task costs (i.e., the difference between dual- and single-response RTs, also referred to as dual-response costs, due to the specificity of the used dual-task setting) in pairwise combinations of simultaneous oculomotor, manual, and vocal responses (see also Section 1.3.1). Instead of separate stimulus presentation typical for dual-task studies, they utilized a single-onset paradigm, in which the same aspect of a stimulus (a tone on the left vs. right ear) triggered both responses (i.e., a cross-modal response compound) in dual-response conditions (e.g., Fagot & Pashler, 1992; Huestegge et al., 2014; Huestegge & Koch, 2009, 2010; Pieczykolan & Huestegge, 2014, 2017, 2018). They observed systematic differences among effector systems in that oculomotor responses were associated with smaller dual-response costs than vocal or manual responses, and vocal responses were associated with smaller dual-response costs than manual responses when pairwise combined, respectively. Especially the latter finding is clearly inconsistent with a "first come, first served" model, as in the vocal-manual combination manual responses were executed faster overall but still associated with greater dual-response costs. Instead, this is more in line with an alternative view that has been proposed for explaining costs associated with multiple action demands, namely flexible (parallel) resource sharing (Navon & Miller, 2002; Tombu & Jolicœur, 2003). Resource sharing frameworks presume that multitasking costs arise because cognitive resources must be divided between the two action demands, since resources are too limited to allow for unimpaired parallel task processing (see Section 1.2, for more details).

The findings of Huestegge and Koch (2013) suggest that resource allocation could depend on specific effector system characteristics. In particular, their results were in line with the idea of the existence of an ordinal general prioritization structure among effector systems. Furthermore, they observed that dual-response costs did not only differ between effector systems but that dual-response costs of the same (vocal) response were greater when combined with an additional oculomotor than with a manual response (see also Pieczykolan & Huestegge, 2014). This observation demonstrates that the context effector system affects the amount of dual-response costs that a specific effector system suffers. Together, these previous observations demonstrate that resource allocation is highly dependent on the effector system itself as well as on the specific combination of effector systems.

However, there are still some limitations regarding the generalisability of a systematic effector system prioritization as proposed by Huestegge and Koch (2013) regarding more typical dual-task situations. First, due to the use of one stimulus for both responses (probably promoting dual-response compounds; cf. also Fagot & Pashler, 1992; Pieczykolan

& Huestegge, 2014, 2017, 2018), we cannot ensure if two separate response selections have taken place. Possibly, participants just copied response codes of the first executed task to the second task (as both required responses were always interconnected, either always spatially congruent or always spatially incongruent, in the case of Pieczykolan & Huestegge, 2014). Second, by examining three pairwise combinations of three effector systems, the study of Huestegge and Koch (2013) was associated with a relatively high a priori probability to find a consistently ordinal hierarchical pattern without any circular triads. Third, due to the use of exclusively auditory stimuli, we cannot asses any potential influence on effector system prioritization by stimulus modality or stimulus to response modality combinations in terms of input-output modality compatibility (IOMC; Göthe et al., 2016; Halvorson et al., 2013; Hazeltine et al., 2006; Stelzel et al., 2006; Stelzel & Schubert, 2011; Stephan et al., 2013; Stephan & Koch, 2010, 2011). According to the idea of input-output modality compatibility, vocal response are assumed to have a naturally especially good fit to auditory stimuli and manual responses correspondingly to visual stimuli, resulting in smaller overall dual-task costs in compatible (auditory-vocal visual-manual) compared to reversed and therefore incompatible (auditory-manual visual-vocal) stimulus-response modality mappings (see Section 1.3, for a more detailed discussion regarding these limitations and potential underlying mechanisms of IOMC effects).

To systematically address these limitations, in the present study we employed the simultaneous onset paradigm (Schumacher et al., 2001; Stelzel et al., 2006) by presenting two distinct stimuli simultaneously (i.e., with an SOA = 0 ms). If effector system prioritization also holds for more typical dual-task settings, we should observe asymmetrical dual-task costs based on effector system characteristics in line with the prioritization structure suggested by Huestegge and Koch (2013) in the context of response compounds. Consequently, oculomotor responses should exhibit fewer dual-task costs when compared to performance decrements exhibited in vocal or manual tasks (oculomotor prioritization; see also Pieczykolan & Huestegge, 2014). Furthermore, vocal responses should exhibit smaller dual-task costs than manual responses, indicating prioritization of vocal over manual responses.

Moreover, we extended the range of effector systems by adding pedal responses to explore whether they can be consistently integrated into the previously suggested prioritization scheme without contradicting its ordinal logic. Consequently, in the present study, we aim at focusing on resource allocation among independent tasks executed by four different effector systems. Interestingly, pedal responses have relatively seldom been studied in multitasking research (Liepelt et al., 2011; Naefgen et al., 2017; Sangals et al., 2007). Consequently, little is known about the role of characteristics of the pedal effector system in dual-task control, although foot control is constantly relevant in everyday life (i.e., when walking, standing, driving). It seems plausible that characteristics of foot movements are similar to those of manual movements as both represent limbs. This would suggest a place close to the manual system in the prioritization structure. On the other hand, it is just as well possible that particularly strong prioritization of foot responses can be observed due to a general important role of foot control in everyday life, for instance, regarding maintaining balance (e.g., Beurskens, Haeger, Kliegl, Roecker, & Granacher, 2016; Beurskens, Helmich, Rein, & Bock, 2014; Beurskens & Bock, 2012; Granacher, Muehlbauer, & Gruber, 2012, for reviews). Six experiments are reported in the present study in which all four effector systems are combined in a pairwise manner. In this way, we are able to gather reliable evidence for or against the assumption of an ordinal structure of effector system prioritization.

Lastly, to gather more insight regarding the influence of stimulus modality or stimulus-response modality mappings, we implemented auditory and visual stimuli. Crucially, systematically manipulating the S-R modality mapping in each dual-task experiment allows us to assess its influence on performance in terms of dual-task costs. While we expect the typical

IOMC effect for the combination of the manual and the vocal effector system, our S-R modality mapping manipulation can additionally reveal if similar IOMC effects also play a role for other effector system combinations. However, the main purpose of this manipulation was to explore a potential influence of S-R modality mappings on effector system prioritization. Especially, we wanted to examine whether dual-task cost asymmetries are modulated by S-R modality mapping. Two contrasting outcomes are conceivable: If the dual-task cost asymmetry pattern is not affected by the S-R modality mapping, then resource allocation among the effector systems would be solely based on effector system characteristics. Alternatively, if S-R modality mapping affects the effector system prioritization structure, this would suggest a rather flexible prioritization scheme that is additionally based on the strength of the particular modality-based S-R processing pathways involved.

As we combined tasks executed in four different effector systems in a pairwise manner, we conducted six experiments overall in which we combined oculomotor-vocal, oculomotor-pedal, oculomotor-manual, pedal-vocal, pedal-manual, and vocal-manual dual tasks (in this order referred to as Experiments 1-6). In order to examine how effector systems as well as specific effector system combinations determine resource allocation policies, we analysed dual task-associated performance decrements according to three rationales. First, we compared dual-task costs between the two respective effector systems within each experiment to compare corresponding resource policies within each pairwise effector system combination. Second, we wanted to investigate the influence of the effector system associated with a respective context task on dual-task interference within effector systems. Specifically, we compared dual-task costs for each effector system as a fixed focus task as a function of the effector system associated with the respective context task, that is, across experiments. Lastly, we examined whether the proposed ordinal effector system structure can also be observed across experiments under constant context requirements, that is, across tasks in different effector systems that are combined with a fixed context task executed in the same (fixed) effector system, respectively.

2.2 Experiment 1 – Oculomotor-Pedal

2.2.1 Method

Participants

A power-analysis using the smallest partial eta-square (= .30) regarding the crucial interaction (indicating a cost asymmetry) in the results of Huestegge and Koch (2013) with an alpha of 5% and a power of 95% revealed an optimal sample size of ten participants. Due to counterbalancing, due to the assumption that cost asymmetry effects might be smaller for some effector system combinations, and because we were also interested in the potential influence of S-R modality mapping on cost asymmetries, we decided to test 24 participants in each experiment. Regarding Experiment 1, data of seven participants had to be excluded because they consisted of more than 35% invalid trials. Furthermore, one participant aborted the experiment due to physical discomfort. In order to ensure full counterbalancing and same sample size per experiment we substituted these with data of eight new participants. Mean age of the final sample was 22.7 years (*SD* = 2.7). One of the twenty-four participants was male. All were right-handed and had normal or corrected-to-normal vision and hearing. They gave informed consent and received course credits or monetary compensation for participation. All participants were recruited from the local university's student panel and were naïve about the aim of the study.

Apparatus and Stimuli

Participants were seated approx. 67 cm in front of a 21-inch cathode ray tube screen with a temporal resolution of 100 Hz and a spatial resolution of 1024 x 768 pixels. An eye tracker sampling eye movements at 1000 Hz (Eyelink 1000, SR Research Mississauga, Ontario, Canada) was utilized to register saccade latencies and amplitudes of the right eye, while head movements were minimized by means of a chinrest with forehead support. To register pedal responses we utilized a custom-made foot pedal device consisting of two (left/right) switches. This custom-build device registered as a USB computer mouse (standard USB-HID protocol). Before the experiment, participants familiarized themselves with the foot pedal in terms of haptic feedback and required pressure. For reasons of comparability, pedal responses were always executed with the same (right) foot. A designated area in the middle between the two switches was used as a resting position where the foot should be placed between responses (comparable to central fixation for eye movements, but also a central resting position of the finger used in Experiment 3, 5, and 6).

Experiment Builder (version 1.10.163, SR Research) was used to run the experiment and to log response events. Throughout each block, a green fixation cross (size = 0.43° of visual angle) at the centre of a black background and two green rectangular squares at an eccentricity of 8.5 degrees of visual angle (size = 0.43° each) to the left and right of the central fixation cross remained present on the screen. Visual stimuli consisted of a green arrow presented 0.43° over the fixation cross that pointed either to the right or to the left (“<” or “>”, size = 0.86°). Auditory stimuli consisted of 1000 Hz sinusoidal tones that were presented to either the right or the left ear via supra-aural headphones.

Procedure

Each block started with an instruction screen which informed participants about the tasks (single pedal, single oculomotor, and dual task) and the S-R modality mapping (visual-oculomotor & auditory-pedal (VO-AP) or visual-pedal & auditory-oculomotor (VP-AO)). This was followed by a three-point horizontal calibration routine. In each trial (in both single- and dual-task conditions), the visual arrow and the auditory signal were presented simultaneously for 80 ms. There were four possible stimulus combinations (i.e., left vs. right arrow + left vs. right auditory signal) that occurred equally often in each experimental condition. Participants were instructed to focus on the central fixation cross and to place their foot on the resting position of the foot pedal device at the beginning of each trial. The pedal task was to press the spatially congruent key/switch in response to the direction/location of the stimulus (either visual or auditory depending on the current S-R modality mapping) and then to return to the central resting area. In blocks requiring an oculomotor response (single-oculomotor and dual-task conditions), participants were instructed to move their gaze to the spatially congruent target square (to the left/right of the fixation cross) and to return to the central fixation cross afterwards. The interstimulus interval (ISI) was 3000 ms irrespective of response execution (in consistence with Huestegge & Koch, 2013 and further studies in related fields, e.g., Huestegge et al., 2014). All participants completed a sequence of 3 (oculomotor, pedal, dual) x 2 (S-R modality mapping) x 3 (=18) blocks with each block containing 32 randomized trials. The order of single-oculomotor, single-pedal, and dual-task blocks was counterbalanced across participants but constant within participants (i.e., each participant repeated a specific sequence of the three different task blocks three times in a row for one S-R modality mapping). The S-R modality mapping was switched after half of the experiment (i.e., after nine blocks). One half of the participants started with the visual-oculomotor & auditory-pedal mapping, the other half with the visual-pedal & auditory-oculomotor mapping.

Design

Independent within-subject variables were effector system (oculomotor vs. pedal), task condition (single vs. dual) and S-R modality mapping (VO-AP vs. VP-AO). As dependent variables we measured RTs and error rates.

2.2.2 Results and Discussion

The most important statistical test results regarding the six experiments are summarized in Table 2.1 (three-way ANOVAs regarding RTs with the independent within-subject variables effector system, task condition, and S-R modality mapping) and Table 2.2 (the same three-way ANOVAs regarding accuracy), while the RT pattern across experiments is depicted in Figure 2.1 and corresponding dual-task costs as difference measurement are depicted in Figure 2.2. In the following, statistical indices presented in Table 2.1 or Table 2.2 will not be reiterated for the sake of brevity.

2.2.2.1 Data Treatment

Invalid trials (trials in which a commission or omission error occurred) as well as outliers (trials in which RTs differed more than two standard deviations from the individual mean of each participant and block condition) were excluded from all further analyses. In the next step, all trials in which directional errors occurred for oculomotor or pedal responses (e.g., left instead of right) were defined as errors. This resulted in 78.5% valid data with a mean accuracy of 79.8%. Only valid and correct trials were included in the RT analyses.

2.2.2.2 Reaction Times

Oculomotor responses ($M = 446$ ms) were significantly faster than pedal responses ($M = 969$ ms), and single-task responses ($M = 561$ ms) were significantly faster than dual-task responses ($M = 854$ ms), as indicated by significant main effects of effector system and task condition, respectively. Crucially, the significant interaction of effector system and task condition indicates that dual-task costs were significantly smaller for oculomotor responses ($M = 243$ ms) than for pedal responses ($M = 343$ ms). Importantly, these asymmetrical dual-task costs can be interpreted as an indication that the oculomotor effector system was prioritized over the pedal system.

Table 2.1

Overview of statistical test results of the three-way ANOVAs with independent variables effector system, task condition, and S-R modality mapping regarding RTs.

	Effector System Combination																	
	Oculomotor-Pedal			Oculomotor-Vocal			Oculomotor-Manual			Pedal-Vocal			Pedal-Manual			Vocal-Manual		
Source of Variation	$F(1, 23)$	p	η^2_p	$F(1, 23)$	p	η^2_p	$F(1, 23)$	p	η^2_p	$F(1, 23)$	p	η^2_p	$F(1, 23)$	p	η^2_p	$F(1, 23)$	p	η^2_p
Effector System	600.79	< .001	.96	682.74	< .001	.97	218.58	< .001	.91	6.09	.021	.21	18.58	< .001	.45	123.30	< .001	.84
Task Condition	380.20	< .001	.94	164.38	< .001	.88	229.69	< .001	.91	316.65	< .001	.93	279.82	< .001	.92	283.23	< .001	.93
S-R Modality Mapping	1.14	.297	.05	31.44	< .001	.58	0.11	.740	.01	4.41	.047	.16	0.58	.453	.03	2.18	.153	.09
Effector System x Task Condition	17.87	< .001	.44	48.59	< .001	.68	49.71	< .001	.69	10.11	.004	.31	14.43	.001	.39	1.40	.248	.06
Effector System x S-R Modality Mapping	18.92	< .001	.45	0.56	.463	.02	14.98	.001	.39	5.94	.023	.21	7.74	.011	.25	2.78	.109	.11
Task Condition x S-R Modality Mapping	0.89	.354	.04	27.15	< .001	.54	0.13	.727	.01	7.39	.012	.24	0.26	.613	.01	4.15	.053	.15
Effector System x Task Condition x S-R Modality Mapping	4.64	.042	.17	1.69	.207	.07	3.49	.075	.13	0.41	.529	.02	1.14	.242	.06	0.47	.501	.02

Note. The cost asymmetry effect, which is the focus of the research question, is reflected in the interaction effect of effector system and task condition, while any modulation of this effect by S-R modality mapping would be reflected in the three-way interaction of effector system, task condition, and S-R modality mapping.

Table 2.2

Overview of statistical test results of the three-way ANOVAs with independent variables effector system, task condition, and S-R modality mapping regarding accuracy

	Effector System Combination																	
	Oculomotor-Pedal			Oculomotor-Vocal			Oculomotor-Manual			Pedal-Vocal			Pedal-Manual			Vocal-Manual		
Source of Variation	$F(1, 23)$	p	η^2_p	$F(1, 23)$	p	η^2_p	$F(1, 23)$	p	η^2_p	$F(1, 23)$	p	η^2_p	$F(1, 23)$	p	η^2_p	$F(1, 23)$	p	η^2_p
Effector System	187.42	< .001	.89	12.78	.002	.36	21.68	< .001	.49	1.35	.257	.06	5.13	.033	.18	4.58	.043	.17
Task Condition	150.52	< .001	.87	42.21	< .001	.65	105.94	< .001	.82	39.35	< .001	.63	28.19	< .001	.55	17.94	< .001	.44
S-R Modality Mapping	11.11	.003	.33	25.75	< .001	.53	2.84	.105	.11	16.15	.001	.41	1.32	.262	.05	8.53	.008	.27
Effector System x Task Condition	21.36	< .001	.48	2.69	.115	.11	19.34	< .001	.48	8.87	.007	.28	3.41	.078	.13	8.92	.007	.28
Effector System x S-R Modality Mapping	102.48	< .001	.82	29.11	<.001	.56	19.01	<.001	.45	5.16	.033	.18	5.05	.035	.18	15.73	.001	.41
Task Condition x S-R Modality Mapping	0.51	.483	.02	9.63	.005	.30	0.83	.371	.04	13.82	.001	.38	2.26	.146	.09	12.91	.002	.36
Effector System x Task Condition x S-R Modality Mapping	30.01	<.001	.57	10.42	.004	.31	21.39	<.001	.48	16.89	<.001	.42	7.70	.011	.25	7.27	.013	.24

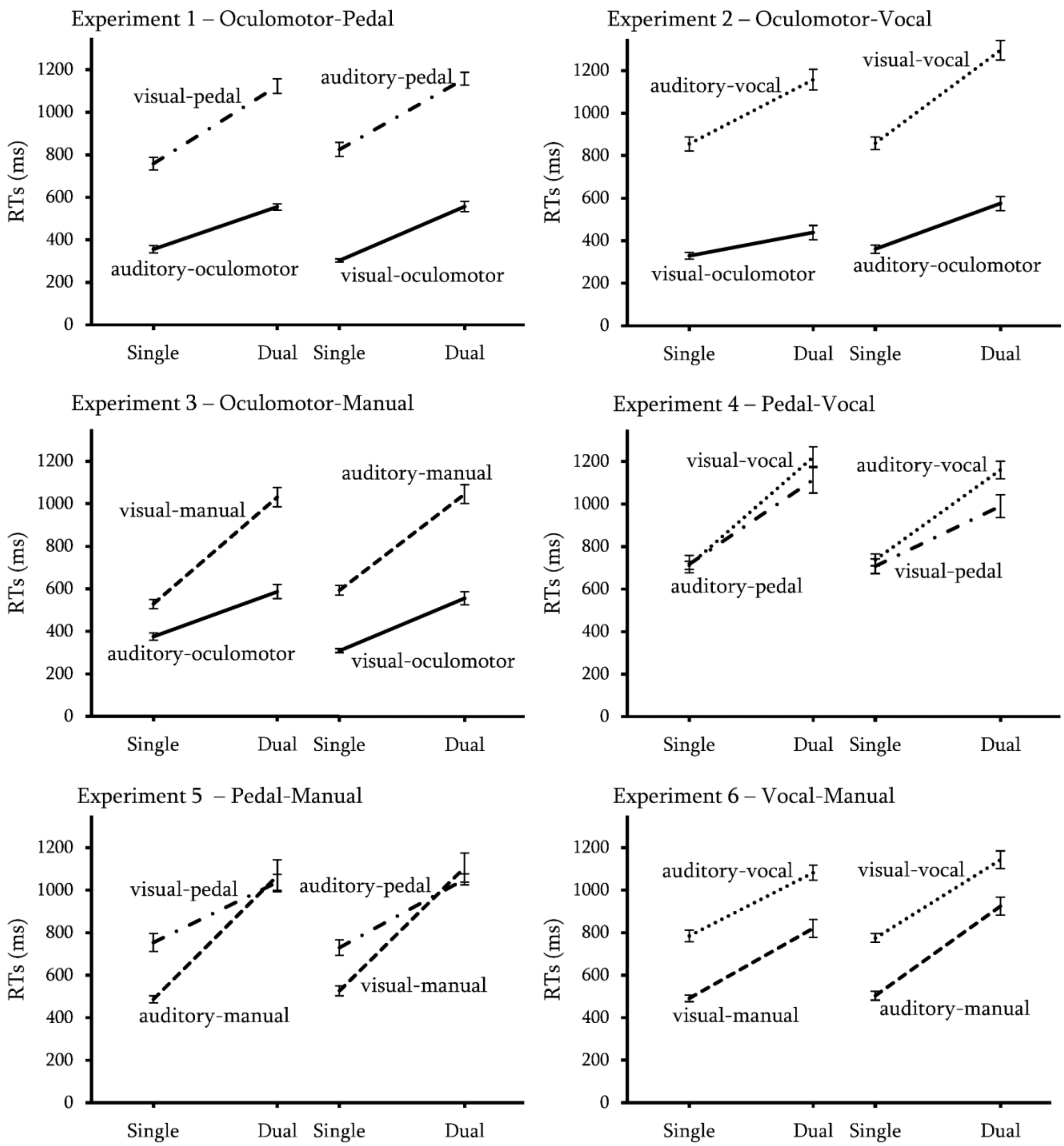

Figure 2.1. Mean RT data across all six experiments. Error bars represent mean standard errors (SEs).

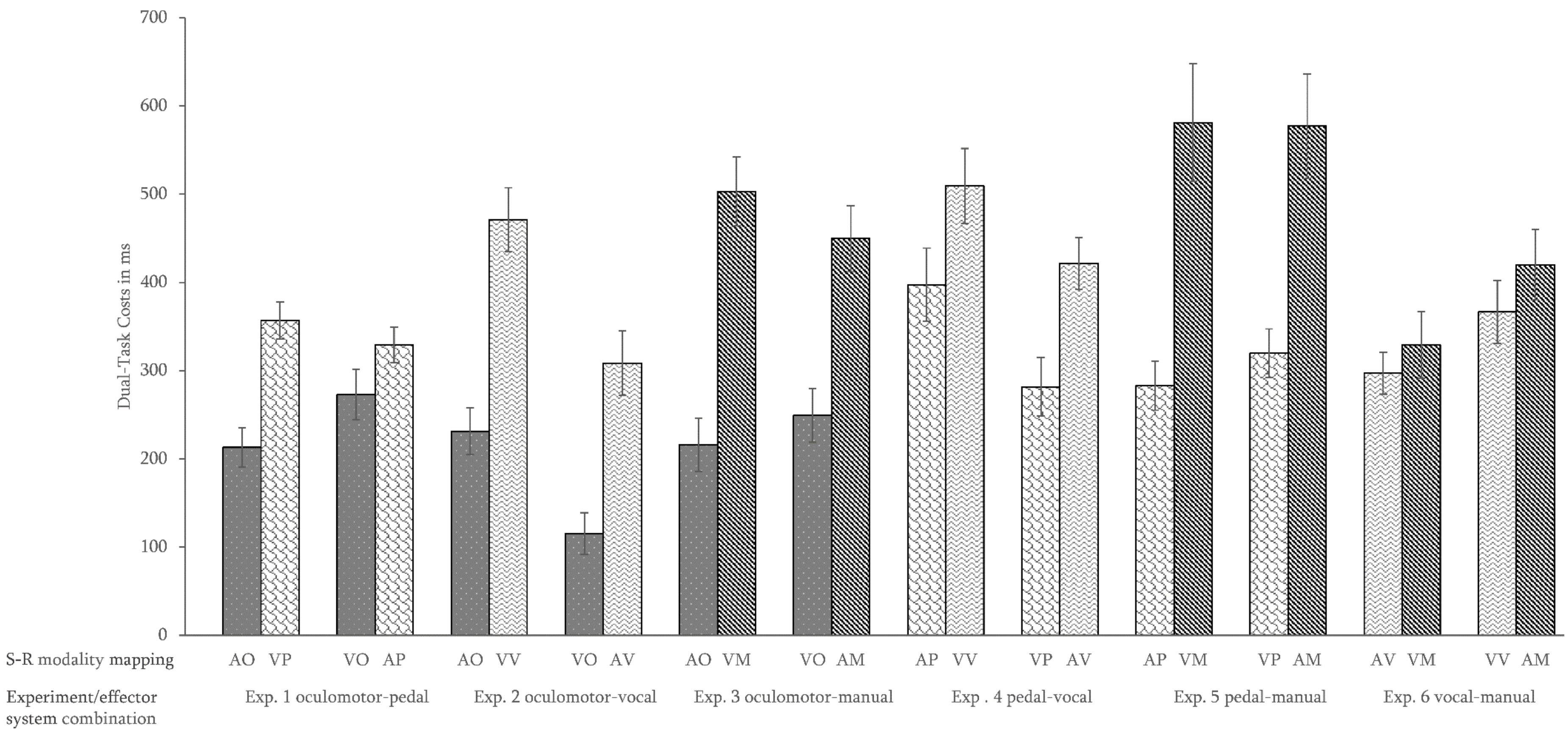

Figure 2.2. Dual-task costs across experiments as a function of effector system and S-R modality mapping. Error bars represent mean SEs.

Furthermore, the significant interaction of effector system and S-R modality mapping revealed that responses triggered by visual stimuli (oculomotor responses in the VO-AP mapping and pedal responses in the VP-AO mapping) were executed faster (M = 688 ms) than responses triggered by auditory stimuli (M = 727 ms). Post hoc contrasts showed that this difference can be observed for pedal responses (M = 944 ms vs. M = 995 ms), $F(1, 23) = 9.11$, $p = .006$, $\eta^2_p = .28$, as well as for oculomotor responses (M = 433 ms vs. M = 459 ms), $F(1, 23) = 4.80$, $p = .039$, $\eta^2_p = .17$. However, the visual (over auditory) advantage was overall (as well as for both effector systems separately) only significant for responses in single-task conditions (overall: $F(1, 23) = 17.77$, $p < .001$, $\eta^2_p = .44$, oculomotor responses: $F(1, 23) = 10.40$, $p = .004$, $\eta^2_p = .31$, pedal responses: $F(1, 23) = 10.52$, $p = .004$, $\eta^2_p = .31$), but not in dual-task conditions (overall: $F(1, 23) = 1.85$, $p = .188$, $\eta^2_p = .07$, oculomotor responses: $F(1, 23) = 0.05$, $p = .829$, $\eta^2_p = .00$, pedal responses: $F(1, 23) = 2.38$, $p = .136$, $\eta^2_p = .09$). This eventually resulted in the significant three-way interaction of effector system, task condition, and S-R modality mapping.

Together, these effects related to stimulus modality resemble results from a long-standing research tradition showing that visual stimulation often dominates auditory stimulation (visual dominance; Colavita, 1974, 1982; Colavita & Weisberg, 1979; Koppen & Spence, 2007a, 2007b; Pick, Warren, & Hay, 1969; Sinnett, Spence, & Soto-Faraco, 2007; Soto-Faraco, 2000; Soto-Faraco & Kingstone, 2004; Spence & Driver, 2004; Zahn, Pickar, & Haier, 1994), at least as long as the primary discrimination task is spatial (Lukas, Philipp, & Koch, 2014). For example, Colavita (1974) observed that even though single RTs towards an isolated visual stimulus were slower than those towards a single auditory stimulus, these visual stimuli dominated auditory stimuli when both were presented simultaneously: in some cases participants were not even aware of the presentation of an auditory stimulus while they clearly noticed (and responded to) the visual stimulus. While the classic study of Colavita (1974) refers to differences in accuracy, Egeth and Sager (1977) demonstrated dominance of visual over auditory stimuli in RT data, too. While participants responded faster in unimodal auditory than in unimodal visual trials, this pattern was reversed for bimodal trials, in which both stimulus modalities were presented at the same time. Our present finding of a visual stimulation advantage under single-task vs. dual-task conditions matches these observations since our study design in single-task conditions also involved bimodal stimulation. That is, we presented a visual and an auditory stimulus simultaneously even though one of these stimuli is irrelevant and should thus be ignored (which is not the case in dual-task conditions).

2.2.2.3 Error Rates

The analysis of error rates in Experiment 1 revealed significant main effects for all three independent variables, namely effector system, task condition, and S-R modality mapping. Overall, more errors were made in oculomotor ($M = 14.8\%$) than in pedal responses ($M = 10.6\%$), in dual-task ($M = 22.2\%$) than in single-task conditions ($M = 3.2\%$), and in the VP-AO mapping ($M = 14.2\%$) than in the VO-AP mapping condition ($M = 11.1\%$). Notably, there was no interaction between effector system and task condition.

We also observed a significant interaction between effector system and S-R modality mapping, indicating that while more oculomotor than pedal errors were made in the VP-AO mapping condition (20.1% vs. 9.4%), this pattern was reversed in the VO-AP mapping condition (8.3% vs. 12.9%). Thus, there were more errors made in response to auditory stimuli than to visual stimuli, which is in line with Colavita's (1974) claim that it is more difficult to correctly detect auditory stimuli when visual stimuli are presented simultaneously. This difference was significant for all pairwise post hoc t-test comparisons, namely for oculomotor errors in single-task, $t(23) = 7.26$, $p < .001$, $d = 2.18$, and in dual-task conditions, $t(23) = 6.82$, $p < .001$, $d = 1.50$, as well as for pedal responses in single-task, $t(23) = 3.47$, $p = .002$, $d = 0.60$, and dual-task conditions, $t(23) = 4.42$, $p < .001$, $d = 1.22$. Overall, this pattern resulted in a significant three-way interaction of effector system, task condition, and S-R modality mapping. There was no interaction of task condition and S-R modality mapping. In sum, the error data did not compromise our interpretation of the RT data in terms of oculomotor prioritization.

2.3 Experiment 2 – Oculomotor-Vocal

2.3.1 Method

Participants

A new sample of 24 participants was recruited. Data of one participant had to be discarded and replaced due to too many blinks during the eye movement measurement, which resulted in more than 35% invalid trials. The final sample had a mean age of 25.9 years (*SD* = 6.5) and contained seven males. They were recompensed by course credit or monetary reward and gave written informed consent.

Apparatus, Stimuli, Procedure, and Design

In this experiment, oculomotor and vocal responses were combined. Therefore, participants were seated in front of a microphone (Sennheiser e 835-S). The integrated voice key function of the programming software (Experiment Builder, version 1.10.1) was used for measuring vocal RTs. Vocal response identity was coded online by the experimenter. The two S-R modality mappings were now visual-oculomotor & auditory-vocal (VO-AV) and visual-vocal & auditory-oculomotor (VV-AO). All further methodological details were the same as in the previous experiment.

2.3.2 Results and Discussion

2.3.2.1 Data Treatment

Similar to the procedure in the previous experiment, invalid trials (7.8%) and outliers (5.9%, identified by the same definition as in Experiment 1) were excluded from all further analyses. Furthermore, 9.2% erroneous (of valid) trials were detected. Again, only correct and valid trials were included in RT analyses but error rates were analysed separately.

2.3.2.2 Reaction Times

As indicated by the significant main effects of effector system, task condition, and S-R modality mapping, oculomotor responses (M = 428 ms) were overall executed faster than vocal responses (M = 1052 ms), single-task responses (M = 599 ms) were faster than dual-task responses (M = 881 ms), and responses in the VO-AV mapping condition (M = 695 ms) were faster than responses in the VV-AO mapping condition (M = 785 ms). Importantly, we observed a significant interaction of effector system and task condition, indicating smaller dual-task costs for oculomotor responses (M = 173 ms) than for vocal responses (M = 390 ms). Furthermore, we additionally observed significantly smaller dual-task costs in the VO-AV mapping condition (M = 212 ms) than in the VV-AO mapping condition (M = 351 ms), which is indicated by the significant interaction of task condition and S-R modality mapping.

Similar to Experiment 1, these findings indicate a clear effect of oculomotor prioritization in terms of a corresponding dual-task cost asymmetry. Besides, the latter observation is in line with a wide range of evidence suggesting input-output modality compatibility for auditory input coupled to vocal output (cf. e.g., Hazeltine et al., 2006), since we here observe smaller dual-task costs in the corresponding mapping condition. However, our data additionally extend such previous IOMC findings by demonstrating modality compatibility in the context of oculomotor responses. The classic IOMC effect, in contrast, normally refers to vocal-manual task combinations. Amount and direction of the dual-task cost asymmetry between oculomotor and vocal responses, however, were not modulated by the S-R modality mapping (as indicated by the lack of a significant three-way interaction).

2.3.2.3 Error Rates

Regarding error rates, we observed significant main effects of effector system (indicating higher error rates in oculomotor responses, $M = 9.0\%$, than in vocal responses, $M = 4.2\%$), of task condition (indicating smaller error rates in single-task conditions, $M = 2.1\%$, than in dual-task conditions, $M = 11.1\%$), and of S-R modality mapping (indicating smaller error rates in the VO-AV mapping, $M = 4.2\%$, than in the VV-AO mapping, $M = 9.0\%$). Furthermore, there was a significant interaction of effector system and S-R modality mapping (indicating smaller error rates for responses triggered by a visual stimulus, $M = 3.3\%$, than for responses triggered by an auditory stimulus, $M = 9.9\%$), as well as of task condition and S-R modality mapping (indicating greater dual-task costs in error rates in the VV-AO mapping, $M = 11.8\%$, than in the VO-AV mapping, $M = 6.2\%$). There was no indication for an interaction of effector system and task condition, but a significant three-way interaction of effector system, task condition, and S-R modality mapping. Post hoc t-test comparisons revealed that this interaction was driven by the fact that dual-task costs in error rates differed between oculomotor ($M = 17.3\%$) and vocal responses ($M = 6.3\%$) in the VV-AO mapping condition, $t(23) = 4.42$, $p < .001$, $d = 1.03$, but not in the VO-AV mapping condition, $t(23) = 1.02$, $p = .318$, $d = 0.32$ (4.3% vs. 8.2%, respectively). Thus, at least in one condition (the VO-AV mapping condition) we can clearly interpret the RT cost asymmetry in terms of oculomotor prioritization.

2.4 Experiment 3 – Oculomotor-Manual

2.4.1 Method

Participants

24 new participants were recruited. These were 15 females and nine males with a mean age of 26.0 years (*SD* = 4.5). Again, all participants received course credit or monetary reward, were naïve regarding the purpose of the study, and gave informed written consent.

Apparatus, Stimuli, Procedure, and Design

Methodical details regarding stimuli and procedure were very similar to those in Experiment 1 and 2. As we now combined oculomotor with manual responses, the left and right arrow key on a standard (German) QWERTZ keyboard served as manual response keys that were operated by the participant´s right index finger. Accordingly, at the beginning of each block participants were instructed to place their right index finger on the *arrow down* key (located centrally between the two response keys) as a resting position. In blocks requiring a manual response (single-manual and dual-task conditions), they were instructed to press the key (left or right) that was spatially congruent to the stimulus and to return to the central key position after each response. The two S-R modality mappings corresponding to Experiment 3 were visual-oculomotor & auditory-manual (VO-AM) and visual-manual & auditory-oculomotor (VM-AO).

2.4.2 Results and Discussion

2.4.2.1 Data Treatment

7.5% of the trials contained either commission or omission errors regarding oculomotor or manual key press responses. These trials were excluded as invalid from all further analyses.

All trials in which manual or oculomotor RTs were smaller or greater than the mean RT for each individual and condition plus/minus two standard deviations, were defined as outliers and discarded as well. In total, this approach resulted in 87.4% valid data. Moreover, erroneous trials (10.5% of valid trials) were excluded from the RT analyses.

2.4.2.2 Reaction Times

Across all conditions, oculomotor responses were executed faster (*M* = 452 ms) than manual responses (*M* = 798 ms), and overall responses were faster in single-task conditions (*M* = 448 ms) than in dual-task conditions (*M* = 802 ms). Crucially, the significant interaction of effector system and task condition corroborated the hypothesis that oculomotor responses were associated with significantly smaller dual-task costs (*M* = 233 ms) than manual responses (*M* = 476 ms). These data are in line with the assumption of a prioritization of the oculomotor effector system over the manual effector system in dual-task control (oculomotor prioritization; cf. Experiments 1 and 2; Huestegge & Koch, 2013; Pieczykolan & Huestegge, 2014).

The significant interaction of effector system and S-R modality mapping was rooted in the fact that again responses were faster when triggered by a visual stimulus (manual responses in the VM-AO mapping and oculomotor responses in the VO-AM mapping, *M* = 603 ms) than by an auditory stimulus (oculomotor responses in the VM-AO mapping and manual responses in the VO-AM mapping, *M* = 646 ms). This suggested a general advantage of visual over auditory stimulation in line with our previous observations discussed above. Post hoc comparisons further corroborated this observation: Oculomotor responses triggered by visual stimuli (*M* = 429 ms) were significantly faster than when triggered by auditory stimuli (*M* = 476 ms), $F(1, 23) = 6.94$, $p = .015$, $\eta^2_p = .23$, and the same tendency was found for manual responses (*M* = 779 vs. 817 ms), $F(1, 23) = 4.22$, $p = .051$, $\eta^2_p = .16$. Again, this performance advantage for visual (vs. auditory) stimuli was only significant in single-task conditions overall (visual: *M* = 416 ms, auditory: *M* = 480 ms), $F(1, 23) = 29.58$, $p < .001$, $\eta^2_p = .56$, as well as when considering both effector systems individually (oculomotor: *M* = 304 ms vs. *M* = 368 ms, $t(23) = 4.88$, $p < .001$, $d = 0.82$; manual: *M* = 527 ms vs. *M* = 592 ms, $t(23) = 4.16$, $p < .001$, $d = 0.60$). There was no effect of stimulus modality in dual-task conditions, neither averaged over both effector systems (*M* = 792 ms vs. *M* = 813 ms), $F(1, 23) = 1.19$, $p = .286$, $\eta^2_p = .05$, nor in one of them individually, $t(23) = 7.21$, $p = .296$, $d = 0.20$, and $t(23) = 7.21$, $p = .767$, $d = 0.05$, for oculomotor (*M* = 553 ms vs. *M* = 584 ms) and manual responses (*M* = 1030 ms vs. *M* = 1041 ms; cf. discussion regarding visual dominance; Colavita, 1974, in Experiment 1, Section 2.2.2.2).

2.4.2.3 Error Rates

We found main effects of effector system (indicating higher error rates for oculomotor responses, *M* = 9.5% than for manual responses, *M* = 5.6%), and of task condition (indicating lower error rates in single tasks, *M* = 3.2%, than in dual tasks, *M* = 11.9%). There was no significant main effect of S-R modality mapping.

Furthermore, the observed interaction of effector system and task condition indicates greater dual-task costs in error rates for oculomotor responses (*M* = 10.9 %) than for manual responses (*M* = 6.5 %). Note that this dual-task cost asymmetry in error rates is opposed to the corresponding pattern in RTs (see above). There was also a significant interaction of effector system and S-R modality mapping (based on increased error rates in responses triggered by an auditory stimulus – i.e., oculomotor responses in the VM-AO mapping and manual responses in the VO-AM mapping – than in those triggered by a visual stimulus). Finally, we observed a significant three-way interaction of effector system, task condition, and S-R modality mapping, indicating greater dual-task costs for oculomotor than for manual responses in the VM-AO mapping condition (14.5% vs. 4.1%) but not in the VO-AM mapping condition (7.2% vs. 8.9%). There was no significant interaction between task condition and S-R modality mapping.

At first sight, the reversed dual-task cost asymmetry in error rates (as compared to RTs) appears to make it somewhat difficult to clearly interpret overall performance in terms of a clear oculomotor prioritization over manual responses. However, three arguments speak against an alternative interpretation in terms of a speed-accuracy trade-off. First, higher error rates in oculomotor (vs. manual) control have often been observed previously (e.g., Huestegge & Koch, 2010, 2014; Pieczykolan & Huestegge, 2017), and are likely based on different fundamental properties of oculomotor (vs. key press) control: While we are not forced to execute key press responses all the time, the eyes are bound to move (usually many times a second) even in the absence of specific task demands. This higher movement prevalence might make saccades generally more error-prone. Second, our overall RT data pattern closely resembles similar observations of oculomotor dominance in previous studies (Huestegge & Koch, 2013; Pieczykolan & Huestegge, 2014), and thus these previous instances of oculomotor dominance nicely corroborate our interpretation of our present results in terms of oculomotor prioritization. Third, and probably most importantly, the significant three-way interaction regarding error rates suggests that there was only a dual-task cost asymmetry in error rates in the VM-AO mapping condition, but not in the VO-AM mapping condition. Thus, the interpretation of the RT data in the latter condition is in no way compromised. Taken together, the pattern of results in Experiment 3 are thus nicely in line with our hypothesis of a prioritization of a task requiring oculomotor responses over a task requiring manual responses in a dual-task setting. Furthermore, again this effect is (despite the significant overall visual stimulus processing advantage in single-task conditions) not substantially altered as a function of S-R modality mapping.

2.5 Experiment 4 – Pedal-Vocal

2.5.1 Method

Participants

24 new participants were recruited to take part in Experiment 4. Data of four participants had to be excluded and substituted with new participants due to a high rate of invalid data (> 35%). The remaining sample had a mean age of 22.8 years (*SD* = 3.1) and consisted of 18 females and six males.

Apparatus, Stimuli, Procedure, and Design

In this experiment, vocal responses were combined with pedal responses and therefore the corresponding devices were in use. Otherwise, procedure and design were the same as in the former experiments. Participants were instructed to fixate the central fixation cross throughout each block. To achieve comparable perceptual input across experiments, the two visual squares that previously served as targets for oculomotor responses (on the left and right side of the central fixation cross) were also always present. S-R modality mapping conditions were now visual-pedal auditory-vocal (VP-AV) and visual-vocal auditory-pedal (VV-AP).

2.5.2 Results and Discussion

2.5.2.1 Data Treatment

Commission and omission errors regarding pedal and vocal response and trials in which a saccade was erroneously executed (total of 17.0%), as well as outliers (additional 4.3%) were regarded invalid and excluded from all further analyses. 4.3% directional errors in valid data were detected. Erroneous trials were excluded from RT analyses.

2.5.2.2 Reaction Times

Overall, pedal responses (*M* = 881 ms) were significantly faster than vocal responses (*M* = 956 ms), single-task responses (*M* = 717 ms) were significantly faster than dual-task responses (*M* = 1120 ms), and responses in the VP-AV mapping condition (*M* = 896 ms) were significantly faster than responses in the VV-AP mapping condition (*M* = 941 ms). This was indicated by significant main effects of effector system, task condition, and S-R modality mapping, respectively. As expected, we again observed asymmetrical dual-task costs: Dual-task costs were greater for vocal RTs (*M* = 465 ms) than for pedal RTs (*M* = 339 ms), as indicated by the significant interaction of effector system and task condition. Additionally, there was a significant interaction of effector system and S-R modality mapping, indicating reduced RTs for visually triggered (*M* = 906 ms) than for auditorily triggered responses (*M* = 931 ms), which is again in line with the assumption of visual dominance (cf. Colavita, 1974). However, when analysed separately post hoc contrasts did not reveal a significant difference between stimulus modalities neither under single-task (*M* = 708 ms vs. *M* = 726 ms), $F(1, 23) = 1.83$, $p = .190$, $\eta^2_p = .07$, nor under dual-task conditions (*M* = 1103 ms vs. *M* = 1135 ms), $F(1, 23) = 3.69$, $p = .067$, $\eta^2_p = .14$. Furthermore, post hoc contrasts revealed that the overall influence of the stimulus modality was only present in pedal responses (*M* = 846 ms vs. *M* = 916 ms), $F(1, 23) = 9.05$, $p = .006$, $\eta^2_p = .28$, but not in vocal responses (*M* = 946 ms vs. *M* = 966 ms), $F(1, 23) = 0.71$, $p = .409$, $\eta^2_p = .03$.

The interaction of task condition and S-R modality mapping was significant, too, revealing significantly smaller dual-task costs in the VP-AV mapping condition (*M* = 352 ms) than in the VV-AP mapping condition (*M* = 453 ms). Similar to Experiment 2, we observed smaller dual-task costs in the mapping in which vocal responses were triggered by an auditory stimulus (and now pedal responses by a visual stimulus, respectively) than in the reversed mapping. This is again in line with the well-known IOMC effect (e.g., Hazeltine et al., 2006).

This combination, interestingly, represents a case in which a simple explanation of dual-task cost differences in terms of a “first come, first served” mechanism would clearly not fit our data. More precisely, here the clear dual-task cost asymmetry cannot be explained by basic RT level differences, because there was no significant difference between RTs of the two effector systems in single-task conditions (pedal: 711 ms vs. vocal, 723 ms), $F(1, 23) = 0.18$, $p = .680$, $\eta^2_p = .01$ (cf. also the results of the following Experiment 5).

2.5.2.3 Error Rates

Regarding error rates we found significant main effects of task condition (indicating smaller error rates in single-task conditions, $M = 0.9\%$ than in dual-task conditions, $M = 5.7\%$), and of S-R modality mapping (indicating smaller error rates in the VP-AV mapping condition, $M = 1.6\%$, than in the VV-AP condition, $M = 5.0\%$). Error rates did not differ overall between effector systems. However, all interactions were significant. Dual-task costs in error rates were greater for pedal responses ($M = 6.3\%$) than for vocal responses, as well as in the VV-AP mapping condition ($M = 7.3\%$) in comparison to the VP-AV mapping condition ($M = 2.5\%$). The interaction between the effector system and S-R modality mapping indicated that overall more errors were made in responses triggered by an auditory stimulus ($M = 4.4\%$) than in those triggered by a visual stimulus ($M = 2.2\%$). Finally, the three-way interaction of effector system, task condition and S-R modality mapping was significant, too. Post hoc t-test comparisons showed that dual-task costs in error rates differed between pedal and vocal responses in the VV-AP mapping condition (pedal responses: $M = 10.8\%$ vs. vocal responses: $M = 3.8\%$), $t(23) = 3.78$, $p = .001$, $d = 0.81$, but did not clearly differ in the VP-AV mapping condition (pedal responses: $M = 1.8\%$, vocal responses: $M = 3.1\%$), $t(23) = 1.90$, $p = .070$, $d = 0.43$. Thus, while the reversed dual-task cost asymmetry in error rates compared with the corresponding RT pattern somewhat compromises a clear interpretation in the VV-AP mapping condition, there is uncompromised evidence for prioritization of pedal over vocal responses in the VP-AV mapping condition.

2.6 Experiment 5 – Pedal-Manual

2.6.1 Method

Participants

24 new participants were tested. Data of nine of them had to be excluded from analyses because it consisted of more than 35% invalid trials. We recollected these data with nine new participants. Mean age of the final sample was 26.1 years (*SD* = 4.0) and 19 of them were female. All gave written consent and received course credit or monetary reward.

Apparatus, Stimuli, Procedure, and Design

Apparatus, stimuli and procedure were the same as in the preceding experiments despite that now pedal and manual responses were combined and therefore the corresponding devices in use. Again, participants were instructed to fixate the central fixation cross throughout. The two S-R modality mappings were now visual-manual & auditory-pedal (VM-AP) vs. visual-pedal & auditory-manual (VP-AM).

2.6.2 Results and Discussion

2.6.2.1 Data Treatment

Again, commission or omission errors, trials in which a saccade was erroneously executed, and outliers (defined as described previously) were excluded from further analyses. This resulted in 81.0% valid data (14.5% invalid trials, 4.6% outliers). Only directional errors for pedal or manual responses were considered for error analyses (12.5% of valid trials). Incorrect trials were not included in RT analyses.

2.6.2.2 Reaction Times

The significant main effect of effector system indicates that manual responses (*M* = 795 ms) were executed faster than pedal responses (*M* = 891 ms). Furthermore, single-task responses (*M* = 623 ms) were significantly faster than dual-task responses (*M* = 1063 ms), indicating overall dual-task costs of 440 ms. We observed dual-task costs of 320 ms for pedal responses in the VP-AM mapping but 283 ms in the VM-AP mapping, and of 577 ms for manual responses in the VP-AM mapping and 581 ms in the VM-AP mapping. Post hoc t-test comparisons revealed significant differences between effector systems only in single-task conditions (in both the VP-AM mapping, $t(23) = 7.14$, $p < .001$, $d = 1.26$, and the VM-AP mapping, $t(23) = 7.90$, $p < .001$, $d = 1.35$), but not in dual-task conditions, ($t(23) = 1.01$, $p = .323$, $d = 0.17$, in the VP-AM mapping, and $t(23) = 0.56$, $p = .579$, $d = 0.08$, in the VM-AP mapping).

Again, we found a dual-task cost asymmetry, indicated by the significant interaction of effector system and task condition. Dual task-costs were smaller for pedal (*M* = 301 ms) than for manual responses (*M* = 579 ms). Additionally, we again found evidence for an overall advantage of visual stimuli (*M* = 832 ms) over auditory stimuli (*M* = 854 ms), which drives the significant interaction of effector system and S-R modality mapping (cf. Results and Discussion Experiment 1, 3, and 4; as well as Colavita, 1974). Post hoc contrasts revealed that this advantage of visual stimuli was again significant only for single-task conditions, $F(1, 23) = 4.73$, $p = .040$, $\eta^2_p = .17$ (*M* = 607 ms vs. *M* = 639 ms), but not for dual-task conditions, $F(1, 23) = 3.13$, $p = .090$, $\eta^2_p = .12$ (*M* = 1057 ms vs. *M* = 1069 ms). Furthermore, post hoc contrasts showed that in this case this effect was only driven by significantly faster manual responses after visual (*M* = 777 ms) than after auditory stimuli (*M* = 813 ms), $F(1, 23) = 5.21$, $p = .032$, $\eta^2_p = .19$, while there was no such difference in pedal RTs (*M* = 887 ms vs. *M* = 895 ms), $F(1, 23) = 0.13$, $p = .724$, $\eta^2_p = .01$. There was no influence of S-R modality mapping on dual-task costs or on the dual-task cost asymmetry, since there was neither a significant interaction of task condition and S-R modality mapping nor a significant three-way interaction.

Post hoc t-test comparisons revealed that dual-task costs for pedal responses were significantly smaller than for manual responses in the VP-AM mapping condition (320 ms vs. 577 ms), $t(23) = 3.62$, $p = .001$, $d = 1.17$, as well as in the VM-AP mapping condition (283 ms vs. 581 ms), $t(23) = 3.78$, $p = .001$, $d = 1.23$. This shows that pedal responses were prioritized over manual responses throughout, independent of the particular S-R modality mapping. Especially interesting in this combination is that pedal responses dominated manual responses, although manual responses showed smaller RTs under single-task conditions. This finding cannot be explained with a rigid structural model like the response selection bottleneck model, because such a model would always assume a shift in resource allocation towards the task which is executed first, which should result in greater costs in the slower response (cf. also Experiment 6).

2.6.2.3 Error Rates

Regarding error rates we observed a significant main effect of effector system, indicating higher error rates on average for manual ($M = 6.1\%$) than for pedal responses ($M = 4.8\%$). There was also a significant main effect of task condition, indicating more errors in dual-task conditions ($M = 9.2\%$) than single-task conditions ($M = 1.7\%$). The interaction of effector system and S-R modality mapping was significant, too. Specifically, the overall higher error rates in manual responses than in pedal responses were only driven by the VP-AM mapping condition (pedal: 1.0% errors under single-task, 6.7% under dual-task condition; manual: 2.3% single task, 14.3% dual task), $F(1, 23) = 13.77$, $p = .001$, $\eta^2_p = .37$. In the VM-AP mapping condition, on the other hand, descriptively more errors were made in pedal responses (2.2% and 9.4% vs. 1.5% and 6.5%), but without differing significantly, $F(1, 23) = 1.03$, $p = .321$, $\eta^2_p = .04$, as revealed by post hoc contrasts. This indicates that more errors were made associated with an auditory stimulus than with a visual stimulus, and this holds especially for dual-task conditions as indicated by the significant three-way interaction of effector system, task condition and S-R modality mapping. There was no clearly significant interaction of effector system and task condition. The ANOVA revealed no other significant effects. In sum, the error data do not compromise our interpretation of the RT data, which indicated a prioritization of pedal over manual responses.

2.7 Experiment 6 – Vocal-Manual

2.7.1 Method

Participants

24 new participants participated in this experiment. Again, six participants had to be substituted due to high rates of invalid trials (see previous experiments). Furthermore, data of one participant was discarded due to an unusually high rate of directional errors of 67% (note that all remaining participants in all experiments exhibited less than 33% directional errors). Mean age of the final sample was 24.0 years (*SD* = 3.7), seven of them were male and all naïve regarding the purpose of the study. They gave informed consent and were rewarded by course credit or monetary reimbursement.

Apparatus, Stimuli, Procedure, and Design

Again, all details regarding apparatus, stimuli and procedure were the same as in the other experiments. Now, vocal and manual responses were combined and the corresponding devices in use. S-R modality mappings were visual-vocal & auditory-manual (VV-AM) vs. visual-manual & auditory-vocal (VM-AV), respectively.

2.7.2 Results and Discussion

2.7.2.1 Data Treatment

Similar to the previous analyses, invalid trials and outliers were excluded, resulting in 83.4% valid data (5.3% outliers). Among these valid trials, there were 5.3% directional errors, which were not considered in RT analyses, but analysed separately.

2.7.2.2 Reaction Times

Manual responses (M = 683 ms) were significantly faster than vocal responses (M = 944 ms), and single-task responses (M = 637 ms) were significantly faster than dual-task responses (M = 990 ms). Neither the main effect for S-R modality mapping nor any interaction reached the level of significance. Therefore, dual-task costs in manual (403 ms) and vocal (374 ms) responses did not differ significantly.

Only regarding the interaction of task condition and the S-R modality mapping results can be considered as potentially revealing a trend (p = .053, see Table 2.1). Post hoc t-test comparisons revealed that while descriptively dual-task costs were smaller under the VM-AV than under the VV-AM mapping condition for both effector systems, this difference was significant only for manual, $t(23) = 2.27$, $p = .033$, $d = 0.48$ (329 ms vs. 420 ms), but not for vocal responses, $t(23) = 1.56$, $p = .132$, $d = 0.47$ (297 ms vs. 367 ms). This again could be interpreted in terms of an input-output modality compatibility effect (e.g., Hazeltine et al., 2006), in that manual responses benefit from being triggered visually instead of auditorily.

The absence of any significant difference in dual-task costs between effector systems in RTs is somewhat surprising, when considering the findings of Huestegge and Koch (2013). Remember that Huestegge and Koch found smaller dual-response costs for vocal responses than for manual responses in RTs in a paradigm in which both responses were always made to the same aspect of a stimulus. While in the present study the data descriptively point into the same direction, the corresponding interaction of task condition and effector system was not significant. Since the ordinal prioritization scheme among effector systems suggested by Huestegge and Koch (2013) as well as the present data suggest that both effector systems are located at the end of the prioritization dimension (i.e., all other effector systems are relatively prioritized over both the vocal and the manual system, thus the latter are located relatively close together on this dimension), it is possible that vocal prioritization over manual responses is relatively weak. Therefore, miniscule details, such as the particular stimulus dimensions involved in the present study (auditory and visual) vs. in the Huestegge and Koch (2013) study (only auditory), might determine whether this particular prioritization can be observed in the RT pattern or not. In sum, it can be concluded that the present RT results at least do not speak against a prioritization of vocal over manual responses (in terms of an effect in the opposite direction).

2.7.2.3 Error Rates

Regarding error rates, we observed significant main effects of effector system (indicating higher error rates for manual, M = 5.1%, than for vocal responses, M = 2.6%), task condition (indicating smaller error rates for single-task conditions, M = 1.4%, than for dual-task conditions, M = 6.3%), and S-R modality mapping (indicating smaller error rates in the VM-AV mapping condition, M = 1.8%, than in the VV-AM mapping condition, M = 5.8%). Importantly, there was a significant interaction between effector system and task condition, indicating greater dual-task costs in error rates for manual (M = 6.7%) than for vocal responses (M = 3.2%).

There was also a significant interaction of effector system and S-R modality mapping (indicating higher error rates in responses to an auditory stimulus, M = 6.0%, than to a visual stimulus, *M* = 1. 7%), as well as of task condition and S-R modality mapping (indicating greater dual-task costs in error rates in the VV-AM mapping condition, *M* = 8. 6%, than in the VM-AV mapping condition, *M* = 1.3%). Finally, the significant three-way interaction of effector system, task condition, and S-R modality mapping indicated that differences in dual-task costs between effector systems were significant for the VV-AM mapping condition (manual: 12.3%, vocal: 4.8%), $t(23) = 3.32$, $p = .003$, $d = 0.64$, but not for the VM-AV mapping condition (manual: 1.0%, vocal: 1.5%), $t(23) = 0.35$, $p = .732$, $d = 0.10$, as indicated by post hoc t-test comparisons.

Taken together, the interaction of effector system and task condition in error rates can be interpreted in terms of a prioritization of vocal over manual responses (at least regarding the VV-AM mapping condition). Note that this is the only experiment of the present set of data in which such evidence was observed in error rates only (and not in the RT data). Such a prioritization effect in error rates has not been reported in previous studies on effector system prioritization (Huestegge & Koch, 2013; Pieczykolan & Huestegge, 2014), most likely because in these studies errors occurred only very rarely given that responses were not triggered by two distinct stimuli.

2.8 Comparison Across Experiments

2.8.1 Dual-Task Costs of each Effector System as a Function of the Context Effector System

To assess the influence of the specific context task on dual-task interference observed in a focus task, we additionally compared dual-task costs of each effector system as a function of the respective context effector system across experiments. For instance, we wanted to examine if oculomotor dual-task costs differ depending on whether they were yielded due to an additional pedal, vocal, or manual context task. Four separate ANOVAs regarding dual-task costs of each effector system (averaged across S-R modality mapping conditions) were computed using context effector system as a between-subjects variable. Therefore, we compared dual-task costs as a function of the effector system of the additional context task for each of the three effector systems in the focus task separately. Results revealed a significant main effect of context effector system on dual-task costs for oculomotor responses, $F(2, 69) = 3.66$, $p = .031$, $\eta^2_p = .10$, for vocal responses, $F(2, 69) = 6.33$, $p = .003$, $\eta^2_p = .16$, and for manual responses, $F(2, 69) = 6.07$, $p = .004$, $\eta^2_p = .15$, but not for pedal responses, $F(2, 69) = 0.53$, $p = .590$, $\eta^2_p = .02$.

We further conducted post hoc pairwise t-test comparisons to identify in which specific combinations significant differences in dual-task costs emerged. Oculomotor dual-task costs were smaller when oculomotor responses were combined with a vocal context task ($M = 162$ ms) vs. a manual context task ($M = 237$ ms), $t(46) = 2.17$, $p = .036$, $d = 0.63$, or vs. a pedal context task ($M = 246$ ms), $t(46) = 2.65$, $p = .011$, $d = 0.76$. There was no difference in oculomotor dual-task costs when the additional task was a manual vs. a pedal context task, $t(46) = 0.26$, $p = .800$, $d = 0.07$.

A similar pattern was observed regarding manual dual-task costs. Manual dual-task costs did not differ when the manual task was combined with an oculomotor ($M = 482$ ms) vs. pedal ($M = 586$ ms) context task, $t(46) = 1.56$, $p = .126$, $d = 0.45$, but were significantly smaller when caused by an additional vocal context task ($M = 375$ ms) than when combined with both of the former two context effector systems, $t(46) = 2.34$, $p = .022$, $d = 0.69$, and $t(46) = 3.14$, $p = .003$, $d = 0.96$, respectively.

Vocal dual-task costs were significantly smaller when combined with a manual context task ($M = 334$ ms) than when combined with a pedal context task ($M = 464$ ms), $t(46) = 3.91$, $p < .001$, $d = 1.13$. The difference between dual-task costs in vocal responses when combined with a pedal vs. oculomotor context task ($M = 382$ ms) narrowly missed the level of significance, $t(46) = 1.97$, $p = .055$, $d = 0.57$. There was no significant difference in vocal dual-task costs for oculomotor vs. manual responses as a context task, $t(46) = 1.35$, $p = .183$, $d = 0.39$.

Because there was no significant effect of the context effector system on pedal dual-task costs, no corresponding pairwise post hoc comparisons were computed. Numerically pedal responses were associated with mean dual-task costs that amounted to 342 ms when combined with an oculomotor context task, 336 ms when combined with a vocal context task, and 310 ms when combined with a manual context task.

Based on these comparisons we can conclude that resource allocation in dual tasking (evidenced by the extent of dual-task costs) does not only depend on the specific effector system, in which a response has to be executed, but also on the specific combination of effector systems used in the two tasks. This is indicated by the differences in dual-task costs as a function of the context effector system and demonstrates a relative flexibility in resource allocation. However, the particular pattern cannot be explained by assuming that dual-task costs are especially low when the context response is located "far away" at the end of the prioritization structure (e.g., that oculomotor responses display especially low dual-task costs, indicating particularly strong prioritization, when combined with manual responses).

Instead, it rather appears as if some specific effectors (particularly pedal responses) generally induce high dual-task costs in the companion effector systems, while the presence of other effector systems (particularly vocal responses) generally induce relatively small costs in the companion effector systems. For instance, it is possible that interference between tasks is stronger in those effector system combinations that resemble each other regarding their requirements for monitoring feedback of an executed response. This would be in line with the observation of greater manual dual-task costs in Experiment 4 and 5 than in Experiment 6. That is, task interference for the manual response was higher when combined with an additional oculomotor or pedal than with a vocal task. Potentially, these tasks require more monitoring of perceptual feedback (e.g., regarding tactile movements in the combination of pedal and manual responses) than a vocal context task, what hampers efficient task execution Similarly, this observation goes also in line with the idea of reduced interference when different working memory systems are in use (e.g., sound/verbal vs. visuospatial; cf. Halvorson & Hazeltine, 2015; Wickens, 1980).

2.8.2 Dual-Task Costs for Effector Systems with a Fixed Context Modality

If some effector systems are prioritized over others in that corresponding processes receive a larger amount of (limited) cognitive resources based on effector system characteristics, then those effectors should be also associated with smaller dual-task costs than the dominated systems when all other task characteristics, including the context modality, are constant. Therefore, we also compared dual-task costs of the individual effector systems for fixed context effector systems. We conducted four separate one-way ANOVAs for each effector system of the context task (oculomotor, pedal, vocal, manual) with the between-subject variable effector system (of the respective focus task). That is, we compared pedal, vocal, and manual dual-task costs with a fixed oculomotor context task, oculomotor, vocal, and manual dual-task costs with a fixed pedal context task, oculomotor, pedal, and manual dual-task costs with a fixed vocal context task, and lastly, oculomotor, pedal, and vocal dual-task costs with a fixed manual context task.

The first analysis regarding dual-task costs associated with an oculomotor task revealed a significant effect of effector system in the focus task (pedal, vocal, manual), $F(2, 69) = 7.31$, $p = .001$, $\eta^2_p = .18$. Specifically, pedal dual-task costs were the smallest (M = 342 ms), vocal dual-task costs were on an intermediate level (*M* = 382 ms), while manual dual-task costs (*M* = 482 ms) were the largest. Again, we conducted post hoc pairwise t-test comparisons in order to identify specific significant differences. Significant differences were observed when comparing manual dual-task costs with pedal dual-task costs, $t(46) = 4.06$, $p < .001$, $d = 1.17$, and with vocal dual-task costs, $t(46) = 2.27$, $p = .028$, $d = 0.66$, respectively, but not between pedal and vocal dual-task costs, $t(46) = 1.19$, $p = .242$, $d = 0.34$.

There was also a significant effect of effector system for tasks associated with the pedal domain as a fixed context task, $F(2, 69) = 18.51$, $p < .001$, $\eta^2_p = .35$. In this comparison, oculomotor dual-task costs were the smallest (*M* = 246 ms), followed by vocal dual-task costs (*M* = 464 ms), and manual dual-task costs (*M* = 586 ms). Significant differences emerged comparing oculomotor dual-task costs with manual dual-task costs, $t(46) = 5.99$, $p < .001$, $d = 1.73$, and with vocal dual-task costs, $t(46) = 5.36$, $p < .001$, $d = 1.55$, but not for the difference between manual and vocal dual-task costs, $t(46) = 1.86$, $p = .069$, $d = 0.54$.

Furthermore, we observed a significant effect of effector system in tasks with a fixed vocal context task, $F(2, 69) = 15.78$, $p < .001$, $\eta^2_p = .31$. Again, dual-task costs for oculomotor responses were the smallest (*M* = 162 ms), followed by pedal responses (*M* = 336 ms), and manual responses (*M* = 375 ms). In this case, post hoc contrasts revealed significant differences comparing oculomotor dual-task costs with pedal dual-task costs, $t(46) = 4.67$, $p < .001$, $d = 1.35$, and with manual dual-task costs, $t(46) = 5.48$, $p < .001$, $d = 1.58$, respectively, but not between pedal and manual dual-task costs, $t(46) = 0.88$, $p = .386$, $d = 0.25$.

Finally, we observed a significant effect of effector system for tasks associated with a manual fixed context task, $F(2, 69) = 5.04$, $p = .009$, $\eta^2_p = .13$. Oculomotor dual-task costs were the smallest (*M* = 237 ms), followed by pedal dual-task costs (*M* = 310 ms), and vocal dual-task costs (*M* = 334 ms). Again, we conducted post hoc t-test comparisons and identified significant differences between oculomotor dual-task costs compared to pedal dual-task costs, $t(46) = 2.11$, $p = .040$, $d = 0.61$, or vocal dual-task costs, $t(46) = 3.00$, $p = .004$, $d = 0.87$, respectively, but not between pedal and vocal dual-task costs, $t(46) = 0.85$, $p = .399$, $d = 0.25$. In sum, these analyses are consistent with an ordinal prioritization structure (oculomotor < pedal < vocal < manual) across all of these four analyses in terms of the relative size of dual-task costs for effector systems under otherwise comparable (i.e., fixed context) conditions.

2.9 Discussion of Study A

The aim of Study A was to address the influence of effector systems on resource allocation in dual-task control with simultaneous stimulus presentation. Therefore, we systematically compared dual-task costs in tasks that required oculomotor, manual, pedal, and vocal responses in six experiments each representing one pairwise combinations of the four effector systems and utilized dual-task cost asymmetries as markers for effector system-based processing prioritization. Furthermore, we varied the S-R modality mappings (using auditory and visual stimuli) for each effector system pairing to examine whether it affects the pattern of dual-task cost asymmetries.

Overall, results of Study A indeed indicate that processing priorities in simultaneously triggered dual-tasking situations are allocated following an ordinal effector system-based prioritization scheme. Specifically, this scheme indicated that tasks executed in the oculomotor system are prioritized over those tasks that involve any other effector system, tasks executed by the pedal system are prioritized over manual and vocal tasks, and lastly, tasks executed by the vocal system are prioritized over those requiring a manual response. It should be mentioned that this pattern was sure not unambiguously supported by each and every parameter and in each and every condition in all experiments. However, we observed corresponding effects in at least one major part of the data in each experiment: In Experiments 1-5, this cost asymmetry pattern was supported by the RT data without any exception. However it should be noted that in some of these experiments (Experiments 2, 3, 4) the error rates pointed into the opposite direction in one of the two S-R modality mapping conditions, making it more difficult to finally interpret performance in that particular S-R modality mapping condition. In Experiment 6, we only found support for a prioritization of vocal over manual responses in error rates (in one of the S-R modality mapping conditions), but not in RTs, indicating that this particular prioritization is relatively weak and its observation depends on specific task conditions (see also e.g., Fagot & Pashler, 1992; Holender, 1980; Schumacher et al., 2001). Nevertheless, a prioritization of vocal over manual response control in RTs was already reported in a previous study on cross-modal response compound control (Huestegge & Koch, 2013), further supporting the conclusions of the present study (cf. also Study B).

Crucially, the consistency of the ordinal prioritization pattern became particularly evident in the cross-experiment comparison of dual-task costs among effector systems under task requirements with a fixed context effector system. These analyses consistently exhibited the same ordinal prioritization scheme (without any circular triads regarding the ordinal structure): 1) oculomotor, 2) pedal, 3) vocal, and 4) manual responses.

Previous studies have already reported effects of effector system prioritization among oculomotor, vocal, and manual effector systems in cross-modal dual-response situations (Huestegge & Koch, 2013; Pieczykolan & Huestegge, 2014) that were consistent with the present observations regarding these three effector systems. However, Study A provides novel insights in that it is the first study to demonstrate flexible effector system-based resource allocation in a typical dual-task situation with two independent component tasks. Moreover, by additionally focusing on the pedal effector we were now also able to examine its role in dual-task control. This is especially interesting as pedal responses represent an effector system that received only little attention in previous multitasking research (but see Liepelt et al., 2011;

Naefgen et al., 2017). Interestingly, data suggest that pedal responses receive relatively high processing priorities and in that distinguish from manual responses – although one could have assumed a relative similarity as both of them represent limb movements.

To examine whether the S-R modality mapping might affect the pattern of dual-task costs asymmetries we included a systematic S-R modality mapping manipulation in all experiments. Only in one experiment (Exp. 1, in the combination of oculomotor and pedal responses), we observed a significant three-way interaction in RTs. This shows that cost asymmetries were not strongly attenuated for a particular S-R modality mapping condition. Still, it should be noted that significant three-way interactions were consistently observed in error data. All in all, results clearly suggest that S-R modality mappings did not essentially impact the prioritization pattern among effector systems, as there were overall no switches in the relative position of an effector system in the ordinal prioritization hierarchy as a function of S-R modality mapping. The minor impact of stimulus modality and the stimulus and response modality combination also suggests that dual-task processing prioritization effects are to a much greater extent determined by effector systems than by sensory input channels or characteristics of input-output modality combinations.

Notwithstanding, effects of general S-R modality compatibility on dual-task costs were observable very consistently in both RT data and accuracy in all experiments that involved vocal responses (Experiments 2, 4, and 6). Specifically, this was shown in form of reduced dual-task interference in S-R modality mapping conditions in which vocal responses were mapped to auditory stimuli, but not in Experiment 1, 3, and 5, in which the vocal system was not required. This observation can be interpreted as an indication for the IOMC effect (Göthe et al., 2016; Halvorson et al., 2013; Hazeltine et al., 2006; Stelzel et al., 2006; Stelzel & Schubert, 2011; Stephan & Koch, 2010) to be mainly based on an especially good fitting within the auditory-vocal combination rather than within the visual-manual pathway.

On a theoretical level, the IOMC effect can either be explained by overlearned stimulus-response modality associations (e.g., in oral communication we are used to respond vocally to spoken information processed through the auditory channel), or in terms of a resemblance of stimulus characteristics and typical perceptual after-effects (i.e., vocal actions usually result in perceived sound, ideo-motor view; see Stephan & Koch, 2010; Stephan et al., 2013; see also Section 1.3.2). Especially the latter explanation account goes nicely in line with our observed data, as in our lab participants were certainly able to perceive the auditory after effects of their vocal response (the sound of their own voice) but potentially not the visual effects of moving their finger as the light in the lab was dimmed and participants were instructed to fixate the fixation cross throughout.

It is also notable that in some experiments (Experiment 1, 3, and 5) we found a performance advantage for responses that were triggered by a visual (vs. auditory) stimulus in single-task conditions (similar to a visual dominance effect; see Colavita, 1974, 1982; Colavita & Weisberg, 1979; Cooper, 1998; Koppen & Spence, 2007a, 2007b; Sinnett et al., 2007; Zahn et al., 1994). However, such an advantage was not observable in dual-task conditions, where it is not necessary to selectively attend to one relevant (and ignore the irrelevant) stimulus (see individual discussions for details).

Several reasons are conceivable that might evoke prioritized processing among tasks (as reflected differences in the extent of in dual-task interference). Following the idea of a classic all-or-none central processing account, one would expect that the faster task (more precisely, the one in which response selection starts first) should be prioritized. That is, both in terms of response order (the task in which stimulus processing is terminated first should be executed first) and dual-task costs (this task then should be associated with none or at least remarkably smaller dual-task costs). Anyhow, only the second task should suffer from processing postponement until clearance of the (all-or-none) central processing bottleneck (Pashler, 1994).

Indeed, such a simple "first come, first served" model clearly cannot explain the present data. Across experiments, single-task data indicate that tasks requiring oculomotor responses are fastest (overall mean = 334 ms), followed by manual responses (528 ms), and then pedal (750 ms), and lastly vocal responses (786 ms). However, except for oculomotor responses, the analogous dual-task cost hierarchy among effector systems does not follow the same pattern (oculomotor: 216 ms, manual: 486 ms, pedal: 328 ms, vocal: 410 ms). Thereby, overall task processing speed can be ruled out to crucially determine the observed dual-task cost pattern.

Specifically, the finding that in some combinations the faster task suffers from greater dual-task costs than the respectively slower task is not conformable with a "first come, first served" account, as such a model would always predict greater costs in the slower than in the faster task (Pashler, 1994). To be precise, in a typical bottleneck model actually even the endpoint of stimulus processing and therefore the time point in which response selection could be initiated should determine which task is entering the response selection stage bottleneck first rather than overall processing speed in single-task conditions. Indeed, since we used a simultaneous onset paradigm, which stimulus is processed faster should then completely determine task prioritization, which in this case would have had to depend on stimulus modality. Again, results contradict this idea, as is evinced by the lack of any relevant influence of stimulus modality on the pattern of dual-task cost asymmetries.

In contrast, models that assume parallel central (response-related) processing (Meyer & Kieras, 1997a, 1997b; Navon & Miller, 2002; Tombu & Jolicœur, 2003) in principle allow for the occurrence of stronger dual-task interference in the faster/firstly initiated task, as it in fact has been observed in the present data. Therefore, these models are considered as a much more promising theoretical alternative to an all-or-none serial response selection mechanism. Certainly, this raises the crucial question how specifically such processing resources are then scheduled across tasks, that is, which task characteristics determine resource allocation. In this study, we demonstrated effector systems to be a potentially strong determining factor of resource scheduling across tasks. Specifically, our observations of a dual-task cost pattern that is not in line with overall processing speed and dual-task costs within one system being affected by the effector system of the context task strongly support the assumption of such flexible resource sharing models. Nevertheless, also these accounts do not yet readily offer a satisfactory explanation for the substantial impact of task characteristics that lay in effector systems on resource scheduling demonstrated here.

There are several theoretical models that account for mechanisms of resource scheduling and highlight the principal relevance of modalities in dual-task control. As these models and their restrictions to account for our observations are discussed in more detail in the General Discussion (Section 6.2), the following paragraph gives only a short overview.

Noteworthy theoretical frameworks that might be relevant considering our observations are the *executive control theory of visual attention* (ECTVA; Logan & Gordon, 2001), Wickens' *four-dimensional multiple resources model* (1984, elaborated by Wickens & Hollands, 2000; see also Wickens, 2008) and the *executive-process interactive control* (EPIC) architecture of Meyer and Kieras (1997a). While Wickens' four-dimensional resources model and the EPIC architecture include dimensions to account for output modalities, the promising feature of ECTVA is that it already allows for phenomena of task prioritization. However, interestingly, this does not relate to effects of effector systems. On the other hand, although a potential relevance to differentiate between effector systems is implied by the four-dimensional resources model as well as EPIC, neither of them includes any suggestion whether and how effector systems could affect resource scheduling nor provides a specific mechanism for any prioritization policies. Moreover, none of these models considers all four effector systems studied here. Therefore, so far, neither of these frameworks can explain effector system prioritization as proposed here and is suited to sufficiently explain the results of the present study.

To this point, the functional significance of the proposed effector system prioritization scheme remains an open question. As already discussed regarding flexible resource sharing models, resource allocation is assumed to be potentially altered based on strategic reasons. It indeed appears strategically plausible to shift an especially high amount of cognitive resources to those responses that either cannot be stopped or altered after response initiation (such as oculomotor responses, ballistic account) or necessitate relatively more resources to be efficiently processed due to task difficulty (e.g., due to differences in the complexity of response selection). From a more global perspective, effector system prioritization could be evolved due to a hereditary evolutionary advantage or based on implicit training effects due to long lasting learning history in everyday life situations. Note, however, that to date we are not able to draw any final, evidence-based conclusions regarding this issue. These approaches as well as their restrictions and relevance in future research are discussed in more detail in the General Discussion (see Sections 6.3 and 6.4).

2.9.1 Conclusion of Study A

Study A revealed consistent effects of different processing priorities in the control of simultaneously initiated dual tasks among oculomotor, pedal, vocal, and manual responses according to an ordinal, effector system-based prioritization pattern. Crucially, the results are not in line with a structural “first come, first served” mechanism, but rather support models that allow for parallel task processing as well as for sharing limited cognitive resources among tasks. Thereby, we demonstrated a significant influence of execution-related task characteristics (i.e., the effector system executing the response) on dual-task control processes. This conclusion suggests effector-specific response selection processes based on the anticipation of effector system-related task characteristics. The observation of an influence of the context effector system on dual-task interference within some effector systems, moreover, reveals task prioritization mechanisms to be flexibly adaptive based on specific effector system combinations. All in all, Study A demonstrated that it is reasonable to integrate effector system-specific weighting parameters in existing frameworks of dual-task control (e.g., the ECTVA framework of Logan & Gordon, 2001).

3. Study B: Resource Allocation between Manual and Vocal Responses Associated with Intra-Modal Stimulation

3.1 Introduction

As discussed in the previous chapters, typical experiments in the field of multitasking research often focus on tasks that are executed in a rather restricted range of effector systems, which is done to ensure a highly controlled experimental situation. Nevertheless, as in everyday life we are more often confronted with situations in which we react in different effector systems, the question of whether the used effector systems or their specific combinations itself affects dual-task performance is highly relevant. But until now, this issue has drawn relatively little attention in previous research and corresponding theories (see e.g., Logan & Gordon, 2001; Meyer & Kieras, 1997a, 1997b; Navon & Miller, 2002; Pashler, 1994; Tombu & Jolicœur, 2003).

The pathbreaking study of Huestegge and Koch (2013) discussed above (see Section 1.3.1) found first evidence for a remarkable impact of effector systems on resource allocation among responses. Specifically, in this dual-response compound control paradigm, they observed systematic differences in the extent of dual-response costs associated with oculomotor, vocal or manual responses. Crucially, this was interpreted as an indication for prioritized processing of those responses associated with smaller dual-response costs over those associated with greater dual-response costs based on an asymmetrical allocation scheme of limited cognitive resources among responses. Results pointed towards an ordinal prioritization pattern among effector systems in that oculomotor responses were associated with smaller dual-response costs than both vocal and manual responses, while vocal responses were associated with smaller (or rather no substantial) dual-response costs when combined with manual responses.

Especially the latter finding regarding the vocal-manual task combination was interesting, as in this case the overall slower (vocal) response, which was typically executed second, was nevertheless prioritized in terms of dual-response interference. This observation challenges the often (in former research) discussed approach to explain asymmetrical resource allocation to be based on task order (cf. also PRP effect; Telford, 1931; see Pashler, 1994, for a review). Instead, Huestegge and Koch (2013) interpreted their observations as an indication for rather parallel response selection processing with resource sharing among tasks in an effector system-dependent manner (cf. also Meyer & Kieras, 1997a, 1997b; Navon & Miller, 2002; Tombu & Jolicœur, 2003, for parallel processing theories) based on an ordinal effector system hierarchy (oculomotor > vocal > manual, in terms of a decreasing prioritization; already strengthened by the findings of Pieczykolan & Huestegge, 2014; and the above presented results of Study A).

On the other hand, many studies focused on the influence of the combination of sensory systems and effector systems on multitasking performance (input-output modality compatibility, IOMC; Fintor, Stephan, & Koch, 2018; Göthe et al., 2016; Greenwald, 1972, 2003; Halvorson et al., 2013; Hazeltine et al., 2006; Maquestiaux, Ruthruff, Defer, & Ibrahime, 2018; Stelzel et al., 2006; Stelzel & Schubert, 2011; Stephan et al., 2013; Stephan & Koch, 2010, 2011). The observation of IOMC effects as a substantial influence of the combination of input and output modalities on dual-task performance represent a considerable limitation in interpreting the findings of Huestegge and Koch (2013) as clear evidence for the influence of vocal-over-manual prioritization on resource allocation. Indeed, it is possible to derive an alternative explanation of these findings in terms of an influence at earlier processing stages. Crucially, due to the use of only one, namely auditory, stimulus, the observed prioritization of vocal over manual responses might actually be also explained by the relation of effector systems to the stimulus modality. This relation might influence task control processes in a way that resembles input-output modality compatibility effects (e.g., Hazeltine et al., 2006). According to the idea of the IOMC effect, some stimulus and response modality combinations result in a better fit than others (potentially because responses in specific effector systems produce effects that resemble the respective stimulus modalities; see also Section 1.3.2). Accordingly, it is possible that the use of only auditory stimuli created a setting in which vocal task demands were associated with a particular advantage compared to manual task demands.

Note however, that previous IOMC studies always compared overall performance in both effector systems between the two possible (compatible vs. incompatible, sometime also referred to as “standard” vs. “non-standard” pairings; see Hazeltine et al., 2006) assignments of stimulus and response modalities. In the study of Huestegge and Koch (2013), however (as well as in the present study as described in more detail below), both response modalities were linked to one and the same stimulus modality and therefore without any contrasting assignments that could be compared. Analogously to the logic of IOMC effects, one might still assume that vocal responses are compatible to auditory stimuli and therefore, in the design of Huestegge and Koch (2013) vocal responses would have had an a priori advantage over manual responses. Due to these differences to what is usually defined as an IOMC effect, we refer to such a benefit as an “IOMC-like” effect. An explanation of the observed asymmetry pattern between vocal and manual responses in dual-response costs in terms of this IOMC-like effect, crucially, would not imply a general vocal prioritization in a purely effector system-based manner.

At first sight, it might appear as if Study A already provided sufficient evidence that effector system prioritization is not substantially altered by S-R modality mappings as it also included the combination of a manual and a vocal task (see Study A, Experiment 6, Section 2.7). However, in Study A we utilized bimodal stimulation and two varying input-output modality assignments (as in a classic IOMC setup) implying that the two tasks were always both either input-output modality compatible or incompatible. As a consequence, Study A was not suited to finally answer the question whether the observed vocal-over-manual prioritization observed by Huestegge and Koch (2013) was influenced by stimulus modality nor whether effector system prioritization can generally be modulated by the stimulus modality in a situation in which one task is input-output modality compatible while the other task is not.

In contrast, the results of Study A highlight the importance to further investigate the specific (and theoretically highly relevant) combination of vocal-manual dual tasks. This is because Experiment 6 was the only case in which we did not observe a clear effector system prioritization effect in dual-task costs in raw RT data (but in error rates as well as in the across-experiment analyses). Indeed this indicates that the combination of vocal-manual dual tasks might be associated with an especially weak effector system prioritization. This concern becomes even more relevant by taking a closer look on the results of Pieczykolan and Huestegge (2014) that replicated vocal-over-manual prioritization in auditorily triggered dual-response compounds only with respect to proportional dual-response costs, but not when directly comparing dual-response costs in raw RT data.

Further indications of the importance of stimulus characteristics when considering vocal-manual dual-task performance are also given by the fact that the assumption of vocal-over-manual prioritization as assumed by Huestegge and Koch (2013), Pieczykolan and Huestegge (2014), and Study A is incompatible with a number of former studies. Specifically, some previous dual-task studies reported greater dual-task costs for vocal than for manual responses (e.g., Fagot & Pashler, 1992; Holender, 1980; Schumacher et al., 2001). Crucially, these studies used visual stimuli or only one fixed assignment of stimulus to response modalities (in the case of Schumacher et al., 2001). This demonstrates that further evidence is needed to ultimately answer whether there is a general prioritization of the vocal over the manual system in resource allocation or whether the observed asymmetrical performance costs can actually be explained by a benefit of vocal responses triggered by auditory stimuli due to an IOMC-like effect. Indeed, the opposing results in previous research suggest that dual-task control in this specific combination is highly dependent on specific stimulus conditions.

Therefore, in Study B we compared dual-task costs between vocal and manual tasks using either only visual or only auditory stimuli to control for the role of stimulus modality. To ensure independent initialization of the two responses (i.e., two discrete response selection processes, cf. Fagot & Pashler, 1992) we used single stimuli with two independent features to trigger the two responses.

As we assume a general effector system prioritization of tasks executed by the vocal effector system over those executed by the manual effector system, we should observe smaller dual-task costs for vocal than for manual responses irrespective of the stimulus modality condition. This difference, however, could be modulated by stimulus modality in the sense of a boost by auditory stimulation and/or an attenuation by visual stimulation due to IOMC-like effects. Independent of the latter, evidence towards the former hypothesis would represent another example for the observation of prioritization of the overall slower response, which would also promote parallel processing accounts (cf. Meyer & Kieras, 1997a, 1997b; Navon & Miller, 2002; Tombu & Jolicœur, 2003).

If, in contrast, IOMC-like effects if form of a better fit of vocal responses to auditory stimuli were the main reason behind vocal-over-manual effector system prioritization observed by Huestegge and Koch (2013), we should observe manual-over-vocal prioritization (indexed by smaller dual-task costs associated with manual responses than with vocal responses) when visual stimuli trigger the two responses. Note that our design also allows for a comparison of overall performance between the two stimulus modality conditions, an approach that might give us a new viewpoint regarding the mechanisms behind IOMC effects.

3.2 Method

Participants

32 naïve participants took part in this study. Similar to Study A, we used a pre-set criterion to exclude participants that produce more than 33% invalid or more than 35% incorrect trials. Four participants fell under the criterion regarding invalid trials (including trials in which a saccade was executed prior the instructed response, omission and commission errors, and outliers). No participant fell under the criterion regarding accuracy. To still allow for full counterbalancing, we recollected data of four new participants. The final sample consisted of six males and 26 females with a mean age of 29.5 years (*SD* = 10.2). All participants gave informed consent, were compensated by course credit or a monetary reward and had normal or corrected to normal hearing and vision

Apparatus and Stimuli

Participants were seated approx. 67 cm in front of a 21-inch cathode ray tube screen a temporal resolution of 100 Hz and a spatial resolution of 1024 x 768 pixels. Furthermore, participants sat in front of a standard German QWERTZ keyboard and a Sennsheiser e 835-S microphone wearing supra-aural headphones (Sennheiser, PMX 95). As software to run the experiment and log response events (left and right arrow key presses operated by the participant's right index finger and vocal RTs by the integrated voice key function) we utilized the Experiment Builder software (version 2.1.140, SR Research). Vocal responses were registered online by the experimenter and additionally recorded (to allow for later verification). The same Eyelink 1000 (SR Research) eye tracking system as used in Study A (sampling rate = 1000 Hz) registered eye movements of the right eye and a chinrest was used to minimize head movements. A green fixation cross (approximate size = 0.4° of visual angle) was presented centrally and two green rectangular squares (also with a size of approximately 0.4° each) were presented at an eccentricity of 8.5° on a black background during all blocks. Although these squares were irrelevant for the present study, this was done to ensure optimal comparability to Study A. As auditory stimuli served sinusoidal tones of either high (1000 Hz) or low (400 Hz) frequency presented either on the right or on left ear via the headphones mentioned above. Visual stimuli were the capital letters L and R, presented in green and either mirrored (and therefore "pointing" to the left side, ⅃ & Я) or not (pointing to the right side, L & R) with the size of 0.6° displayed about 0.4° above the central fixation cross.

Procedure and Design

Each block started with instructions in written and oral (by experimenter) form, including information about task condition, stimulus modality and the assignment of stimulus component to effector system (e.g., reacting verbally to tone pitch and manually to tone location). An explicit instruction to always react as fast and accurately as possible was also included. Following the instruction screen, a three-point horizontal calibration routine of the eye tracker was conducted. Stimulus modality (either visual or auditory stimuli) and task condition (instruction to respond either vocally, manually or to execute both tasks) were manipulated across blocks. In each trial, a stimulus was presented for 80 ms. All stimulus components (high vs. low frequency, presented to the left vs. the right ear, L vs. R, mirrored vs. not) were equally likely and presented in random order in each experimental condition.

Participants were instructed to respond manually by key presses of the right or left arrow key with their right index finger and/or (depending on the current block) vocally by uttering the word "rechts" or "links" (German for right and left). Thereby, responses should always be given in a spatially congruent manner to the stimulus component, which meant a left response for an L, a mirrored orientation, a sound presented to the left ear, or a low frequency (analogous to the pitch-location mapping on a piano keyboard) and a right response for the opposed component identities, respectively.

Analogous to Study A, the next trial started with the presentation of the next stimulus after a fixed interstimulus interval of 3000 ms (cf. also Huestegge et al., 2014; Huestegge & Koch, 2013). Each block consisted of 32 trials. Each participants experienced all twelve different types of blocks twice, that is 24 blocks in total. More precisely, this number is composed of 3 task condition blocks (single manual, single vocal, or dual task) x 2 stimulus modality conditions (auditory or visual) x 2 assignments of stimulus component to effector system per stimulus modality (letter orientation to manual responses and letter identity to vocal responses or vice versa regarding visual stimuli, tone pitch to manual responses and tone location to vocal responses or vice versa regarding auditory stimuli, respectively) x 2 repetition of all blocks.

To minimize confusion for participants, we applied three restrictions in counterbalancing the sequence of the conditions. Namely, for all participants the first block consisted of a single-task condition (either manual or vocal, counterbalanced across participants), which could be followed by either the respective other single- and then the dual-task condition or vice versa. In both cases, these two following blocks included the same stimulus modality condition and the same stimulus component to task assignment as in the first block. After these first three blocks, the exact same conditions were repeated once in the same order (e.g., single manual – dual task – single vocal, all involving auditory stimulation with the assignment of pitch to manual and location to vocal responses). This was followed by six blocks with the other stimulus modality, respectively but with the same sequence of task conditions, which stayed constant within participants throughout the experiment (e.g., single manual – dual task – single vocal, but now using visual stimulation). Regarding the next six blocks the stimulus modality changed again (back to the firstly presented modality, auditory regarding the given example), but now the stimulus component to effector system assignment was reversed (e.g., pitch to vocal/location to manual responses). Lastly, the same holds for the final six blocks regarding the second stimulus modality condition.

Stimulus modality order and the order of stimulus component to effector system assignment were again counterbalanced across participants. The experimental design consisted of the independent within-subject variables effector system (manual vs. vocal), task condition (single vs. dual), and stimulus modality (auditory vs. visual). This implies a 2x2x2 within-subject design. As dependent variables we measured RTs and error rates.

3.3 Results

3.3.1 Data Treatment

All omission and commission errors in vocal and/or manual responses were defined as invalid and excluded from further analyses. The same holds for all trials in which a saccade was registered prior to the requested manual and/or vocal response and in which vocal or manual RTs were below 50 ms (to make sure that the relevant RTs were not delayed due to a firstly executed movement in another effector system and no voice key artefacts were included). Outliers, (RTs > + 2 SDs or < - 2 SDs of the individual mean of each participant within conditions) were also discarded. This account resulted in a total of 84.4% valid data. 4.6% of valid data contained directional errors in manual and/or vocal responses (e.g., uttering “right” instead of “left”) which were analysed separately but not included in RT data analyses.

3.3.2 Reaction Times

A 2x2x2 ANOVA (analysis of variance) with the independent within-subject variables effector system, task condition, and stimulus modality on RT data revealed that overall, vocal responses (994 ms) were executed slower than manual responses (765 ms), indicated by a significant main effect of effector system, $F(1, 31) = 107.45$, $p < .001$, $\eta^2_p = .78$. A significant main effect of task condition, $F(1, 31) = 415.54$, $p < .001$, $\eta^2_p = .93$ revealed overall dual-task costs (of 373 ms) in form of longer dual-task (1066 ms) than single-task RTs (693 ms). Dual-task costs as a function of effector system and stimulus condition are illustrated in Figure 3.1. Moreover, a significant main effect of stimulus modality, $F(1, 31) = 10.65$, $p = .003$, $\eta^2_p = .26$, indicated overall smaller RTs in the visual stimulation condition (850 ms) than in the auditory stimulation condition (909 ms). As most crucial result, we observed a significant interaction of effector system and task condition indicating smaller dual-task costs for vocal (306 ms; 1147 ms RTs in dual-task conditions minus 841 ms RTs in single-task conditions) than for manual responses (440 ms; 985 ms RTs in dual-task conditions minus 545 ms RTs in single-task conditions), $F(1, 31) = 12.55$, $p = .001$, $\eta^2_p = .29$.

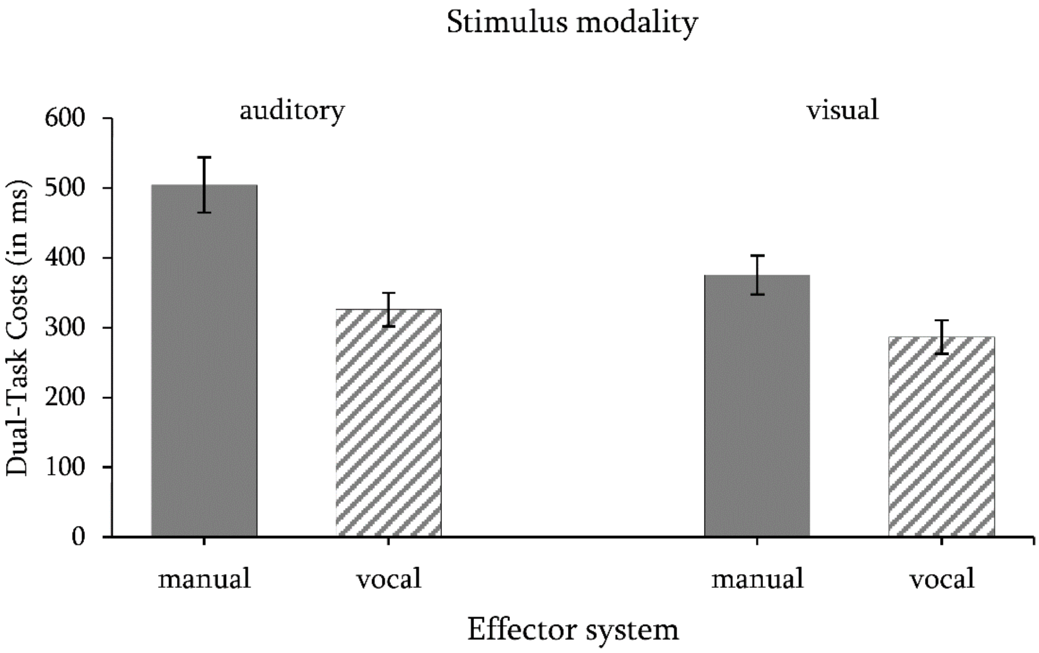

Figure 3.1. Dual-task costs as a function of effector system and stimulus modality. Error bars represent mean SEs.

Interestingly, also the three-way interaction was significant, $F(1, 31) = 21.11$, $p < .001$, $\eta^2_p = .41$, which further qualified the above described difference in dual-task costs between the effector systems. Notably, post hoc t-test comparisons revealed that vocal dual-task costs were significantly smaller than manual dual-task costs in both stimulus modality conditions. Specifically, in the auditory stimulus condition, there was a difference of 178 ms in dual-task costs between effector systems as vocal dual-task costs amounted to 326 ms (=1196 ms dual-task RTs minus 870 ms single-task RTs) and manual dual-task costs amounted to 505 ms (=1036 ms dual-task RTs minus 532 ms single-task RTs), $t(31) = 4.45$, $p < .001$, $d = 0.95$. In the visual stimulus condition, however, the dual-task costs difference between effector systems amounted to only 88 ms between vocal dual-task costs of 287 ms (= 1098 ms dual-task RTs minus 811 ms single-task RTs) and manual dual-task costs of 375 ms (=933 ms dual-task RTs minus 558 ms single-task RTs), $t(31) = 2.35$, $p = .026$, $d = 0.60$. Furthermore t-test comparisons revealed greater manual dual-task costs in the auditory (505 ms) than in the visual (375 ms) stimulus condition, $t(31) = 4.58$, $p < .001$, $d = 0.63$, but no significant difference in vocal dual-task costs between the two stimulus modality conditions (326 ms vs. 287 ms, respectively), $t(31) = 1.54$, $p = .134$, $d = 0.29$.

In addition, we observed a significant interaction of effector system and stimulus modality, $F(1, 31) = 22.48$, $p < .001$, $\eta^2_p = .42$, as well as of task condition and stimulus modality, $F(1, 31) = 11.30$, $p = .002$, $\eta^2_p = .27$. Post hoc contrasts revealed faster RTs in response to a visual stimulus (944 ms) than in response to an auditory stimulus (1014 ms) for vocal responses (auditory: 944 ms vs. visual: 1014 ms), $F(1, 31) = 16.76$, $p < .001$, $\eta^2_p = .35$, as well as for manual responses (auditory: 784 ms vs. visual: 746 ms), $F(1, 31) = 4.71$, $p = .038$, $\eta^2_p = .13$. The interaction of task condition and stimulus modality evinced that overall dual-task costs were smaller in the visual (331 ms = 1016 ms dual-task RTs minus 685 ms single-task

RTs) than in the auditory stimulus condition (415 ms = 1116 ms dual-task minus 701 single-task RTs).

3.3.3 Error Rates

Only 4.6 % of valid data contained a directional error. Nonetheless, overall significantly more errors were made in manual (4.9%) than in vocal (3.8%) responses, $F(1, 31) = 4.84$, $p = .035$, $\eta^2_p = .14$ (main effect of effector system). There were also more errors made in dual-task conditions (6.9%) than in single-task conditions (1.7%), $F(1\ \ 31) = 26.30$, $p < .001$, $\eta^2_p = .46$ (main effect of task condition).

Furthermore, there was a significant three-way interaction of effector system, task condition, and stimulus modality, $F(1, 31) = 6.30$, $p = .017$, $\eta^2_p = .17$. Post hoc t-test comparisons indicated that this interaction was driven by the effect that manual responses to a visual stimulus were associated with greater dual-task costs in error rates (6.0%, = 7.8% errors in dual-task conditions minus 1.8% errors in single-task conditions) than vocal responses to a visual stimulus (3.6% = 5.0% errors in dual-task conditions minus 1.4% errors in single-task conditions), $t(31) = 3.21$, $p = .003$, $d = 0.41$. However, in response to an auditory stimulus there was no significant difference in dual-task costs between the two effector systems (vocal: 5.5% = 7.2% minus 1.5% vs. manual: 5.6% = 7.2% minus 1.5%), $t(31) = 0.14$, $p = .887$, $d = 0.02$. Note that all remaining analyses regarding error rates revealed non-significant results, all other *p*s > .118.

3.3.4 Congruency

Supplementary, we also wanted to investigate whether vocal-over-manual effector system prioritization could be modulated by effects of spatial stimulus congruency. That is, for some stimuli both stimulus dimensions require a spatial response selection regarding one and the same side (e.g., a non-mirrored R), while encoding the two dimensions of other stimuli would lead to one "left" and one "right" response (e.g., a non-mirrored L). Consequently, in dual-task conditions trials with spatial stimulus congruency implicitly involved spatial response-response congruency, as otherwise they would contain a directional or omission error and therefore had been discarded from all RT analyses. However, as in single-task conditions only one response was required but stimuli still contained both dimensions, single-task trials still involved spatial stimulus (in)congruency.

Note that we can differentiate between two interesting aspects in congruency analyses. First, we can evaluate performance differences between congruent vs. incongruent trials overall. The presentation of incongruent trials leads to more interference between the two tasks, which should be observed in terms of prolonged response latencies. This effect could also be interesting as another marker for priority settings among tasks, in the sense that one task could suffer more from this interference than the other one, similar to asymmetries in dual-task costs. Second, a special case of interference effects due to response-response (in)congruency is the phenomenon of stronger interference (marked by longer RTs) in dual-task situations in the first executed response when the second executed response is spatially incongruent. This phenomenon is referred to as backward crosstalk effect (Hommel, 1998; see also e.g., Janczyk, 2016; Janczyk, Pfister et al., 2014).

Therefore, we conducted two further ANOVAs including the additional independent within-subject variable congruency. First, we analysed all valid and correct trials regarding RTs and all valid trials regarding error rates using a 2x2x2x2 analysis. For the sake of convenience, we will focus exclusively on effects of congruency in this paragraph and will not report the above presented effects regarding this additional subsequent analysis again. Second, we conducted a further additional 2x2x2 analysis in which we compared RTs of vocal vs. manual responses in R-R congruent vs. incongruent trials, with visual vs. auditory stimulation but exclusively for the firstly executed response in the dual-task condition (which was the manual response in 74.1% and the vocal response in 25.8% of trials). Thereby, we could investigate the influence of backward crosstalk between effector systems.

The 2x2x2x2 ANOVA regarding the first supplementary question revealed a significant effect of congruency, $F(1, 31) = 108.21$, $p < .001$, $\eta^2_p = .78$, showing the typical congruency effect of longer RTs in response to an incongruent (922 ms) than to a congruent (848 ms) stimulus. Interestingly, this effect was overall more pronounced for manual responses (92 ms) than vocal responses (55 ms) as shown by a significant interaction of congruency and effector system, $F(1, 31) = 27.91$, $p < .001$, $\eta^2_p = .47$. Moreover, it was more pronounced in dual-task (111 ms) than in single-task conditions (37 ms), revealed by a significant interaction of congruency and task condition, $F(1, 31) = 41.51$, $p < .001$, $\eta^2_p = .57$. Finally, also the three-way interaction of congruency, effector system, and task condition, $F(1, 31) = 15.47$, $p < .001$, $\eta^2_p = .33$, and the four-way interaction of congruency, effector system, task condition, and stimulus modality, $F(1, 31) = 8.58$, $p = .006$, $\eta^2_p = .22$, revealed significant effects. Specifically, the difference in the congruency effect between vocal and manual responses was smaller in single-task conditions (30 ms vs. 44 ms) than in dual-task conditions (81 ms vs. 139 ms). While this pattern held for both stimulus modalities, however, it was less pronounced in responses to an auditory stimulus (congruency effects of 13 vs. 41 ms in single tasking but 81 ms vs. 132 ms in dual tasking) than for visual stimulation (congruency effects of 45 vs. 47 ms in single-task but 81 vs. 148 ms in dual-task conditions). The respective four-way interaction was therefore probably mainly reflecting the absence of any difference in the congruency effect between the two effector systems in single tasking in the visual stimulus condition (cf. 46 ms vs. 47 ms). No other interaction that included congruency reached the level of significance, *p*s > .230.

Regarding congruency effects on error rates (ERs) the same approach revealed a similar pattern, respectively. Again, we observed an overall congruency effect, $F(1, 31) = 34.01$, *p* < .001, η^2_p = .52, in form of lower ERs after congruent (1.2%) than incongruent (7.7%) stimulus presentation. Importantly, also the interactions of congruency and effector system, *F*(1, 31) = 9.43, *p* = .004, η^2_p = .23, and congruency and task condition, *F*(1, 31) = 20.58, *p* < .001, η^2_p = .40, pointed in the same direction as RT data, showing a smaller congruency effect in vocal (4.8%) than in manual (8.1%) and similarly in single-task (2.5%) than in dual-task (10.3%) conditions. Descriptively, there was a trend that the difference in the congruency effect between vocal and manual responses was smaller in single-task conditions (1.7% vs. 3.5%) than in dual-task conditions (8.9% vs. 12.7%) which, however, (unlike regarding the RT data) failed to reach the level of significance, *F*(1, 31) = 3.89, *p* = .058, η^2_p = .11. Also a trend for an interaction of congruency and stimulus modality that pointed in the direction of a slightly stronger congruency effect in the visual (7.3%) than the auditory (5.5%) stimulation condition did not reach significance, *F*(1, 31) = 3.42, *p* = .074, η^2_p = .10. No other effect including congruency was observed in ERs, *p*s > .106.

Note that in the second supplementary analysis regarding a potential backward crosstalk effect (BCE) not the full sample set was included, as some participants always responded in the same task order and therefore produced no first response data in one of the two effector systems. This analysis revealed a significant BCE in that averaged over both effector systems firstly executed responses were executed faster when they were followed by a congruent (915 ms) than followed by an incongruent (1001 ms) second response, *F*(1, 23) = 23.48, *p* < .001, η^2_p = .51. There was a trend in the direction that this effect tended to be descriptively stronger in manual (120 ms) than in vocal (52 ms) first responses, *F*(1, 23) = 3.64, *p* = .069, η^2_p = .14. No further congruency-related effects were revealed by this analysis, *p*s > .206. There was also a significant BCE observable in ERs, *F*(1, 24) = .31.15, *p* < .001, η^2_p = .57, revealing more errors in first responses that were followed by an incongruent (10.1%) than by a congruent

(2.6%) second response. There were no significant differences in the BCE in ERs among effector systems, stimulus modalities, nor an interaction of both, *p*s > .310.

3.4 Discussion of Study B

In Study B, we compared vocal vs. manual dual-task costs in a typical dual-task situation involving intra-modal stimulus conditions. That is, we used either auditory or visual stimuli with two independent components (tone pitch and location and letter identity and orientation, respectively) to ensure that, although in each trial only one relevant stimulus modality was present, response selection of both responses had to be processed independently. Therefore, we could further investigate vocal-over-manual effector system prioritization (that became manifest in differences in dual-task costs) and its relation to the stimulus modality.

Substantially, we observed significant performance decrements due to multitasking in both effector systems throughout both stimulus conditions in form of increased RTs as well as error rates. This represents a crucial difference to the findings of Huestegge and Koch (2013), who did not observe any substantial vocal dual-response costs at all when both responses were triggered by one and the same aspect of a single stimulus, and a similarity to the findings in Experiment 6 of Study A. These observations highlight the relevance to establish a typical dual-task situation when investigating effector system prioritization in dual-task control, which results in more substantial dual-task costs. By using different aspects of intra-modal stimuli we were able to ensure that participants had to effectively select two responses and it was not sufficient to copy the response code of the first response (which was substantially more often the manual response than the vocal response) to successfully select the appropriate second response under still constant stimulus modality conditions.

Crucially, results of Study B further confirm the assumption of effector system prioritization of vocal over manual responses as reported by Huestegge and Koch (2013), Pieczykolan and Huestegge (2014), and also in Study A, indexed by significantly smaller dual-task costs associated with vocal than with manual responses what was not compromised by any reversed pattern regarding error data. Importantly, Study B provides an essential additional scientific value as it was the only study that was suited to conclusively rule out the possibility that the vocal-over-manual prioritization as observed by Huestegge and Koch (2013) was critically dependent by the used stimulus modality due to IOMC-like effects (cf. Fintor, Stephan et al., 2018; Göthe et al., 2016; Halvorson et al., 2013; Hazeltine et al., 2006; Maquestiaux et al., 2018; Stelzel et al., 2006; Stelzel & Schubert, 2011; Stephan et al., 2013; Stephan & Koch, 2010, 2011). As Study B now demonstrated, the relation of the two effector systems in the prioritization pattern is thereby not altered as a function of input-output modality compatibility. This observation again indicated a generally more pronounced influence of effector systems and their specific combinations on resource allocation policies in dual-task control compared to input modalities and their relation to output modalities.

Moreover, in contrast to Huestegge and Koch (2013) and Pieczykolan and Huestegge (2014) we here could demonstrate vocal prioritization not in the context of dual-response compounds but now additionally in a more typical dual-task situation. Results of Study B were even more clear-cut compared to the results of Study A, in that we now observed a significant differences in dual-task costs in raw RT data in the direct pairwise comparison.

Interestingly, while we observed significantly greater manual than vocal dual-task costs in both stimulus modality conditions, this effect was even more pronounced in auditory than in visual stimulation conditions, as indicated by the above reported three-way interaction. This observation would be in line with a modulation of effector system prioritization due to IOMC-like effects, as it suggests an especially pronounced vocal-over-manual prioritization in compatible stimulus modality conditions (or likewise an attenuation when the stimulus modality was compatible to the relatively dominated, manual effector system). However, the analysis of the error rates pointed in the opposite direction, which compromises such a clear conclusion. Thus, we cannot rule out that this effect simply reflects a speed-accuracy trade-off.

Nevertheless, it should not be neglected that such a potential effect of stronger prioritization in auditory stimulation conditions would fit former findings regarding input-output modality compatibility (e.g., Hazeltine et al., 2006). Hereby it is important to keep in mind that IOMC effects typically are observed in differences of overall smaller dual-task (or switch) costs in compatible mappings in comparison to incompatible mappings (e.g., Göthe et al., 2016; Hazeltine et al., 2006; Stephan et al., 2013; Stephan & Koch, 2010, 2011). Therefore, our setting implies a substantial difference to former IOMC studies. Specifically, our main focus was not to compare overall dual-task costs summarized over both responses, but differences between both effector systems within stimulus conditions. However, if we assume that there is a general disadvantage for vocal responses regarding dual-task costs when triggered by visual vs. auditory stimuli and/or likewise for manual responses when triggered by auditory vs. visual stimuli, this provides a suitable explanatory approach for a boost of our observed difference between effector systems in dual-task costs in auditory stimulation conditions and an attenuation of this effect by visual stimulation, respectively.

This assumption, however, cannot sufficiently explain the difference to some previous studies that observed greater dual-task costs for vocal than manual responses using visual or (simultaneous) visual and auditory stimulation (e.g., Fagot & Pashler, 1992; Holender, 1980; Schumacher et al., 2001; Stelzel et al., 2006). These studies involve some potentially important differences to our setting. First, none of these studies controlled for saccade occurrence. Meanwhile we observed cumulative evidence for an influence of the execution of an additional saccade on performance in another task (see e.g., Study A; Huestegge & Koch, 2013; Pieczykolan & Huestegge, 2014). Additionally, none of these studies was methodically directly comparable to our crucial approach to use intra-modal stimulus conditions involving stimuli with two independent features to trigger two responses (implying two separate response selection processes). Specifically, in the case of the experiments conducted by Fagot and Pashler (1992) that involved simultaneous stimulation as well as the study of Holender (1980), both responses were triggered by the same component of one visual stimulus, while Schumacher and colleagues (Schumacher et al., 2001) as well as Stelzel and colleagues (Stelzel et al., 2006) used two distinct (visual and auditory) stimuli.

Additionally, our approach to use stimuli with two independent dimensions added spatial stimulus congruency as a potential independent variable to our design and therefore allowed us to conduct respective supplementary analyses. Interestingly, the analysis of congruency reflected a very similar pattern of an asymmetrical effect between the two effector systems as analyses of dual-task interference. Consistent with the asymmetrical allocation of dual-task costs, also the congruency effect was more pronounced for manual than for vocal responses. Since this effect is also caused by interference among tasks, this observation might be interpreted as another marker for a prioritization of vocal over manual responses under task demands dealing with limited resources.

As the results of the present study represent a further example of a case in which we observed a prioritization of the overall slower (vocal) effector system over the overall faster (manual) effector system, they can again neither be explained by the response selection bottleneck model nor by any kind of rigid "first come, first served" mechanism. In contrast, in this setting, the response selection bottleneck model (Pashler, 1994) would predict same chances for prioritized processing of the two tasks, since stimulus processing should be finished for one and the same stimulus at the same time, especially because we counterbalanced the assignment of stimulus component to effector system. An adjusted version of the RSB model which would account for overall response speed and the possibility that the slower responses would suffer from more interference simply because it has more time to receive it, in contrast, would have predicted a reversed pattern, in which the overall faster response should be prioritized.

Similar to Study A, our results support capacity sharing or resource scheduling models that allow for parallel task processing (Meyer & Kieras, 1997a, 1997b; Navon & Miller, 2002; Tombu & Jolicœur, 2003). Moreover, they further strengthen the suggestion discussed in Study A that allocation of resources is also determined by task characteristics including effector systems due to a mechanism that allows for a relatively early anticipation of effector systems (see Section 6.3, for more details). As a consequence, results of Study B emphasize the feasibility to extend computational theories of dual-task control such as *executive control of the theory of visual attention* (*ECTVA*) by Logan and Gordon (2001) by incorporating effector system-based attentional weighting parameters (cf. Section 6.2).

Another interesting side aspect of our results was the observation that while vocal dual-task costs did not significantly differ as a function of stimulus modality, manual dual-task costs did, as indicated by an increase in manual dual-task costs in auditory stimulation conditions (driving the significant three-way interaction). This could be a first hint towards a deeper insight of mechanisms that are responsible for the IOMC effect (cf. Greenwald, 1972, 2003; Hazeltine et al., 2006). The IOMC effect has been assumed be mainly driven by an especially strong association of vocal responses to auditory stimuli rather than within the combination of manual responses to visual stimuli (cf. Ruthruff, Hazeltine, & Remington, 2006; see also Section 2.9). If we take this idea seriously, one could assume that the stronger manual dual-task costs in conditions with auditory stimulation originated in a strong tendency to interconnect the perceived auditory information (in this case based on both stimulus dimensions) to vocal responses. This potentially rather “automatic” link then has to be overcome to successfully perform response selection for the manual response according to the appropriate stimulus dimension. If this inherent interconnection, in contrast, is weaker for the link of visual stimulation to manual responses, it would require less cognitive control to overcome this association to be able to appropriately link vocal responses to the relevant visual stimulus dimension. This idea would further be in line with our observation of overall smaller dual-task costs for visual than auditory stimuli. It should be noted, however, that these considerations were not in the focus of our theoretical research question and therefore should be considered as indications that might be of interest in future research. The need for more evidence to draw any conclusion regarding these considerations is further underlined by the finding of opposing results regarding error rates (potential speed-accuracy trade-off).

Furthermore, while we observed strong evidence for effector system prioritization of vocal over manual responses with intra-modal stimulation, still further research is needed to examine the function of and the underlying mechanism causing this allocation. This is further discussed in the General Discussion (see Section 6.4).

All in all, we can conclude that Study B demonstrated prioritized resource allocation to vocal over manual tasks in a dual-task situation using auditory as well as visual stimulation. We can thus rule out that this prioritization is only driven by IOMC-like effects. Therefore, while the specific combination of input modality to effector system can to some extent modulate effector system prioritization due to IOMC-like effects by affecting (at least) speed-accuracy policies, it does not reverse or abolish effector system prioritization. Since manual responses were overall faster and stimulus processing was highly controlled, our findings indicate potential parallelism of all stages of task processing. Moreover, the scheduling of cognitive resources between those two tasks running in parallel cannot only be influenced by components that affect early stages of task processing (such as stimulus order or stimulus modality) but also by aspects that are usually assumed to be associated with late stages of task processing (effector systems). Conclusively, Study B again provides evidence for a more substantial influence of effector system characteristics on resource allocation among tasks in a typical multitasking situation compared to IOMC relations.

4. Study C: Two Sources of Task Prioritization: The Interplay of Response Order and Response Modalities

4.1 Introduction

In everyday life, we are often confronted with situations in which we have to perform more than one task at a time. Typically, performance (in at least one of the tasks) suffers in such situations when compared to executing only one task in isolation. To investigate the rules according to which cognitive resources are allocated among tasks, multitasking research typically compares behaviour under different, systematically manipulated task requirements.

As described in the General Introduction (see Section 1.4.1), several methodological approaches have been established to address cognitive mechanisms underlying dual-task control. In Study A and B we already examined dual-task differences when using the *simultaneous onset paradigm,* in which two stimuli (each requiring a distinct single response) are presented at exactly the same time (or as in the special case of Study B, one stimulus that, however, contains imperative information on two independent dimensions). In this paradigm, performance is then compared between single- vs. dual-task conditions (cf. also e.g., Huestegge & Koch, 2013; Pieczykolan & Huestegge, 2014, 2017, 2018; Schumacher et al., 2001; Stelzel et al., 2006). One disadvantage of this paradigm is, however, that single- and dual-task conditions not only differ with respect to the degree to which tasks are performed simultaneously, but also whether one or two task representations need to be prepared (or kept active) during a particular trial.

Consequently, maybe the most prominent paradigm to study dual-task control processes is the *psychological refractory period* (PRP) paradigm, in which two tasks are executed in each trial while the temporal overlap is manipulated. Specifically, this is done by presenting stimuli with a short, variable temporal delay (the SOA), whereby the degree of temporal overlap of cognitive task requirements varies systematically (Telford, 1931; Welford, 1952; see also Bratzke et al., 2008; Hirsch, Declerck, & Koch, 2015; Janczyk, Augst, & Kunde, 2014; Kunde, Wirth, & Janczyk, 2018; Pashler, 1984, 1994; Strobach, Becker, Schubert, & Kühn, 2015)

As an empirical consequence, a decrease of the SOA typically yields an increase in RTs of the task in which the stimulus was presented second, in which usually also the response is executed second (Task 2). RTs of the firstly executed task (Task 1, associated with the stimulus which is presented first) typically remain unaffected by SOA. This pattern is normally referred to as the PRP (or SOA) effect (e.g., Bratzke et al., 2008; Fagot & Pashler, 1992; Janczyk & Kunde, 2010; Pashler, 1984; see also Pashler, 1994).

Based on these observations, Pashler (1994) proposed the response selection bottleneck (RSB) model including a bottleneck at a central processing stage of tasks that has already been introduced above (see Section 1.2). Crucially, Pashler interpreted the PRP effect as evidence that selection of the task-appropriate response of two tasks can only occur serially. While regarding stimulus processing and response execution possible parallelism in both tasks is assumed, Pashler proposed that response selection in Task 2 is always delayed (i.e., cannot proceed) until completion of response selection in Task 1. Remember that this is assumed to conceptualized in an all-or-none fashion and solely based on task order

According to these assumptions, the PRP effect (i.e., the influence of SOA on Task 2 RTs) is solely determined by the duration of response selection in Task 1. The main reason for the bottleneck-based prioritization of Task 1 over Task 2 is that stimulus processing in Task 1 is usually finished first (due to SOA), and thereby Task 1 arrives earlier at the central (response selection) stage, where it occupies all available resources first. As relevant for the present work, a PRP effect was also demonstrated using different effector systems, including oculomotor responses (e.g., Pashler, Carrier, & Hoffman, 1993). Bratzke and colleagues (Bratzke et al., 2008) furthermore were able to demonstrate the stability of the PRP effect when the effector systems associated with the two tasks were reversed across tasks. Importantly though, the study of Bratzke and colleagues was not conducted to compare any potential differences in the extent of the PRP effect among effector systems or caused by effector system reversals.

Meanwhile, the assumption of strictly serial central processing of response-related task features has been challenged on various levels (cf. Section 1.2). Especially, Hommels (1998) observation of the backward crosstalk effect (influence of response-response congruency on Task 1 RTs; cf. Section 1.2, for a deeper discussion; see also Durst & Janczyk, 2018, 2019; Hommel & Eglau, 2002; Huestegge et al., 2018; Janczyk et al., 2018; Janczyk & Huestegge, 2017; Janczyk, Pfister et al., 2014; Renas et al., 2018) has been interpreted in terms of (at least partly) parallel central processing across tasks. Resource sharing theories, on the other hand, even propose the possibility of completely parallel response selection processes across tasks while limited cognitive resources must be shared continuously (Meyer & Kieras, 1997a, 1997b; Navon & Miller, 2002; Tombu & Jolicœur, 2003). However, while these models are based on a substantially different rationale than a serial response selection account, their predictions regarding performance after sequential stimulus presentation in fact are quite similar. They still assume that a major portion of resources is allocated to Task 1 response selection first, until later resources are shifted to complete Task 2 response selection. So, similar to the RSB model, also here task order is a major factor for predicting task prioritization policies. However, they disagree with the idea of an inflexible, all-or-nothing mechanism. Instead, they rather suppose that resource allocation can be flexibly, modulated in a graded fashion, for instance, due to strategic reasons, by particular task demands, or instructions (see Fischer & Plessow, 2015, for an overview; Logan & Gordon, 2001, for a discussion). This is, for example, supported by findings of Miller and colleagues (Miller et al., 2009) who demonstrated that parallel processing is fostered in situations in which it represents a particular efficient strategy (in the context of particularly frequent short SOAs). Taken together, resource sharing models interpret the typical observation of Task 2 performance dependency on SOA manipulation as reflection of specific resource allocation policies (prioritizing Task 1 based on subtask order), that, however, potentially is modulated by other subtask characteristics.

When we now consider previous findings regarding the influence of effector systems and effector system combinations demonstrated above, this leads us to a new, interesting research question. Remember, that we could already demonstrate particular effector systems associated with the tasks at hand as substantial factor to influence resource allocation, in situations in which both tasks were triggered at the exact same time and therefore without any externally suggested (or instructed) subtask order. This was previously observed in multiple (simultaneous) action control situations when only one stimulus was used (Huestegge & Koch, 2013; Pieczykolan & Huestegge, 2014) as well as in paradigms with two discrete stimuli (Study A) or single stimuli with two relevant dimensions (Study B). The important rationale that holds for all studies mentioned here is that systematic differences among tasks associated with different effector systems in the size of dual-task costs (i.e., the RT difference between single- and dual-task performances) were interpreted as a marker for effector system prioritization. Note that we here also refer to the manipulation of two vs. one motor execution processes (in respectively different effector systems) in response to one and the same stimulus, as used by Huestegge and Koch (2013) and Pieczykolan and Huestegge (2014). Based on the results presented above, we assumed that the relative size of dual-task costs suggested a prioritization of oculomotor responses over pedal responses, of pedal over vocal responses, and of vocal over manual responses in a consistent hierarchy.

It is essential to bear in mind that this pattern is in line with predictions of flexible resource sharing but neither with the RSB model nor with any corresponding “first come, first served" mechanism. Specifically, previous data suggest that response selection processes associated with particular effector systems are flexibly weighted in terms of allocated resources.

We here identified two sources that presumably play a role in how cognitive resources are allocated in dual-task situations: task order and effector system. Until now, however, nothing is known about the interplay of these two sources of task prioritization. In Study C, therefore, we want to examine whether the PRP effect – as a marker for the extent of task prioritization based on task order – can be modulated by effector system prioritization. Since flexible resource sharing accounts incorporate the assumption that the PRP effect is a reflection of in principle flexible and parallel resource allocation, it is reasonable to expect such a modulation by order-unrelated task characteristics. Nevertheless, although some dual-task studies already investigated PRP effects under the usage of various effector systems, (e.g., Bratzke et al., 2008; Fagot & Pashler, 1992; Hibberd, Jamson, & Carsten, 2010; Janczyk & Kunde, 2010) the here addressed question if the PRP effect is modulated by effector system prioritization effects has never been tackled in previous research.

One possibility is that task order-based effects are so strong that the corresponding allocation policy is immune to any effects of effector systems prioritization. This would seem plausible if we assume that information about task characteristics associated with effector systems is processed relatively late (e.g., only at the last stage of response execution-related processing). On the other hand, our observations of Study A and B rather supported the idea that participants anticipate associated effector systems at a relatively early processing stage whereby resource allocation policies were affected. Based on this rationale, PRP effects might vary as a function of effector system, as the resource allocation scheme might be modulated by effector system anticipation also in situations of sequential task initiation. To be specific, we here refer to a modulation of the PRP effect as a function of the effector system associated with Task 2 with a perfectly controlled (i.e., the same) Task 1.

In Study C, we combined oculomotor, vocal, and manual responses in three pairwise combination groups in a typical PRP setup involving two basic spatial left/right decision tasks triggered by sequentially presented auditory and visual stimuli. To control for any effects of stimulus processing related to stimulus modality as well as IOMC effects, we additionally again varied the assignment of stimulus to response modality (S-R modality mapping) within combination groups (cf. Study A). Task order (which effector system is associated with Task 1 vs. Task 2, respectively) was also manipulated within groups so that each participant experienced both possible task order conditions of their specific effector system combination (e.g., “vocal first and manual second” as well as “manual first and vocal second” for all participants in the vocal-manual combination group).

Based on cumulative evidence for the influence of task order in the PRP paradigm we generally expected to observe typical PRP effects in form of longer Task 2 RTs in short SOA conditions than in long SOA conditions in all effector systems and S-R modality mappings. Crucially, although included in our analyses we did not mainly focus on a comparison of PRP effects as a function of effector system order *within* each pairwise combination group. That is because the observation of asymmetrical PRP effects within groups would only indicate that response selection processes are not abstract in the sense that they are constant for any left/right decision, irrespective of the effector system that is associated with this decision. In these comparisons, any difference between the size of the PRP effect could also be based on different Task 1 effector systems. Instead, we compared PRP effects in different Task 2 effector systems that both are combined with the same Task 1, that is *across* pairwise combination groups. Specifically, we compare PRP effects in vocal vs. manual Task 2s after an oculomotor Task 1, in vocal vs. oculomotor Task 2s after a manual Task 1, and in oculomotor vs. manual Task 2s after a vocal Task 1.

Two outcomes are conceivable. If the PRP effect is solely determined by Task 1 response selection duration (as would be predicted from a classic RSB framework that assumes an all-or-none resource allocation policy), it should not differ as a function of Task 2 effector system as long as Task 1 is held constant. Note that this would also be conceivable with the predictions of flexible resource sharing if effector system prioritization is cancelled out by task order-based resource allocation policies, as soon as tasks are initiated sequentially. However, under the assumption of task order-based prioritization of Task 1 in a flexible resource allocation framework that interacts with other sources of task prioritization such as effector systems, a modulation of the size of the PRP effect (as marker for underlying resource allocation policies) by the effector system associated with Task 2 becomes possible. Specifically, the PRP effect (reflecting the extent of task order-based prioritization of Task 1 over Task 2) should be smaller when Task 2 is associated with an effector system with a higher priority within the ordinal effector system prioritization pattern (oculomotor > vocal > manual).

4.2 Method

Participants

In total, 72 participants took part in Study C, 24 in each of the three pairwise combination groups of oculomotor, vocal, and manual tasks. Overall, eleven participants fell under a pre-set exclusion criterion of producing more than 33% invalid or erroneous trials (cf. Study A and B): Data of three further participants had to be excluded due to technical issues during data collection. We recollected data from 14 new participants in order to sustain constant group size and full counterbalancing within groups. The final sample (22 males, 50 females) had a mean age of 24.3 years (*SD* = 6.6). Participants were recruited from the local university's student panel and compensated by course credit or monetary reward for their participation. All were right handed and had normal or corrected to normal hearing and vision. All participants gave informed written consent to take part in the experiment and were naïve regarding the purpose of the study.

Apparatus and Stimuli

In most respects, apparatus and stimuli were the same as in Study A. Participants were seated approx. 67 cm in front of the same 21 inch cathode ray tube screen (spatial resolution of 1024 x 768 pixels, temporal resolution of 100 Hz) and directly in front of a microphone (Sennheiser e 835-S; same as used in Study B and Experiment 2, 4, and 6 in Study A). Moreover, the same eye tracker system sampled eye movements at 1000 Hz (Eyelink 1000, SR Research Mississauga, Ontario, Canada) in order to register saccade latencies and direction of the right eye in those conditions requiring oculomotor responses (oculomotor-vocal combination group and oculomotor-manual combination group), or otherwise to control for unintended saccades (vocal-manual combination group). Head movements were minimized with help of a chinrest (including forehead support). Vocal response latencies were measured by means of the voice key function integrated in the programming software (Experiment Builder, version 2.1.140, SR Research) via the microphone and vocal responses were coded online by the experimenter and additionally recorded. Manual keypress responses had to be executed by operating the left and right arrow key on a standard (German) QWERTZ keyboard with participant’s right index finger. The Experiment Builder software was used to run the experiment and to log events related to oculomotor, manual, and vocal behaviour.

Similar to Study A and B, throughout each block a green fixation cross (size = 0.43° of visual angle) at the centre of the screen and two green rectangular squares at an eccentricity of 8.5 degrees of visual angle (size = 0.43° each) to the left and right of it were presented in front of a black background. These green squares served as targets for oculomotor responses, but were also present in the vocal-manual combination group to keep the visual input constant in order to provide comparability among groups. Visual stimuli were (easily distinguishable) green arrows presented 0.43° above the fixation cross pointing either to the left or to the right (“<” or “>”, size = 0.86°). Auditory stimuli were 1000 Hz sinusoidal tones (the same as used in Study A, same holds for visual stimuli) presented either to the left or right ear via supra-aural headphones (Sennheiser, PMX 95).

Procedure

At the beginning of the experiment, participants received instructions (verbally by the experimenter and visually on an instruction screen). The experiment contained of four different block types, based on two task orders (e.g., vocal response first, manual second vs. manual response first, vocal second in the vocal-manual combination group), and two S-R modality mappings (e.g., visual stimuli triggering manual responses and auditory stimuli triggering vocal responses, VM-AV, vs. the reversed mapping, VV-AM). As each block type was repeated, the experiment contained eight blocks in total that each consisted of 64 trials (approximated experiment duration was 45 minutes).

In order to reduce participant confusion, the S-R modality mapping stayed constant for the first half of the experiment and was switched only once (after the first half). The order of S-R modality mappings as well as the sequence of the different task order blocks was counterbalanced across participants (but kept constant for each individual). So, for instance, a participant had to respond manually first, vocally second in the first two blocks (vocal-manual combination group) and vocally first, manually second in the third and fourth block, all along with the visual-vocal auditory-manual S-R modality mapping. Next, this sequence regarding task order was repeated in the visual-manual auditory-vocal S-R modality mapping condition in the second half of the experiment. Stimuli were consistently presented in the same order in which participants should respond. For example, in the “manual first” condition of the vocal-manual combination group, participants in the VV-AM mapping condition always heard the auditory stimulus before the visual stimulus appeared in screen and vice versa in the VM-AV mapping condition.

Each block started with an instruction (containing information about stimulus order, corresponding required response order, and S-R modality mapping). The instruction screen was followed by a three-point horizontal calibration routine of the eye tracking system, followed by a short reminder of the current task. Stimulus presentation duration (for visual as well as auditory stimuli) was always 80 ms, followed by a variable SOA of 50, 200, 400, or 800 ms until the second stimulus was presented (again for 80 ms). All directional combinations of both stimuli (auditory sinusoidal tone on the right or left ear and visual arrow pointing to right or left) occurred in randomized order equally often in each block.

Instructions specified that participants should always focus on the central fixation cross when no oculomotor response was required. That is, participants in the vocal-manual combination group should fixate the central screen throughout each block of the experiment. In the oculomotor-vocal and oculomotor-manual combination groups, participants were instructed to return with their gaze to the fixation cross as soon as they had executed the required oculomotor response. In combination groups that involved manual responses, participants were instructed to position their right index finger loosely (without pressing the key) on the *arrow down* key on the keyboard as a resting position, prior to and after executing right and left key press responses. This “home key” was located centrally between the two response keys (*arrow right* and *arrow left*). Thereby, we aimed at increasing comparability to oculomotor responses (cf. also Study A). In combination groups involving vocal responses, participants were instructed to utter the words “rechts” or “links” (German for right or left). By instruction, responses should always be executed in a spatially congruent manner to the relevant stimulus (e.g., uttering “links” in response to an arrow pointing left).

Consecutive trials were separated by fixed interstimulus interval (ISI) of 3000 ms. Because second stimuli were presented with a variable SOA, this only refers to the respective first stimulus of two consecutive trials. Consequently, the interval between the second stimulus of a preceding and the first stimulus of a successive trial also varied depending on SOA variation (2950, 2800, 2600, or 2200 ms, respectively). Furthermore, in trials in which participants responded in the wrong order (which was fixed within blocks), or if they already responded (with one of the two effector systems) before the corresponding stimulus had been presented, an error feedback appeared for 300 ms ("error"/"to soon" plus a repetition of the current task requirements, e.g., "key press first"/"saccade first"/"utter first" in the context of a "wrong order" feedback and "pay attention to the tone/arrow" in the context of premature responses).

Design

Independent within-subject variables were stimulus modality associated with Task 2 (visual, auditory) and SOA (50 ms, 200 ms, 400 ms, 800 ms). The independent between-subject variable was the effector system of Task 2 (oculomotor, vocal, manual, which were each combined with both other effector systems in Task 1). As dependent variables, we analysed RTs and error rates (ERs). Note that our crucial comparisons related to PRP effect differences between two different Task 2 effector systems for the same Task 1 (in terms of the same effector system and stimulus modality) and under otherwise comparable (i.e., stimulus modality triggering Task 2) conditions. To be precise, we compared PRP effects in Task 2 for vocal vs. manual Task 2 RTs while both were preceded by the same oculomotor Task 1, the PRP effect for oculomotor vs. vocal Task 2 when both were preceded by the same manual Task 1, and the PRP effect for oculomotor vs. manual Task 2 when both were preceded by the same vocal Task 1, each for both stimulus to response modality assignments separately.

4.3 Results

In case of sphericity violations, Greenhouse-Geisser corrections were used. Uncorrected degrees of freedom and respective ε estimates are reported.

4.3.1 Data Treatment

Overall, 12.4% of all trials had to be discarded from the analyses, because they were afflicted with an omission error regarding one or both of the required responses, with an unwarranted saccade prior to the actually required responses in the vocal-manual combination group, or due to responses execution in the wrong order. Note that due to effector-specific baseline differences in the occurrence of omission errors (e.g., due to differences in the sensitivity of measurement devices), we decided to not consider omission errors in error analyses. In order to exclude measurement artefacts, also responses given within the first 50 ms after stimulus onset were excluded (further 0.3%). Outliers (further 6.8%) were defined as responses slower or faster plus/minus two SDs from the individuals mean in each condition and discarded as well. Finally, 6.0% of the remaining valid trials contained a directional error (e.g., left response when a right response would have been required). Only valid and correct trials were considered in RT analyses but ERs (containing only errors executed in valid trials) were analysed separately.

4.3.2 Reaction Times

The RT distribution over SOAs for the different task conditions are shown in Figure 4.1. Thereby, Figure 4.1 illustrates that PRP effects (in terms of an increase of Task 2 RT with decreasing SOA) were observed throughout all groups and conditions. This indicates a general Task 1 prioritization in line with our predictions, and is an important prerequisite for any search of modulations of this effect by the effector system associated with Task 2

As outlined above, the core comparisons refer to differences in the PRP effect for a constant Task 1 (in terms of its associated stimulus modality and effector system) as a function of Task 2 effector system (i.e., lines that are illustrated in panels side by side in Figure 4.1). This resulted in six 2x4 ANOVAs with the independent between-subject variable Task 2 effector system (i.e., the different effector system combination groups) and the independent within-subject variable SOA.

Task 2 performance

For the comparison of *visually* triggered *vocal* vs. *manual* Task 2 responses after an auditory triggered oculomotor response in Task 1, we observed a significant main effect for Task 2 effector system: Manual responses (809 ms) were overall faster than vocal responses (1113 ms), $F(1, 46) = 29.70$, $p < .001$, $\eta^2_p = .39$. The main effect of SOA, representing an increase of RTs with decreasing SOAs (728 ms vs. 884 ms vs. 1071 ms vs. 1159 ms for SOA of 800 ms, 400 ms, 200 ms, and 50 ms, respectively), $F(3, 138) = 365.44$, $p < .001$, $\eta^2_p = .89$, $\varepsilon = .56$, was significant, too. Crucially, we observed a significant interaction of Task 2 effector system and SOA, showing a stronger PRP effect for manual (RT difference between shortest and longest SOA: 514 ms) than for vocal responses (RT difference between shortest and longest SOA: 349 ms), $F(3, 138) = 13.64$, $p < .001$, $\eta^2_p = .23$, $\varepsilon = .56$.

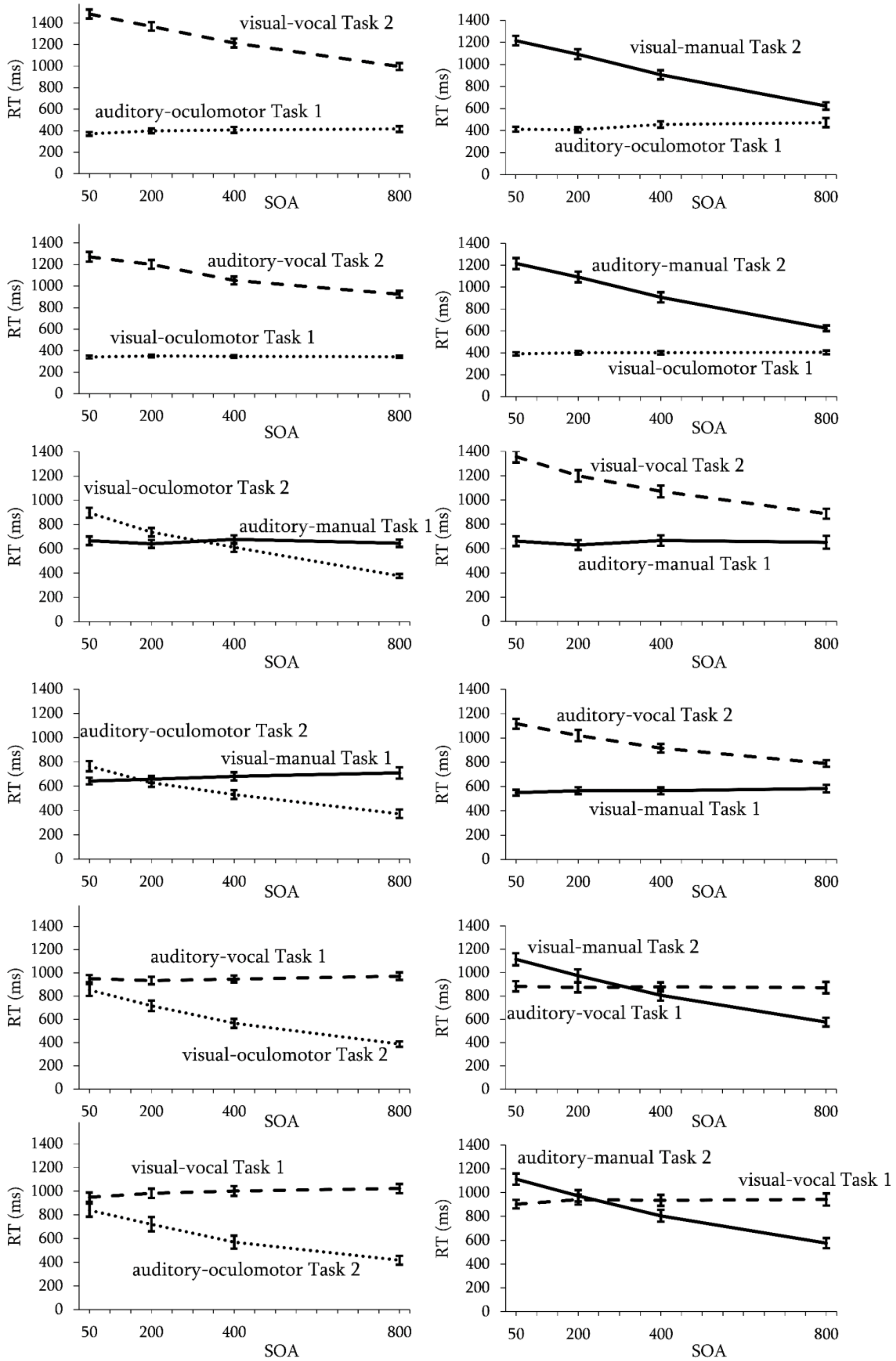

Figure 4.1. RTs for Task 1 and Task 2 as a function of effector combination, Task 2 effector system, and S-R modality mapping. Conditions to be compared (same Task 1 but varying Task 2 effector system) are presented side by side. Error bars represent mean SEs.

The same pattern was observed when comparing *auditorily* triggered *vocal* vs. *manual* Task 2 RTs after a visually triggered oculomotor response in Task 1. Again, manual responses (959 ms) were overall faster than vocal responses (1267 ms), $F(1, 46) = 33.97$, $p < .001$, $\eta^2_p = .43$. Again, RTs overall increased with decreasing SOAs (811 ms, 1062 ms, 1230 ms, 1349 ms), $F(3, 138) = 443.22$, $p < .001$, $\eta^2_p = .91$, $\varepsilon = .66$. The significant interaction of SOA and effector system showed that there was a stronger PRP effect for manual (RT difference between shortest and longest SOA: 590 ms) than for vocal responses (RT difference between shortest and longest SOA: 488 ms), $F(3, 138) = 4.46$, $p = .014$, $\eta^2_p = .09$, $\varepsilon = .66$. An additional comparison revealed that the difference in the PRP effect between conditions involving a vocal and a manual Task 2 was not significantly modulated by stimulus modality, $F(3, 138) = 2.30$, $p = .091$, $\eta^2_p = .05$, $\varepsilon = .86$.

For the comparison of *visually* triggered *oculomotor* vs. *vocal* Task 2 RTs following an auditorily triggered manual response in Task 1, we observed that oculomotor responses (575 ms) were significantly faster than vocal responses (957 ms), $F(1, 46) = 61.97$, $p < .001$, $\eta^2_p = .57$. Task 2 RTs increased with decreasing SOAs (579 ms, 722 ms, 822 ms, 939 ms), $F(3, 138) = 190.03$, $p < .001$, $\eta^2_p = .81$, $\varepsilon = .53$. However, there was no interaction of Task 2 effector system and SOA, $F(3, 138) = 1.38$, $p = .255$, $\eta^2_p = .03$, $\varepsilon = .53$.

The same pattern was observed for the comparison of *auditorily* triggered *oculomotor* vs. *vocal* Task 2 RTs following a visually triggered manual response in Task 1. There was a significant main effect of Task 2 effector system (656 ms vs. 1117 ms), $F(1, 46) = 75.30$, $p < .001$, $\eta^2_p = .62$, and of SOA (631 ms, 839 ms, 962 ms, 1114 ms), $F(3, 138) = 350.62$, $p < .001$, $\eta^2_p = .88$, $\varepsilon = .73$ in the same direction as regarding the reversed S-R modality assignment. Again, there was no significant interaction, $F(3, 138) = 2.13$, $p = .119$, $\eta^2_p = .04$, $\varepsilon = .73$.

Regarding the comparison of *visually* triggered *oculomotor* vs. *manual* Task 2 RTs following an auditorily triggered vocal Task 1, the ANOVA revealed overall faster oculomotor (637 ms) than manual responses (859 ms), $F(1, 46) = 10.81$, $p = .002$, $\eta^2_p = .19$, and increasing Task 2 RTs with decreasing SOAs (510 ms, 695 ms, 836 ms, 951 ms), $F(3, 138) = 376.23$, $p < .001$, $\eta^2_p = .89$, $\varepsilon = .68$. Again, there was no significant interaction between Task 2 effector system and SOA, $F(3, 138) = 1.90$, $p = .155$, $\eta^2_p = .04$, $\varepsilon = .68$.

Finally, we observed exactly the same pattern when comparing *auditorily* triggered *oculomotor* vs. *manual* Task 2 RTs following a visually triggered vocal Task 1. There were faster oculomotor (630 ms) than manual (859 ms) responses, $F(1, 46) = 14.49$, $p < .001$, $\eta^2_p = .24$, an increase of RTs for decreasing SOAs (480 ms, 681 ms, 842 ms, 975 ms), $F(3, 138) = 421.29$, $p < .001$, $\eta^2_p = .92$, $\varepsilon = .54$, and, again, no significant interaction, $F(3, 138) = 2.07$, $p = .143$, $\eta^2_p = .04$, $\varepsilon = .54$. PRP effects in Task 2 RTs in terms of a simplified graphic rendition in form of difference measurements of RTs in the shortest minus the longest SOA conditions are illustrated in Figure 4.2.

In order to rule out a potential alternative explanation of the data, we conducted a further, supplementary analysis. Namely, under the assumption of parallel resource sharing between tasks the observation of significantly greater manual than vocal PRP effects after a constant oculomotor Task 1 could alternatively be explained by different durations of an effector system-specific (manual vs. vocal) response selection process. If response selection for manual responses was generally more time consuming than that of vocal responses, this could yield to a more pronounced manual PRP effect, too. Crucially, this would not necessarily imply any prioritization processes. Instead, merely a shorter time span during which resources had to be shared could yield the same results.

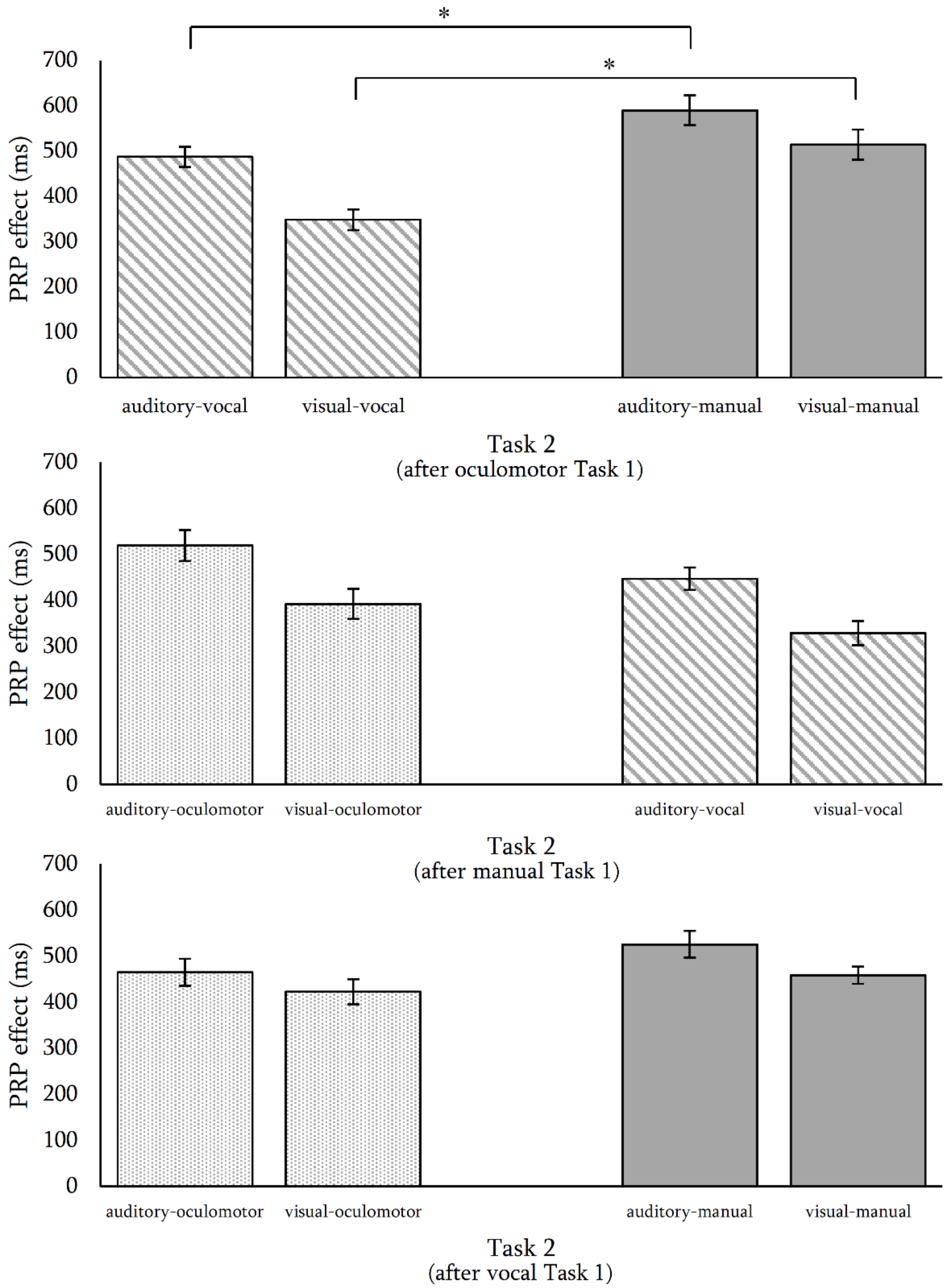

Figure 4.2. PRP effects in RTs (in terms of a difference measurement or RTs in shortest minus longest SOA conditions) as a function of stimulus modality and effector system in comparisons after a respectively same Task 1. Error bars represent mean SEs.

If this is the case, this should also hold true when manual and vocal responses are associated with Task 1 instead of Task 2 (combined with an oculomotor Task 2, respectively). To assure the interpretation of our main results (difference between manual and vocal PRP effects) as marker for effector system prioritization and not solely based on an effector system-specific response selection duration we additionally compared PRP effects observed in oculomotor Task 2 performance as a function of Task 1 effector system. Specifically, we now also compared performance in the visual-oculomotor Task 2 of the oculomotor-vocal vs. oculomotor-manual combination groups when Task 1 was the auditory-vocal vs. auditory-manual task, respectively, and the same for the reversed S-R modality mapping condition (auditory-oculomotor Task 2 performance as a function of visual-vocal vs. visual-manual Task 1).

The corresponding 4 (SOA) x 2 (group, i.e., now referring to different Task 1 effector systems) ANOVA regarding visual-oculomotor Task 2 performance revealed a significant effect of SOA, $F(3, 138) = 354.06$; $p < .001$; $\eta^2_p = .89$; $\varepsilon = .62$. Crucially, it revealed neither a significant effect of group, $F(1, 46) = 0.29$; $p = .592$; $\eta^2_p = .01$, nor a significant interaction, $F(1, 138) = 1.43$; $p = .245$; $\eta^2_p = .03$, $\varepsilon = .62$.

The same pattern was observed for auditory-oculomotor Task 2 performance regarding which we again observed a significant effect of SOA, $F(3, 138) = 222.64$; $p < .001$; $\eta^2_p = .83$; $\varepsilon = .63$, but neither of group, $F(1, 46) = 1.05$; $p = .311$; $\eta^2_p = .02$, nor an interaction, $F(1, 138) = 1.20$; $p = .304$; $\eta^2_p = .03$, $\varepsilon = .63$. Thus, we can rule out that the differences between PRP effects in vocal vs. manual Task 2 performance could be explained in terms of different durations of effector system-specific vocal vs. manual response selection processes.

Task 1 performance

For the sake of completeness, we also compared Task 1 performance within effector systems as a function of Task 2 effector system, for both S-R modality mappings, respectively. Statistical test results are summarized in Table 4.1. As can be seen in Table 4.1, Task 1 response latencies are influences by SOA in most Task 1 types (all despite the auditory-vocal and visual-oculomotor Task 1, whereupon the latter only shortly missed the significance level). This is in the form of a slight increase of Task 1 RTs with increasing SOA (see also Figure 4.1).

There was no influence of Task 2 effector system on Task 1 performance despite for the visual-oculomotor and the visual-manual Task 1. In these two cases, the visual-oculomotor task was associated with slightly higher RTs when followed by an auditory-manual than by an auditory-vocal task, and RTs in the visual-manual task were slightly higher when followed by an auditory-oculomotor than by an auditory-vocal Task 2, respectively. Note that this could be a first hint towards more backward interference in the combination of oculomotor and manual tasks compared to each of these effector systems combined with vocal responses. Crucially however, the gradient of Task 1 RTs over SOA did not differ as a function of Task 2 effector system regarding any Task 1 types.

Table 4.1.

Statistical test results for comparisons of Task 1 performance as a function of SOA and Task 2 effector system.

	SOA				Group			SOA*Group			
	F(3, 138)	p	η^2_p	ε	F(3, 138)	p	η^2_p	F(3, 138)	p	η^2_p	ε
Visual-oculomotor Task 1	2.64	.052	.05		7.72	.008	.14	1.19	.316	.03	
Auditory-oculomotor Task 1	8.41	.001	.16	.56	1.24	.271	.03	1.33	.268	.03	.56
Visual-manual Task 1	5.58	.015	.11	.42	7.01	.011	.13	1.41	.246	.03	.42
Auditory-manual Task 1	3.15	.040	.06	.77	0.05	.825	.00	0.42	.686	.02	.77
Visual-vocal Task 1	7.74	.001	.14	.72	1.22	.276	.03	0.70	.508	.02	
Auditory-vocal Task 1	1.40	.245	.03		2.20	.15	.05	1.15	.331	.02	

4.3.3 Error Rates

Errors occurred relatively rarely (overall 6% of valid data). Nevertheless, we conducted the same six ANOVAs as for Task 2 RTs also for Task 2 ERs. Regarding the comparison of Task 2 ERs between a *visually* triggered *vocal* vs. *manual* Task 2 (after an auditory-oculomotor Task 1) ERs did not differ significantly overall between the vocal (2.1%) vs. the manual (4.1%) task, $F(1, 46) = 3.04$, $p = .088$, $\eta^2_p = .06$. However, ERs increased significantly with decreasing SOAs (1.5%, 2.6%, 3.1%, 5.1%), $F(3, 138) = 10.39$, $p < .001$, $\eta^2_p = .18$, $\varepsilon = .63$. Unlike in RTs, there was no significant interaction of Task 2 effector system and SOA regarding ERs, $F(3, 138) = 0.10$, $p = .900$, $\eta^2_p = .00$, $\varepsilon = .63$.

In the comparison of *auditorily* triggered *vocal* vs. *manual* Task 2 ERs (after a visual-oculomotor Task 1) we observed no significant effect of Task 2 effector system (3.2% errors in the vocal vs. 2.6% errors in the manual tasks), $F(1, 46) = 0.42$, $p = .520$, $\eta^2_p = .01$, nor a significant effect of SOA, $F(3, 138) = 2.77$, $p = .052$, $\eta^2_p = .06$, $\varepsilon = .87$ – although there was a slight trend towards fewer errors with increasing SOA (1.9%, 3.1%, 3.4%, 3.2%). Again, there was no significant interaction, $F(3, 138) = 1.78$, $p = .161$, $\eta^2_p = .04$, $\varepsilon = .87$.

The comparison of *visually* triggered *vocal* vs. *oculomotor* Task 2 ERs (after an auditory-manual Task 1) revealed a significant effect of SOA (2.0%, 4.3%, 5.7%, 6.2%), $F(3, 138) = 7.83$, $p < .001$, $\eta^2_p = .15$, $\varepsilon = .83$. But there was neither an effect of Task 2 effector system (oculomotor: 5.6%; vocal: 3.5%), $F(1, 46) = 1.78$, $p = .189$, $\eta^2_p = .04$, nor an interaction, $F(3, 138) = 1.60$, $p = .201$, $\eta^2_p = .03$, $\varepsilon = .83$.

A comparable pattern was observed for comparing *auditorily* triggered *oculomotor* and *vocal* Task 2 ERs (after a visual-manual Task 1). There was a significant effect of SOA (3.7%, 4.8%, 6.2%, 5.0%), $F(3, 138) = 3.38$, $p = .030$, $\eta^2_p = .07$, $\varepsilon = .79$, but neither a significant effect of Task 2 effector system (oculomotor: 4.2% vs. vocal: 5.7%), $F(1, 46) = 0.29$, $p = .591$, $\eta^2_p = .01$, nor a significant interaction, $F(3, 138) = 0.74$, $p = .501$, $\eta^2_p = .02$, $\varepsilon = .79$.

Comparing *visually* triggered *oculomotor* vs. *manual* Task 2 ERs (after an auditory-vocal Task 1) revealed a significant effect of Task 2 effector system (oculomotor: 7.1%, manual: 2.3%), $F(1, 46) = 10.58$, $p = .002$, $\eta^2_p = .19$, as well as a significant effect of SOA (2.5%, 3.9%, 5.6%, 6.9%), $F(3, 138) = 6.19$, $p = .002$, $\eta^2_p = .12$, $\varepsilon = .76$. Again, there was no interaction, $F(3, 138) = 0.29$, $p = .776$, $\eta^2_p = .01$, $\varepsilon = .76$.

Finally, regarding the comparison of *auditorily* triggered *oculomotor* vs. *manual* Task 2 ERs (after a visual-vocal Task 1) we observed higher ERs in the oculomotor (2.7%) than in the manual (0.6%) task, $F(1, 46) = 12.70$, $p = .001$, $\eta^2_p = .22$. Here, we also observed a significant effect of SOA, $F(3, 138) = 5.09$, $p = .002$, $\eta^2_p = .10$, as well as a significant interaction, $F(3, 138) = 5.93$, $p = .001$, $\eta^2_p = .11$. However, the latter was mainly caused by the fact that there was no notable alteration of generally low manual ERs among SOAs (0.2%, 1.0%, 0.8%, 0.5%), whereas there was an unexpected influence of SOA for oculomotor responses that was reversed compared to all other conditions reported above (SOA 800 ms: 4.3%, SOA 400 ms: 3.7%, SOA 200 ms: 2.1%, SOA 50 ms: 0.7%). This also resulted in an unusual pattern regarding the main effect of SOA (2.2%, 2.3%, 1.4%, 0.6%).

4.3.4 Comparison Within Pairwise Combination Groups

For the sake of completeness, we additionally conducted three separate 2x4x2 ANOVAs with the independent within-subject variables effector system order, SOA and stimulus modality regarding Task 2 RTs and Task 2 ERs for each of the three pairwise combination groups. The corresponding statistical test results are depicted in Table 4.2 (regarding RTs) and Table 4.3 (regarding accuracy). Note that effector system order also includes the Task 2 effector system, but differs from this independent variable of the above described analyses in regard that within pairwise combinations the order of two fixed effector systems is the manipulation of interest. The results indicate that in the vocal-manual and in the oculomotor-manual group, the PRP effect differed as a function of effector system order, suggesting that response selection of a comparable left/right decision takes a different amount of time for the two effector systems (there was no corresponding effect in the oculomotor-vocal group). This was not compromised by the error data.

Table 4.2

Overview of statistical test results (three-way ANOVAs regarding Task 2 RTs) in the pairwise combination groups.

Pairwise combination group		Vocal-Manual				Oculomotor-Manual				Oculomotor-Vocal			
Source of Variation	*df*	*F*	*p*	η^2_p	ε	*F*	*p*	η^2_p	ε	*F*	*p*	η^2_p	ε
Effector system order	1, 23	90.62	< .001	.80		109.14	< .001	.83		375.27	< .001	.94	
SOA	3, 69	459.65	< .001	.95	.50	292.86	< .001	.93	.50	386.71	< .001	.94	.45
Stimulus modality	1, 23	35.34	< .001	.61		64.48	< .001	.74		17.00	< .001	.53	
Effector system order x SOA	3, 69	20.68	< .001	.47		13.99	< .001	.38	.66	1.60	.211	.07	.70
Effector system order x stimulus modality	1, 23	43.43	< .001	.65		5.35	.030	.19		9.17	.006	.29	
SOA x stimulus modality	3, 69	18.42	< .001	.45		13.01	< .001	.36	.75	13.97	< .001	.38	
Effector system order x SOA x stimulus modality	3, 69	1.53	.215	.06	.55	2.49	.067	.10	.67	3.05	.034	.12	

Note. The interaction of effector system order and SOA reflects PRP effect asymmetries as a function of effector system order within combination groups, while a modulation of this asymmetry by stimulus modality would be reflected in the three-way interaction.

Table 4.3

Overview of statistical test results regarding accuracy within pairwise combination groups (three-way ANOVAs regarding Task 2 ERs).

Pairwise combination group		Vocal-Manual				Oculomotor-Manual				Oculomotor-Vocal			
Source of Variation	*df*	*F*	*p*	η^2_p	ε	*F*	*p*	η^2_p	ε	*F*	*p*	η^2_p	ε
Effector system order	1, 23	4.93	.037	.18		2.63	.118	.10		8.54	.008	.27	
SOA	3, 69	5.34	.008	.19	.67	8.63	< .001	.27		2.87	.059	.11	.76
Stimulus modality	1, 23	0.03	.867	.00		4.06	.056	.15		4.37	.048	.16	
Effector system order x SOA	3, 69	0.33	.803	.01		2.78	.061	.11	.81	1.59	.199	.07	
Effector system order x stimulus modality	1, 23	1.62	.216	.07		0.01	.982	.00		13.08	.001	.36.	
SOA x stimulus modality	3, 69	2.71	.071	.11.	.74	4.51	.012	.16	.77	7.66	< .001	.25	
Effector system order x SOA x stimulus modality	3, 69	1.01	.382	.04	.78	0.18	.846	.01	.69	5.25	.003.	.19	

4.4 Discussion of Study C

In Study C, we addressed the interplay of prioritized resource allocation based on task order and effector system prioritization. Specifically, we tested whether or not PRP effects reflecting a strong initial resource allocation to Task 1 response selection, can be modulated by the effector system of Task 2. In the context of a flexible resource allocation regime, in which the PRP effect is interpreted as reflection of allocation policies associated with task order, and if this allocation scheme is also assumed to be affected by effector systems, one would expect exactly such a modulation (cf. e.g., Hommel, 1998; Meyer & Kieras, 1997a, 1997b; Navon & Miller, 2002; Tombu & Jolicœur, 2003). Under the assumption that the PRP effect solely reflects a complete interruption of Task 2 processing until Task 1 response selection is completed (like a classic RSB model would suppose; Pashler, 1994), in contrast, no modulation of the PRP effect by effector system associated with Task 2 should be possible.

We aimed at answering this question by combining comparable tasks in the PRP paradigm (sequential stimulus presentation with a variable temporal distance) and exclusively manipulating associated effector systems in systematic pairwise combinations (oculomotor, manual, vocal). This resulted in three combination groups of participants (oculomotor-vocal, oculomotor-manual, and vocal-manual). Effector system (or task) order and S-R modality mapping were manipulated within each group.

As a necessary precondition for further analyses regarding any potential modulation, we observed typical PRP effects (i.e., prolongation of Task 2 RTs with decreasing SOAs) across all effector system and stimulus modality conditions that reflects the predicted task order-based prioritized Task 1 processing. Importantly, we then compared these PRP effects for different Task 2 effector systems in the context of constant Task 1 requirements. Crucially, the PRP effect was more pronounced when Task 2 involved a vocal compared to a manual response (following the same oculomotor Task 1), reflecting a modulation of task order-based resource allocation policies by effector system. This effect was observed in both S-R modality mapping conditions. The interpretation of these findings as modulation of task order-based prioritization policies by prioritization policies based on effector system characteristics was not compromised by the error data, since there was no counteracting effect regarding the crucial data (i.e., the interaction of Task 2 effector system and SOA).

Note that we also observed an influence of SOA manipulation on Task 1 performance in form of a slight increase of Task 1 RTs under long SOAs. This was, however, not substantially affected by effector system. Such an influence of SOA on Task 1 performance has been observed before (e.g., Janczyk & Kunde, 2010; McCann & Johnston, 1992), especially under strict instructed response order conditions (cf. Tombu & Jolicœur, 2003). This has been typically interpreted to result from a grouping tendency (e.g., McCann & Johnston, 1992; cf. also Pashler & Johnston, 1989) or in terms of interference between Task 1 processing and Stimulus 2 arrival (cf. Miller et al., 2009).

Overall, our findings reflect a substantial influence of effector system on resource allocation that goes beyond task order-based effects. The direction of this modulatory effect corroborates previous findings regarding effector system prioritization in multitasking settings without externally suggested task order (Huestegge & Koch, 2013; Pieczykolan & Huestegge, 2014, 2017; Study A, Study B). Specifically, we found a smaller PRP effect for vocal than manual Task 2s following a constant oculomotor Task 1, while vocal responses are assumed to be generally prioritized over manual responses (previously reflected in smaller dual-task and respectively dual-response costs), despite the fact that vocal responses are usually characterized by longer RTs overall

Crucially, we can already rule out any alternative explanation that such a modulation of the PRP effect by Task 2 effector system could be sufficiently explained by assuming it merely derived from effector system-specific response selection processes (that therefore differ in their duration) in Task 2. Note that this account already implies the assumption of the occurrence of parallel response selection processes in the first place. Proposing differences in effector system-specific response selection processes might have resulted in predicting unequal PRP effect sizes merely due an unequally long time span during which resources have to be shared between two parallel response selection processes. However, the observation that whether Task 1 was associated with the vocal vs. manual effector systems did not significantly alter PRP effects in an oculomotor Task 2 renders this account highly unlikely.

Interestingly, our results did neither show any modulation of the PRP effect by effector system following a manual Task 1 (oculomotor vs. vocal Task 2), nor following a vocal Task 1 (oculomotor vs. manual Task 2) in any of the S-R modality mapping conditions. This was somewhat surprising, as at first sight, this lack of a modulation of PRP effects when one of these (Task 2 related) effects involves oculomotor (Task 2) responses seems to restrict the generalizability of the significant modulation of the PRP effect reported above. These observations seem to be in conflict with previous cumulative evidence for a general prioritization of the oculomotor system relative to all other effector systems (see Study A; Huestegge & Koch, 2013; Pieczykolan & Huestegge, 2014). When we take a closer look at the absolute RT levels among effector systems, though, especially with respect to oculomotor RTs in direct comparison to manual or vocal Task 1 RTs (see Figure 4.1), we can think of a rationale explanatory account: Typically, oculomotor responses can be executed extremely fast (in relation to other effector systems). Here, we observed RTs of about 395 ms in Task 1. Manual and vocal Task 1 RTs, in contrast, ranged between 637 and 936 ms. Consequently, when comparing oculomotor and vocal (or manual) Task 2 performance (after a manual or vocal

Task 1, respectively), it seems highly likely that the execution of oculomotor responses in short SOA conditions had to be artificially withheld until the execution of the respective Task 1 response. Otherwise, participants would not have stuck to the explicitly instructed task order and consequently received an error feedback message. Note that this idea originally arose based on the subjective expression that participants more often complained about frequent presentation of error feedback regarding task order, which they perceived as unjustified.

Indeed, previous PRP studies that involved oculomotor responses (although to date relatively few) demonstrated numerous response order reversals when the oculomotor system was associated with the task that should be executed second (i.e., oculomotor responses were relatively often executed first even though the corresponding stimulus was presented second, e.g., Pashler et al., 1993; Pieczykolan & Huestegge, 2019). Moreover, this effect might have been reinforced by providing error feedback for response reversals in the first place. Therefore, it might be of interest in future research to examine whether effects of oculomotor effector system prioritization in form of smaller PRP effects under controlled Task 1 requirements might be observed without defining reversed execution order as violations. Evidence that PRP effects can still be observed without instructing participants to stick to stimulus order regarding response execution comes, for example, from studies conducted by Bratzke and colleagues (Bratzke et al., 2008; Bratzke, Rolke, Ulrich, & Peters, 2007). Therefore, although such an approach might be challenging in that a certain response order is still often interpreted as a prerequisite of interpreting Task 2 RT patterns in terms of a typical task order-based PRP effect, it might yield further interesting insight in effector system effects under sequential stimulus presentation situations.

Taking these arguments into account, it appears that it might be difficult to empirically demonstrate PRP effect modulation by oculomotor system prioritization, although this prioritization (as demonstrated in Study A and previously observed by Huestegge & Koch, 2013; and Pieczykolan & Huestegge, 2014, 2017) might also impact on cognitive processes in situations of sequential stimulus presentation (PRP setting). Regarding the present study, there are several hints in the data that suggest that such an effect has been cancelled out in our setting by an artificial delay of oculomotor Task 2 responses initiated with short SOA. The assumption of such an artificial retention of oculomotor responses could also provide a first account to explain the unexpected pattern regarding oculomotor error rates in the oculomotor-vocal combination group. In this condition, we observed surprisingly high oculomotor error rates after a vocal Task 1 especially with short SOA, resulting in a reversed pattern compared to the findings in the other groups and effector system conditions. If we suppose that in trials with a short SOA it was especially difficult for participants to stick to the instructed response order, it appears reasonable that withheld oculomotor responses are especially vulnerable to interference and mistakes. Certainly, this can only be a first post hoc account and another possible explanation could be that this pattern was caused by random error variance. Therefore, future research would be definitively needed to draw any more robust conclusions here.

Another interesting side result of the present study that should be mentioned is that the PRP effect was modulated as a function of effector system order *within* groups of participants (except for the oculomotor-vocal combination group), that is, when the same two tasks (e.g., manual and vocal) were executed in a different sequence. When we interpret the PRP effect as being mainly determined by Task 1 response selection duration, we can further interpret this finding as evidence for response selection processes being not purely abstract, but rather co-determined by the particular effector system that is associated with the selected response. This is in line with the theoretical notion of embodied cognition (e.g., Anderson, 2003; Mahon & Caramazza, 2008; Markman & Brendl, 2005; Wilson, 2002), in that cognitive processes are (at least additionally) determined by bodily systems associated with the tasks at hand instead of being completely abstract. Moreover, this observation could also be interpreted in terms of assuming that the order of the two tasks itself is part of a subordinate higher-order task set that integrates individual subtask characteristics as well as the specific order of tasks (cf. e.g., Hirsch, Nolden, & Koch, 2017; Hirsch, Nolden, Philipp, & Koch, 2018; Kübler, Reimer, Strobach, & Schubert, 2018).

In sum, the present data indicate that effector system prioritization can in fact modulate task prioritization based on task order, which represents a special case of resource allocation in dual-task situations. This highlights the importance to consider effector systems involved when interpreting typical performance effects in dual tasking. Moreover, our results further strengthen the assumption of potential strategic resource allocation among tasks as assumed in parallel processing models (e.g., Tombu & Jolicœur, 2003). In situations involving sequential stimulus onset it provides strategic advantages to shift a lion’s share of available resources towards the task that was triggered first to get it “out of the way” and to reduce task interference. The extent of this order-based task prioritization (as measured in the PRP effect), however, apparently can be adjusted depending on more peripheral task characteristics, including associated effector systems.

All in all, data of Study C support the conclusion that differences in effector system characteristics evoke substantial effects on dual-task control (cf. e.g., Huestegge et al., 2014; Huestegge & Hazeltine, 2011). Here this is shown for task requirements involving sequential stimulus presentation, which is a common paradigm in the recent multitasking literature. Again, the present data further support the assumption of a relatively early anticipation of effector systems allowing for central adaptation processes. Most crucially, the present study sheds further light on the specific mechanisms determining resource allocation regimes in resource sharing models by indicating that effector system anticipation and task order-based prioritization are integrated to eventually determine a specific, demand-appropriate resource allocation policy.

5. Study D: Effector System Differences in Task Switching

5.1 Introduction

Besides demands of simultaneous or overlapping task requirements, everyday life situations often confront us with *successive* demands requiring actions in different effector systems. For example, navigating in traffic can require us to move the eyes to sample new information first, then depress the clutch with the left foot, before we finally use our right hand to shift gears. Basic cognitive research has shown that such effector system switching comes at a cost: Under controlled conditions, that is, when successively executing the same task but with another (vs. the same) effector system, performance decrements were exhibited (e.g., Philipp & Koch, 2011). Study D aims at studying such effector switch costs by comparing oculomotor, manual, and vocal responses and focusing on switch cost asymmetries as potential markers for effector system prioritization. Thereby, Study D completes an integrative set of studies that systematically addressed effector system prioritization in the most relevant paradigms in recent multitasking research.

Traditionally, cognitive mechanisms of sequential task processing have been addressed using the task switching paradigm (originally introduced by Jersild, 1927; see Kiesel et al., 2010; Monsell, 2003, for reviews), in which participants alternate between two (or more) tasks in short temporal succession. Originally, Jersild (1927) simply compared overall performance in task blocks requiring quick switches between two tasks with that in task blocks involving the repeated execution of one and the same task. However, more recent studies utilize advanced and controlled paradigms that allow for better conceptual specificity (e.g., by controlling for mixing costs, working memory load, or arousal). These paradigms comprise the alternating-runs paradigm (involving predictable task switches; Rogers & Monsell, 1995), task cuing (involving unpredictable task switches indicated by cues; e.g., Fintor, Stephan, & Koch, 2019;

Meiran, 1996; Sommer & Lukas, 2018; Sudevan & Taylor, 1987), or voluntary task switching (allowing participants to decide for themselves which task to execute; Arrington & Logan, 2004; recently used by e.g., Fröber & Dreisbach, 2017; Jurczyk, Fröber, & Dreisbach, 2018; Mittelstädt, Miller, & Kiesel, 2018; see Arrington, Reiman, & Weaver, 2014, for a review).

Although task switching can generally be considered as a multitasking situation, it is special in that the tasks never temporally overlap (unlike in, e.g., the PRP paradigm; see Pashler, 1994; cf. Study C). Therefore, performance decrements in task switching cannot easily be attributed to cognitive mechanisms underlying temporally overlapping dual-task control, such as interference between two simultaneous motor control processes, or the resolution of conflict between two selection processes that each result in immediate overt response execution. Instead, these performance costs are rather assumed to be based on the cognitive activation and inhibition of (and potential interference between) competing task sets in working memory. Remember that task set refers to the cognitive representation of task requirements, for instance, regarding information about stimuli, potential responses, and stimulus-to-response mapping rules (cf. e.g., Monsell, 1996, 2003; Rogers & Monsell, 1995; Vandierendonck et al., 2008).

Effects of persistent representations of the previous task set as well as processes of reconfiguration of the currently required task set are assumed to play a major role in task switching (cf. Kiesel et al., 2010). These processes can result in the signature finding that responses are slower and more error-prone in switch trials than in repetition trials within task switching blocks (i.e., *switch costs*). Note that additionally, performance in repetition trials in task switching blocks is still compromised compared with that in single-task blocks (i.e., *mixing costs*), probably reflecting lower working memory load in the latter (among other factors). Interestingly, similar to dual-task costs in other multitasking paradigms also switch costs are often distributed asymmetrically among tasks, suggesting that particular features of the task that has to be configured (or of the task to be switched away from, respectively) matter for processing.

Specifically, many studies reported that switching from a weaker (typically in the sense of less trained) to a stronger (better trained) task resulted in greater switch costs than vice versa (e.g., Allport et al., 1994; Allport & Wylie, 1999; de Jong, 1995; Monsell, Yeung, & Azuma, 2000; Yeung & Monsell, 2003). Meuter and Allport (1999), for example, observed corresponding asymmetric switch costs in the context of language switching: When bilingual participants switched between digit naming in their mother tongue vs. their second language, they responded more slowly in their second language in repetition trials, but faster in their second language in switch trials (compared to responding in their mother tongue, respectively).

These findings provided important insights for the theoretical discussion of whether switch cost asymmetries are mainly driven by inhibitory processes (due to differences in the amount of inhibition needed to suppress a currently irrelevant task set) or rather by differences in (re)configuration ease between two task sets (cf. Kiesel et al., 2010). For example, while the observation of n-2 repetition costs (the phenomenon of increased response times when returning to a task from which one previously had to switch away) suggests a strong role of inhibitory control processes in task switching (e.g., Schuch, Sommer, & Lukas, 2018), there is also evidence for a substantial role of reconfiguration processes in task switching control (e.g., Meiran, 1996; Rogers & Monsell, 1995). However, the latter account would predict that switch costs should generally be lower when switching to well-learned (or dominant) tasks (cf. Meiran, 1996; Rogers & Monsell, 1995), which is at odds with the observed switch cost asymmetry effects reviewed above (e.g., Meuter & Allport, 1999). Thus, the observation that well-trained tasks are associated with particularly high switch costs rather supports the view that it is especially costly to reactivate a task set that before had to be strongly inhibited to allow for an efficient execution of the less well-learned task (Allport et al., 1994; Koch, Gade, Schuch, &

Philipp, 2010; Meuter & Allport, 1999). Crucially, Yeung and Monsell (2003) could demonstrate that switch cost asymmetries did not only rely on stronger or weaker task representations, but can also be influenced by the assignment of effector systems to tasks (manual vs. vocal tasks). This observation represents a first hint that also effector system-related task differences might contribute to switch cost asymmetries.

In the preceding chapters, cumulative evidence provided in recent years was presented that particular effector systems and their specific combination affect central resource allocation policies in temporally overlapping dual tasks (Study A, B, C, Huestegge & Koch, 2013; Pieczykolan & Huestegge, 2014). Taken together, these findings suggested a general ordinal task prioritization pattern in which tasks involving oculomotor responses are prioritized over those involving pedal, vocal, or manual responses, while pedal tasks are prioritized over vocal or manual ones, and finally, vocal tasks are prioritized over manual tasks (as evidenced by smaller dual-task costs as an empirical marker for prioritization). This pattern across effector systems was consistently found in different paradigms, involving a single stimulus as a trigger for two (spatially congruent or incongruent) actions (Huestegge & Koch, 2013; Pieczykolan & Huestegge, 2014), in dual-task paradigms comparing single- vs. dual-task performance using either cross-modal or intra-modal stimulation conditions (Study A and B), and finally, we observed similar effects regarding the comparison of vocal and manual Task 2 responses in the PRP paradigm (Study C).

However, it remains an open question whether similar effects of effector system prioritization can be observed as well in terms of asymmetrical switch costs in the task switching paradigm. This issue is especially interesting on a theoretical level as the executing effector system and corresponding prioritization may only be relevant in temporally overlapping tasks where limited cognitive resources have to be distributed to control two effector systems at around the same time. However, it also appears conceivable that effector system prioritization also affects task switching in a similar manner as tasks differing in their level of training or dominance. This would indicate that effector system prioritization does not rely on temporally overlapping processing but can affect processing by the mere cognitive representation of effector-specific task sets.

Philipp and Koch (2005, 2011) discussed the assumption that the specific effector system required for executing a task might represent a relevant component of a task set. In particular, they demonstrated that switching merely among different effector systems – while keeping all other task characteristics constant – already sufficed to yield performance decrements typically associated with task switching in form of switch costs. This can be interpreted as evidence that effector system switching is comparable to other, previously used task switching settings.

In fact, in one of their studies, Philipp and Koch (2011) already observed first evidence for effector system-based switch cost asymmetries: When switching between vocal and manual responses in the context of an otherwise identical judgement task, switching to a vocal response was associated with greater performance costs (using response modality repetitions as a baseline) than switching to a manual response. However, this study did not focus on systematic differences among effector systems in an ordinal prioritization pattern, only involved a relatively small sample size (of n = 8), and only utilized visual stimuli (thus the observed effects might also be ascribed to particular effects of input-output modality compatibility, IOMC; see Fintor, Poljac, Stephan, & Koch, 2018; Fintor, Stephan et al., 2018; Hazeltine et al., 2006; Stephan & Koch, 2011, 2015; see Section 1.3.2, for a detailed discussion). Therefore, a comprehensive, systematic study of effector system switching, especially regarding differences in the extent of switch costs, is still lacking.

Thus, in the present Study D, we compared switch costs and mixing costs yielded by effector system alternation among oculomotor and vocal (Experiment 1) and oculomotor, vocal, and manual responses (Experiment 2) in a cued task switching paradigm. Based on our prior work (Study A, B, C, but cf. also Huestegge & Koch, 2013; Pieczykolan & Huestegge, 2014), we hypothesized that if effector system prioritization also affects resource allocation in a multitasking environment without temporal task overlap, we should again find evidence for effector system prioritization in a consistent ordinal pattern (oculomotor > vocal > manual).

In contrast to the pattern observed in dual-task costs, we assume that oculomotor responses should yield the greatest switch costs followed by vocal responses, and lastly manual responses should yield the smallest switch costs. This prediction follows from transferring the concept of prioritization directly to the findings indicating that well-trained tasks are associated with greater switch costs (e.g., Allport et al., 1994; Yeung & Monsell, 2003). In consistence with these observations, the effector system with the highest priority should yield the greatest switch costs, which would in turn hint towards the necessity of an especially strong inhibition of the corresponding task sets. This interpretation would also be in line with the observation of greater vocal than manual switch costs reported by Philipp and Koch (2011).

On the other hand, there are also observations discussed in the literature that may result in a different prediction. In particular, there are first hints that effector system prioritization could to some extent be linked to the difficulty of the required response selection processes (cf. Pieczykolan & Huestegge, 2014; see Section 6.3, for more details). Specifically, it was suggested that relatively more cognitive resources are shifted towards the more difficult task, eventually resulting in smaller dual-task costs. If we now assume that stronger or better trained tasks became easier due to training, this reasoning would predict the observation of smaller switch costs for oculomotor than vocal responses (Experiment 1), and smallest switch costs for oculomotor responses, switch costs on an intermediate level for vocal responses, and highest switch costs for manual responses in pairwise combinations of all three effector systems (Experiment 2). Such a pattern would not only further support the assumption of a systematic influence of effector system characteristics on multitasking performance even without temporal task overlap, but would also strengthen the idea that effects of effector system prioritization are linked to task difficulty.

Note that both observations could be interpreted in terms of differences in the extent of task set inhibition yielding asymmetrical switch costs. Specifically, one could assume that greater switch costs are in the former case associated with prioritized and therefore dominant tasks and in the latter case with the relatively easier tasks and thus, in both cases, with the respective tasks that have to be especially strongly inhibited in order to perform the competing task efficiently.

A third possible outcome is that we do not observe any asymmetries in switch costs (or mixing costs) among the tasks with different effector systems at all, despite the fact that switch cost asymmetries for tasks with different training levels have been observed repeatedly. Such an outcome would indicate that inducing effects of effector system prioritization, as shown in Study A, B, and C (and former studies), necessitates temporal task overlap.

5.2 Experiment 1

5.2.1 Method

Participants

16 participants took part in this experiment. All were naïve regarding the purpose of the study and gave informed written consent. All participants were recruited from the local university’s student panel and received monetary reward or course credit for participation. We discarded data from participants that did not perform better than chance level to exclude

participants that were not able or willing to follow instructions. The threshold of chance level was a minimum of 59.0% correct responses (regarding direction and selected effector system) for single-task blocks, and 55.2% correct trials regarding mixing blocks. Based on these criteria we excluded and recollected data of two participants (to ensure full counterbalancing). The final sample consisted of four males and twelve females, 15 right-handed, with a mean age of 27.1 years (*SD* = 6.3). All had normal or corrected to normal hearing and vision.

Apparatus and stimuli

Participants were seated approx. 67 cm in front of a 21-inch cathode ray tube screen (same as in the above presented studies, spatial resolution: 1024 x 768 pixels, temporal resolution: 100 Hz). Again, the eye tracking system sampling eye movements at 1000 Hz (Eyelink 1000, SR Research Mississauga, Ontario, Canada) was utilized to register saccade latencies and amplitudes of the right eye to register oculomotor responses. Head movements were minimized by a chinrest (including forehead support). Vocal RTs were registered and logged via the integrated voice key function of the programming software Experiment Builder (version 2.1.140, SR Research) via a microphone (Sennheiser e 835-S) in front of participants. Experiment Builder was also used to run the experiment. Throughout each block, a white fixation cross (size = 0.43° of visual angle) at the centre of a black background and two white rectangular squares at an eccentricity of 8.5 degrees of visual angle (size = 0.43° each) to the left and right of the central fixation cross remained present on the screen. These white rectangular squares served as target areas for oculomotor responses. For instance, when a right oculomotor response was requested, participants were instructed to look at the right target square (and to redirect their gaze to the central fixation cross directly afterwards).

Small schematic pictures of an eye (height 0.86°, width 1.45° visual angle) indicating the oculomotor response or a mouth (height 0.68°, width 1.97° visual angle) indicating the vocal response were presented at the location of the fixation cross. They served as visual cues indicating which effector system to use. Imperative stimuli were auditory (1000 Hz sinusoidal tones, same as used in Study A and C) presented to either the right or the left ear via supra-aural headphones (Sennheiser, PMX 95).

Procedure

At the beginning of the experiment (as well as at the beginning of each block), participants received instructions verbally by a research assistant and in written format via an instruction screen. The experiment consisted of ten blocks, always starting with two single-task blocks consisting of 40 trials each. In these single-task blocks, participants should always respond either with vocal or with oculomotor responses throughout the entire block. Which effector system was required in the first vs. the second block was counterbalanced across participants. Afterwards, all participants underwent one training block of the mixing condition (consisting of 20 trials) followed by five effector mixing blocks (consisting of 60 trials each). In the end, the two single-task blocks were repeated in the same order as at the beginning of the experiment.

Independently of block type, each trial began with the presentation of a visual cue to indicate which task was to be performed. In single-task blocks, the respective visual cue was presented as well, although in single-vocal blocks there were only mouth cues and in single-oculomotor blocks only eye cues, respectively. In training and effector mixing blocks, in contrast, cue identity switched randomly. After a cue stimulus interval (CSI) of 200 ms, the imperative stimulus was presented for 80 ms. In trials in which a response was registered, the next trial proceeded after an response cue interval (RCI) of 1100 ms (i.e., 1100 ms after response registration). In the case that no response was registered within 4 seconds after stimulus presentation, the next trial proceeded after this threshold. Visual cues remained visible on the screen until response execution (or until automatic procedure proceeding after 4 seconds).

Design

To present the results in an intuitive, succinct manner we decided to analyse our data on two levels: First, we tested for overall differences in performance in tasks associated with the two effector systems and for overall performance decrements in terms of mixing costs and switch costs. Thereby, *mixing costs* are defined as decrements in effector repetition trials in mixing blocks compared to single-block performance. *Switch costs*, on the other hand, refer to performance decrements in effector switch trials compared to effector repetition trials within the mixing blocks. For this first type of analyses, we analysed effects of the independent within-subject variables effector system (oculomotor vs. vocal), task block (single vs mixing), and effector transition (repetition vs. switch) on the dependent variables RTs, effector selection error rates, and directional error rates. Second, we focused on differences between oculomotor and vocal responses regarding mixing and switch costs. For the second type of analyses, effector system served as an independent within-subject variable while mixing costs and switch costs (in terms of difference measurements) served as dependent variables.

5.2.2 Results and Discussion of Experiment 1

5.2.2.1 Data Treatment

Data from training blocks were not considered in the analyses. Additionally, the first trial of single-task blocks and the first two trials of (effector) mixing blocks were discarded. Furthermore, all trials in which either no response, or a response within 50 ms (regarding oculomotor responses) or within 200 ms (regarding vocal responses) after stimulus onset was registered were defined as invalid (2.4%) and excluded from all further analyses to ensure that, for instance, voice key artefacts that do not represent intended responses do not distort the data.

Moreover, all trials following trials in which not the response in the required effector system was executed (because no valid response at all was registered or due to an effector selection error, e.g., uttering “right” instead of looking right) had to be excluded because they cannot be defined as either a switch or a repetition trial. Directional errors (5.2% of valid trials) as well as effector selection errors (7.7%) were not included in RT analyses but analysed separately.

As already mentioned above, we differentiated between two kinds of errors in the following analyses, those in which the wrong effector system was chosen (e.g., uttering “left” instead of looking left) – referred to as effector selection errors (ESEs) – and directional errors (DEs; e.g., looking right instead of left). Note that in 1.3% of all valid trials an error occurred regarding both dimensions (e.g., uttering “right” when the execution of a saccade to the left direction would have been appropriate). Note also that we did not include trials in which no response at all was registered (neither in RT data nor in error rate analyses). This was because they occurred extremely rarely (only seven of in other respects valid trials), and because we cannot rule out that they were merely caused by a relatively lower sensitivity of the integrated voice key function of the Experiment Builder software (in all these seven trials a vocal response would have been required).

5.2.2.2 General Differences Between Effector Systems and General Mixing and Switch Costs

First, we analysed main differences between the two effector systems regarding RTs, ESEs, and DEs overall in three separate t-test comparisons. This approach revealed that oculomotor responses (246 ms) were overall executed faster than vocal responses (662 ms), $t(15) = 21.49$, $p < .001$, $d = 6.14$. Furthermore, there were significantly more oculomotor-instead-of-vocal ESEs (13.1%) than vocal-instead-of-oculomotor ESEs (0.1%), $t(15) = 5.18$,

$p < .001$, $d = 1.97$, as well as more oculomotor (7.3%) than vocal DEs (2.3%), $t(15) = 4.70$, $p < .001$, $d = 1.28$.

Next, we identified significant overall mixing costs of 62 ms in RTs, $t(15) = 4.93$, $p < .001$, $d = 0.92$, of 14.3% in ESEs, $t(15) = 4.39$, $p = .001$, $d = 1.14$, and of 3.8% in DEs, $t(15) = 2.70$, $p = .016$, $d = 0.83$ (comparing overall single block performance with repetitions in mixing blocks). Furthermore, we identified overall switch costs of 93 ms in RTs, $t(15) = 6.02$, $p < .001$, $d = 1.24$ (comparing overall performance in effector repetitions vs. effector switches within mixing blocks), but switch benefits (reversed switch costs) of 8.7% in ESEs, $t(15) = -4.26$, $p = .001$, $d = 0.38$. Regarding DEs, repetition trials (5.8%) and switch trials (7.4%) did not differ significantly, $t(15) = 1.23$, $p = .239$, $d = 0.29$.

All further analyses regarding differences between effector systems in the extent of mixing and switch costs were conducted using calculated mixing costs and switch costs as dependent variables (performance in repetitions in mixing blocks minus single-task performance and performance after an effector switch minus performance after an effector repetition within mixing blocks, respectively). Mean performance (+SDs) in these conditions are depicted in Table 5.1.

Table 5.1

Mean RTs and error rates (+SDs) for oculomotor vs. vocal responses in single-task blocks as well as for repetition trials and switch trials in mixing blocks.

	RTs (in ms)		ESEs (in %)		DEs (in %)	
Condition	*M*	*SD*	*M*	*SD*	*M*	*SD*
Oculomotor single	202.95	42.35	0.0	0.0	3.4	3.1
Vocal single	615.08	89.62	0.0	0.0	0.5	1.1
Oculomotor repetition in mixing blocks	244.53	46.49	19.2	13.3	7.0	6.5
Vocal repetition in mixing blocks	659.11	87.88	0.4	1.1	2.2	3.3
Oculomotor switch	297.24	66.04	9.5	8.5	9.7	6.8
Vocal switch	719.63	93.55	0.1	0.4	4.4	4.6

Note. For an easier presentation, we here decided to represent oculomotor-instead-of-vocal effector selection errors (ESEs) in one row with oculomotor RTs and DEs and vocal-instead-of-oculomotor ESEs in the vocal row, respectively. Note however, that strictly speaking an effector selection error always consists of an incorrect behaviour regarding both effector systems (as it is an commission error regarding the one but an omission error regarding the other effector) and therefore actually cannot that easily be dedicated to one of the two effector systems.

5.2.2.3 Differences Between the Two Effector Systems in Mixing or Switch Costs

Regarding RT data pairwise t-test comparisons revealed no significant differences neither between oculomotor mixing costs (42 ms) and vocal mixing costs (44 ms), $t(15) = 0.13$, $p = .902$, $d = 0.04$, nor between oculomotor switch costs (53 ms) and vocal switch costs (65 ms), $t(15) = 0.31$, $p = .764$, $d = 0.14$. The same applied to comparisons regarding DEs, that amounted to 3.7% oculomotor mixing costs vs. 1.6% vocal mixing costs, $t(15) = 1.45$, $p = .169$, $d = 0.34$, and 2.6% oculomotor switch costs vs. 2.3% vocal switch costs, respectively.

Since no ESEs were made in single-task blocks, all differences between effectors regarding ESEs were rooted in the mixing blocks. Therefore, mixing costs were significantly higher for oculomotor-instead-of-vocal ESEs (19.2%) than for vocal-instead-of-oculomotor ESEs (0.4%), $t(15) = 5.61$, $p < .001$, $d = 2.07$. Interestingly, effector switching within mixing blocks yielded performance benefits regarding effector selection that were significantly greater for oculomotor-instead-of-vocal ESEs (9.7%) than vocal-instead-of-oculomotor ESEs (0.3%), $t(15) = 5.19$, $p < .001$, $d = 1.96$.

Crucially, Experiment 1 overall revealed significant effector mixing as well as effector switch costs. These performance costs occurred in a situation in which we held the basic judgement task (left/right decisions) constant throughout the whole experiment but instructed participants to switch in an unpredictable sequence among executing effector systems indicated by a visual cue. This observation already highly supports our hypothesis derived from Philipp and Koch (2011), that effector systems are an integral component of a task set as their alternation yielded typical effects associated with task alternations. Unlike Philipp and Koch (2011) we used auditory stimuli in the constant judgement task. Therefore, we can exclude that the emergence of effector mixing costs and effector switch costs is restricted to visual stimulation.

Interestingly, we did not observe any significant modulation of mixing costs or switch costs in RT data as a function of executing effector system. There was no evidence for neither a performance advantage nor disadvantage for either task set (i.e., in terms of smaller switch costs associated with one of the two effector systems). Thus, our results do neither support the assumption that oculomotor tasks are easier to configure (resulting in smaller switch costs associated with a dominant or complex oculomotor task), nor that oculomotor tasks are stronger inhibited when they are currently not relevant, eventually resulting in difficulties during reconfiguration (and therefore greater switch costs compared to a switch to the vocal task).

This result represents a first indication that typical effects of effector system prioritization as observed when using other multitasking paradigms as we demonstrated in Study A, B, and C (but cf. also Huestegge & Koch, 2013; Pieczykolan & Huestegge, 2014) is restricted to situations with temporal task overlap. On the other hand, observations of Experiment 1 are still restricted to a very narrow range of effector systems (oculomotor and vocal tasks in combination). As a consequence, in Experiment 2 we aimed at analysing performance decrements (in form of switch costs and mixing costs) yielded by effector alternations throughout a broader range of effector system combinations in order to take a closer look on switch cost difference concerning a bigger part of the ordinal prioritization pattern.

5.3 Experiment 2

Findings of Experiment 1 suggested that there were no indications in performance measures for any prioritization of oculomotor over vocal tasks. This was somewhat surprising considering the cumulative evidence for oculomotor prioritization in other multitasking paradigms presented above and the demonstration of a significant difference in switch costs between two other effector systems by Philipp and Koch (2011). Therefore, we were interested to take a closer look at potential effects when combining other effector systems across tasks. Thus, in Experiment 2 we systematically compared mixing costs and switch costs among tasks involving vocal, oculomotor, and manual effector systems (as the three effector systems regarding which we have gathered the most empirical evidence for effector system prioritization so far, cf. Study B and C, Huestegge & Koch, 2013; Pieczykolan & Huestegge, 2014) in one integrative within-subject design.

5.3.1 Method

Participants

Considering the results of Experiment 1, we decided to collect data of a relatively large sample in order to minimize the risk of observing null effects merely due to low statistical power. Therefore, and due to reasons of counterbalancing, we decided to collect data of 72 new, naïve participants. Following the same rationale as in Experiment 1, we excluded participants that performed not better than chance level (> 41.0% errors in single blocks, > 43.7% errors in mixing blocks) to ensure that all considered participants followed task instructions. Based on this criterion, data of eight participants had to be excluded. One further participant decided to abort the experiment. We replaced these data with that of nine new participants to ensure full counterbalancing of our design. The final sample consisted of 52 females and 20 males and had a mean age of 26.2 years (*SD* = 9.1). All participants were right handed. Again, all gave informed consent, had normal or corrected to normal hearing and vision and were rewarded monetarily or by course credit.

Apparatus, Stimuli, and Procedure

Apparatus and stimuli were the same as in Experiment 1, except that because here also manual responses were required, a visual cue indicating manual keypress responses was additionally included (a small hand, height 1.54°, width 1.71° visual angle). Keypresses were registered by a standard (German) QWERTZ keyboard on which the relevant keys (arrow left for left responses, arrow right for right responses) were labelled by two green stickers. Participants were instructed to execute manual key press responses by their right index finger and to keep it (loosely) on the arrow down key as a resting position before and afterwards. Key press responses and manual response latencies were registered by the Experiment Builder software.

Similar to Experiment 1, Experiment 2 always started and ended with single-task blocks (40 trials) for all (here three) relevant effector systems. Again, the sequence of these effector system-specific tasks was counterbalanced across participants but remained constant (i.e., was repeated in the same order at the end of the experiment) within individuals. The middle part of the experiment consisted of twelve blocks, one trainings block (20 trials) and three repetitions of mixing blocks (60 trials) for each pairwise combination of effector systems (oculomotor-vocal, oculomotor-manual, vocal-manual). The order of pairwise combinations was counterbalanced across participants. Visual cues indicating which effector system was required were randomized in training and mixing blocks. All further details were equivalent to Experiment 1.

Design

As elaborated above (see Experiment 1, Section 5.2.1), we again first examined overall effects of effector systems, and overall mixing costs as well as switch costs (with RTs, ESEs, and DEs as dependent variables). Afterwards, we focused on differences between tasks involving the different effector systems regarding mixing and switch costs (using the respective costs in RTs, ESEs, and DEs as a dependent variable). To analyse differences in mixing costs or switch costs among the tasks involving the three different effector systems, we compared these decrements for oculomotor responses in the context of either vocal vs. manual tasks in mixing blocks, for vocal responses that were mixed with oculomotor vs. manual tasks, and for manual responses mixed with oculomotor vs. vocal tasks (i.e., six different specific response types). We were interested in analyses regarding three rationales: First, we wanted to examine whether mixing costs or switch costs differ within effector systems as a function of the context effector/task. Second, we compared these costs for effector systems (pairwise) when both were combined with the same (constant) context task. Third, we tested whether costs are distributed asymmetrically within mixing blocks of pairwise combined effector systems.

5.3.2 Results and Discussion of Experiment 2

Alike in Study C, in case of sphericity violations, Greenhouse-Geisser corrections were used. Uncorrected degrees of freedom and respective ε estimates are reported.

5.3.2.1 Data Treatment

We used the same rationale to define invalid or erroneous trials as in Experiment 1. Responses within 50 ms (regarding oculomotor responses) or within 200 ms (regarding vocal or manual responses) were discarded to exclude measurement artefacts (1.0%). Moreover, trials in which the voice key trigger registered a sound but no word was uttered and trials in which another key than the left or right arrow key was registered as responses were discarded, too. This approach resulted in 97.1% valid and 88.1% correct trials. Similar to Experiment 1, all trials following trials in which no response in the required effector system was executed were excluded, because they cannot be defied as switch or repetition trials (resulting in 79.6% usable trials altogether). Directional errors (5.1% of valid trials) as well as effector selection errors (5.3%) were not included in RT analyses but analysed separately.

5.3.2.2 General Differences Among Effector Systems and General Mixing and Switch Costs

Similar to Experiment 1, we first analysed overall differences among effector systems regarding RTs, ESEs, and DEs in three separate comparisons (here ANOVAs). We observed significant differences among effector systems regarding RTs, $F(2, 142) = 1134.72$, $p < .001$, $\eta^2_p = .94$, ESEs, $F(2, 142) = 146.02$, $p < .001$, $\eta^2_p = .67$, $\varepsilon = .52$, as well as DEs, $F(2, 142) = 81.92$, $p < .001$, $\eta^2_p = 54$. Post hoc pairwise t-test comparisons revealed that oculomotor responses (286 ms) were executed overall faster than vocal responses (707 ms), $t(71) = 45.73$, $p < .001$, $d = 4.88$, as well as manual responses (494 ms), $t(71) = 24.63$, $p < .001$, *d* = 2.04, and manual responses were executed faster than vocal responses, $t(71) = 24.08$, $p < .001$, $d = 2.10$.

Furthermore, there were significantly more erroneously (i.e., in trials in which another effector system was required) executed oculomotor ESEs (12.9%) than vocal ESEs (0.5%), $t(71) = 12.46$, $p < .001$, $d = 1.78$, and manual ESEs (1.2%), $t(71) = 11.82$, $p < .001$, $d = 1.69$, and significantly more manual than vocal ESEs, $t(71) = 4.72$, $p < .001$, $d = 0.73$. Regarding DEs, there were more oculomotor DEs (9.7%) than vocal DEs (2.1%), $t(71) = 9.81$, $p < .001$, $d = 1.15$, and manual DEs (3.1%), $t(71) = 9.49$, $p < .001$, $d = 1.00$. The difference between vocal and manual DEs was significant, too, $t(71) = 2.34$, $p = .022$, $d = 0.29$.

Next, we identified significant overall mixing costs (averaged over all specific response types) comparing overall single block performance with repetitions in mixing blocks in all three dependent variables. These costs amounted to 52 ms in RTs (437 ms in single blocks vs. 489 ms for repetition trials in mixing blocks), $t(71) = 10.18$, $p < .001$, $d = 0.66$, to 7.7% in ESEs (0.0% in single blocks vs. 7.7% for repetition trials in mixing blocks), $t(71) = 11.13$, $p < .001$, $d = 1.86$, and to 1.5% in DEs (3.3% in single blocks vs. 4.8% for repetitions in mixing blocks), $t(71) = 3.36$, $p = .001$, $d = 0.39$.

Lastly, the comparison of overall performance in effector repetition trials vs. effector switch trials within mixing blocks revealed overall switch costs of 76 ms in RTs (489 ms for repetition trials vs. 565 ms for switch trials), $t(71) = 12.21$, $p < .001$, $d = 0.63$, slight switch benefits of 1.1% in ESEs (7.7% for repetition trials vs. 6.6% for switch trials), $t(71) = -2.11$, $p = .038$, $d = 0.16$, and switch costs of 2.0% in DEs (4.8% for repetition trials vs. 6.9% for switch trials), $t(71) = 4.54$, $p < .001$, $d = 0.33$. Again, all further analyses regarding differences among response types in the extent of mixing and switch costs were conducted using mixing costs and switch costs respectively as dependent variables (as difference measurement of performance in repetitions in mixing blocks minus single task performance and performance after a switch minus after a repetition within mixing blocks, respectively). Switch costs (in RTs) for the six specific response types are additionally illustrated in Figure 5.1.

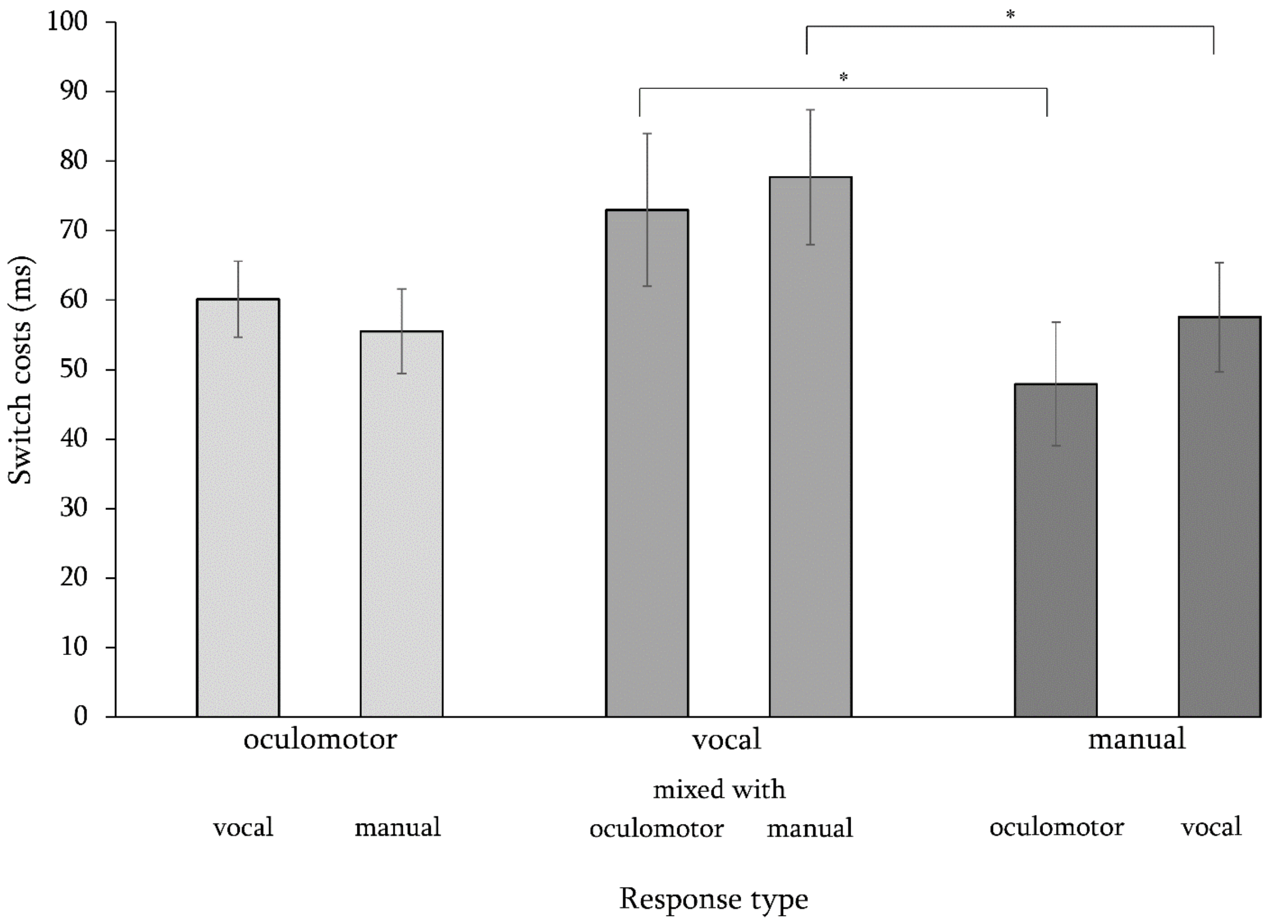

Figure 5.1. Switch costs (in RTs) as a function of response type. Error bars represent plus/minus mean SEs.

5.3.2.3 Mixing Costs Among Response Types

Three one-factor ANOVAs with the independent within-subject variable response type and the dependent variables mixing costs regarding RTs, ESEs, and DEs revealed general differences in mixing costs among response types for RTs, $F(5, 355) = 2.48$, $p = .032$, $\eta^2_p = .03$, $\varepsilon = .75$, and ESEs, $F(5, 355) = 100.87$, $p < .001$, $\eta^2_p = .59$, $\varepsilon = .49$. There was no difference in mixing costs as a function of the response type in DEs, $F(5, 355) = 1.94$, $p = .087$, $\eta^2_p = .03$, $\varepsilon = .59$. Pairwise post hoc t-test comparisons were conducted to identify whether mixing costs differ a) within effector systems as a function of the context effector system, b) between effector systems when both are combined with a constant context effector system, and c) between pairwise combined effector systems within mixing blocks. Statistical test results of these comparisons are depicted in Table 5.2.

These comparisons revealed that mixing costs in RTs only differed between response types regarding the comparisons of oculomotor (56 ms) vs. manual responses (74 ms) when both are combined with a vocal context response in mixing blocks, respectively, as well as again oculomotor (48 ms) vs. manual (72 ms) responses when compared within oculomotor-manual mixing blocks. There were no significant differences for vocal mixing costs in any of these comparisons, neither when they were combined with an oculomotor context responses (65 ms vocal mixing costs) nor with a manual context responses (60 ms vocal mixing costs), respectively.

Table 5.2

Statistical test results of pairwise comparisons of mixing costs in RTs, ESEs, and DEs between the specific response types.

Compared conditions	RTs in ms			ESEs in %			DEs in %		
	t(71)	p	d	t(71)	p	d	t(71)	p	d
Oculomotor mixed with vocal vs. manual context	1.30	.198	0.15	4.42	<.001	0.44	0.11	.915	0.01
Vocal mixed with oculomotor vs. manual context	0.65	.517	0.08	0.99	.327	0.17	1.98	.052	0.17
Manual mixed with oculomotor vs. vocal context	0.34	.738	0.03	3.25	.002	0.45	1.95	.055	0.22
Oculomotor vs. vocal (both with manual context)	1.26	.210	0.20	11.66	<.001	1.61	0.47	.638	0.07
Oculomotor vs. manual (both with vocal context)	2.38	.020	0.32	11.01	<.001	1.64	0.94	.348	0.15
Vocal vs. manual (both with oculomotor context)	0.66	.513	0.10	0.33	.743	0.05	2.23	.029	0.34
Oculomotor vs. vocal within oculomotor-vocal mixing blocks	1.11	.270	0.16	11.85	<.001	1.71	0.34	.738	0.05
Oculomotor vs. manual within oculomotor-manual mixing blocks	2.72	.008	0.41	10.10	<.001	1.59	2.02	.047	0.26
Vocal vs. manual within vocal-manual mixing blocks	1.57	.121	0.21	6.57	<.001	1.07	2.00	.050	0.34

Regarding ESEs, we observed significantly greater mixing costs in erroneously executed oculomotor responses when mixed with vocal (17.6% oculomotor-instead-of-vocal ESE mixing costs) than when mixed with manual context responses (12.9% oculomotor-instead-of-manual ESE mixing costs). Moreover, there were greater mixing costs in erroneously executed manual responses when those were mixed with vocal (3.0% manual-instead-of-vocal ESE mixing costs) than with oculomotor context responses (1.7% manual-instead-of-oculomotor ESE mixing costs). There was no influence of the context response modality on vocal ESEs (1.5% vocal-instead-of-oculomotor ESE mixing costs vs. 0.7% vocal-instead-of-manual ESE mixing costs). Regarding the pairwise comparisons of mixing costs in ESEs between effector systems with a respectively fixed context response we observed greater oculomotor mixing costs than for vocal and manual responses when mixed with manual or vocal context responses, respectively (17.6% vs. 3.0% and 12.9% vs. 0.7% cf. above). Furthermore, all pairwise t-test comparisons within mixing groups were significant, indicating greater oculomotor-instead-of-vocal than vocal-instead-of-oculomotor mixing costs (17.6% vs. 1.5%), greater oculomotor-instead-of-manual than manual-instead-of-oculomotor mixing costs (12.9% vs. 1.7%), and greater manual-instead-of-vocal than vocal-instead-of-manual mixing costs (3.0% vs. 0.7%).

Note that for the sake of completeness, t-test comparisons regarding DEs are included in Table 5.2, but will not be discussed since the corresponding ANOVA showed no significant main effect. Descriptively, mixing costs in DEs amounted to 0.5% for oculomotor responses mixed with a vocal context and 0.6% mixed with a manual context, 0.8% for vocal responses mixed with a oculomotor context and 0.1% mixed with a manual context, and 2.5% for manual responses mixed with an oculomotor context and 1.4% when mixed with a vocal context.

5.3.2.4 Switch Costs Among Response Types

Three one-factor ANOVAs regarding switch costs (in RTs, ESEs, and DEs) with the independent within-subject variable response type revealed differences in switch costs among response types in RTs, $F(5, 355) = 2.31$, $p = .044$, $\eta^2_p = .03$, $\varepsilon = .71$, a significant difference in switch benefits among response types in ESEs, $F(5, 355) = 24.88$, $p < .001$, $\eta^2_p = .26$, $\varepsilon = .58$, but no significant differences in switch costs among response types in DEs, $F(5, 355) = 1.80$, $p = .112$, $\eta^2_p = .03$, $\varepsilon = .78$. Statistical parameters of post hoc pairwise t-test comparisons are depicted in Table 5.3 (including t-test comparisons regarding DEs, without further interpretation due to the lack of a significant main effect in the first place).

Table 5.3

Statistical test results of pairwise comparisons of switch costs in RTs, ESEs, and DEs between different response types.

Compared conditions	RTs in ms			ESEs in %			DEs in %		
	t(71)	*p*	*d*	*t*(71)	*p*	*d*	*t*(71)	*p*	*d*
Oculomotor mixed with vocal vs. manual context	0.69	.493	0.09	3.00	.004	0.41	0.70	.489	0.09
Vocal mixed with oculomotor vs. manual context	0.53	.597	0.05	0.08	.933	0.02	1.30	.197	0.20
Manual mixed with oculomotor vs. vocal context	1.23	.223	0.14	2.52	.014	0.39	0.52	.602	0.08
Oculomotor vs. vocal (both with manual context)	1.99	.050	0.32	5.25	<.001	0.87	0.12	.906	0.02
Oculomotor vs. manual (both with vocal context)	0.24	.812	0.05	5.90	<.001	1.00	1.81	.074	0.29
Vocal vs. manual (both with oculomotor context)	2.28	.025	0.29	0.03	.976	0.01	0.75	.455	0.12
Oculomotor vs. vocal within oculomotor-vocal mixing blocks	0.99	.324	0.18	5.99	<.001	1.07	1.63	.108	0.26
Oculomotor vs. manual within oculomotor-manual mixing	0.73	.468	0.12	4.26	<.001	0.79	1.78	.079	0.23
Vocal vs. manual within vocal-manual mixing blocks	2.23	.029	0.27	3.55	.001	0.61	1.59	.116	0.25

Regarding RTs, the only significant differences among response types were observed when comparing vocal and manual switch costs. This holds true for the comparison of the two effector systems when each was mixed with oculomotor responses as context task (73 ms vocal switch costs vs. 48 ms manual switch costs) but also within vocal-manual mixing blocks (78 ms vocal switch costs vs. 58 ms manual switch costs). In both cases, vocal switch costs were significantly greater than manual switch costs. Moreover, there was a numerical tendency towards greater vocal switch costs than oculomotor switch costs when both were combined with a manual context response (78 ms (see above) vs. 56 ms oculomotor switch costs). For the sake of completeness, it should be noted that oculomotor switch costs in the context of a vocal context response amounted to 60 ms (see also Figure 5.1).

Regarding switch benefits in ESEs, we observed significantly greater switch benefits for oculomotor-instead-of-vocal responses (8.2%) than for oculomotor-instead-of-manual responses (4.8%), as well as for manual-instead-of-vocal responses (1.6%) than for manual-instead-of-oculomotor responses (0.3%). There was no influence of the context response modality on switch benefits in erroneously executed vocal responses (0.3% when mixed with oculomotor as well as when mixed with manual responses). Furthermore, switch benefits in ESEs were significantly greater for oculomotor-instead-of-manual responses than for vocal-instead-of-manual responses as well as for oculomotor-instead-of-vocal responses than for manual-instead-of-vocal responses. Finally, all pairwise comparisons within mixing groups were significant, indicating greater benefits for oculomotor-instead-of-vocal ESEs than vice versa in oculomotor-vocal mixing blocks, greater benefits for oculomotor-instead-of-manual ESEs than vice versa in oculomotor-manual mixing blocks, and greater benefits in manual-instead-of-vocal ESEs than vice versa in vocal-manual mixing blocks.

Switch costs in DEs amounted to 3.2% for oculomotor responses mixed with a vocal context and 2.4% for oculomotor responses mixed with a manual context. Switch costs regarding vocal DEs amounted to 1.3% for vocal responses mixed with an oculomotor context and 1.3% when mixed with a manual context. Lastly, switch costs in manual DEs amounted to 0.6% when manual responses were mixed with an oculomotor context and 1.1% when mixed with a vocal context.

Taken together, the results of Experiment 2 replicated the findings of Experiment 1 as well as those reported in Philipp and Koch (2011): An alternation of effector systems (while keeping other task features constant) yielded effects similar to those observed in other task switching settings (e.g., those in which task switches were defined in terms of a judgement task alternation). Moreover, the observation of greater vocal than manual switch costs in RTs is in line with previous observations in Philipp and Koch (2011).

However, regarding analyses involving oculomotor responses we again observed no systematic differences in switch costs when compared to the tasks involving vocal or manual responses. Interestingly, the numerical difference between oculomotor and vocal switch costs (when both were mixed with a manual context task), which was close to the significance level, even pointed in the direction of smaller switch costs for the oculomotor effector system. This is interesting considering that this effector system was frequently shown to be prioritized in previous studies involving simultaneous action control in two effector systems (cf. Study A; Huestegge & Koch, 2013; Pieczykolan & Huestegge, 2014). This direction would therefore contradict the idea that greater switch costs should be observed for the task involving the dominant effector system (assuming that a strong inhibition of the dominant task is needed when it is currently not relevant) which, however, would be in line with the finding of smaller vocal than manual switch costs as observed in this experiment.

5.4 Discussion of Study D

The aim of the present study was to examine differences in multitasking decrements among different effector systems in the context of a cued task switching paradigm. In Experiment 1, participants switched between oculomotor and vocal tasks, which were otherwise perfectly comparable (in terms of the same basic left/right spatial decision task). In Experiment 2, participants switched between oculomotor, vocal, and manual tasks in pairwise combinations, which were all implemented within each participant. Importantly, in both experiments, we observed reliable mixing costs as well as switch costs overall, suggesting that the alternation of the executing effector system under otherwise constant task requirements affected performance. Thereby, we were able to replicate and substantially extend the previous findings of Philipp and Koch (2011) that gave a first hint that task switching effects can be induced by the mere manipulation of effector systems associated with the tasks. Note moreover, that Philipp and Koch (2011) used a magnitude or parity numerical judgement task instead of a spatial left/right task. The present results indicate that effector systems are indeed an integral component for defining a task set, irrespective of the particular task type.

However, there were no significant switch cost asymmetries between oculomotor and vocal responses or oculomotor and manual responses in either of the two experiments, irrespective of whether performance costs in the two effector systems were compared within the pairwise combination mixing blocks or when combined with a constant context response modality, respectively. Crucially, we observed a switch cost asymmetry between vocal and manual tasks. Specifically, switching towards the vocal response was associated with significantly greater performance costs than switching towards the manual response, irrespective of whether participants switched away from the respectively other effector system (comparison within vocal-manual mixing blocks) or from an oculomotor context task.

This finding further extends the observations of Philipp and Koch (2011) reporting greater vocal compared to manual switch costs within a vocal-manual switching group of eight participants. It should also be noted that Philipp and Koch (2011) used visual stimuli and visual cues, while we chose a design that included visual cues to indicate the required effector system but auditory imperative stimuli. Based on the present results, we can now safely exclude the possibility that these effects might also be ascribed to IOMC effects (e.g., Fintor, Poljac et al., 2018; Fintor, Stephan et al., 2018; Hazeltine et al., 2006; Stephan & Koch, 2011, 2015) or otherwise are restricted to visual stimulation conditions.

Supplementary, it should be noted that we found switch benefits regarding effector selection errors in both experiments that were not explicitly expected. Since previous task switching studies involving different effector systems usually focused on switch costs in RTs and did not explicitly differ between the above introduced two kinds of errors (cf. e.g., Stephan & Koch, 2016), we had no clear a priori hypotheses regarding ESEs. However, these benefits and in particular the corresponding difference among response types in terms of especially high benefits for erroneously executed oculomotor responses are not that surprising when taking natural thresholds to execute an action in the different effector systems into account. While it is extremely unlikely to accidently utter a word without any cognitive initiation of the movement of the vocal tract, oculomotor movements, in contrast, are rather difficult to inhibit. Indeed, we are used to execute spontaneous saccades to explore the outer world without any cognitive effort. Therefore, it appears consequential that we observed more erroneously executed oculomotor movements directly after a response execution in another effector system (during which participants already had to supress spontaneous movements in the oculomotor system) than directly after the execution of a saccade. Note moreover the substantial extent of the difference in ESEs among effector systems in the dimension of a factor of 10-130 (the latter regarding Experiment 1 in which 0.1% vocal ESEs are seen alongside 13.1% oculomotor ESEs) that strengthens the interpretation of switch benefits in ESEs being mainly caused by differences in movement thresholds among effector systems. Therefore, we are confident that our interpretations regarding switch costs allocations in RTs are not compromised by the ESE data.

In general, the observation of greater vocal than manual switch costs is in line with the idea of a stronger persistent inhibition of a dominant task when it is currently not relevant, causing greater performance costs when switching back to it (cf. Allport et al., 1994; Allport & Wylie, 1999; de Jong, 1995; Meuter & Allport, 1999; Monsell et al., 2000; Yeung & Monsell, 2003). This in turn supports the idea that the concept of vocal-over-manual prioritization is directly transferable from cases involving simultaneous action execution in dual tasks as demonstrated in Study A, B, and C (cf. also Huestegge & Koch, 2013; Pieczykolan & Huestegge, 2014) to the concept of task dominance in a task switching setting.

However, another picture emerges when we take the data regarding oculomotor responses into account. Previous studies exhibited strong evidence for oculomotor prioritization over all other studied effector systems including the vocal and manual effector system (Study A; Huestegge & Koch, 2013; Pieczykolan & Huestegge, 2014). Thus, the theoretical account based on especially strong persistent inhibition of a dominant task set causing reconfiguration difficulties when switching from a non-prioritized to a relatively prioritized task would predict that switch costs for the oculomotor task should be particularly high. However, such a pattern was clearly not reflected in our data. In contrast, the results did not reveal any differences between the oculomotor and manual system in switch costs, the two effector systems with the greatest distance in the ordinal prioritization pattern among effector systems proposed by Huestegge and Koch (2013; cf. also Study A; Pieczykolan & Huestegge, 2014; oculomotor > pedal > vocal > manual). Regarding the oculomotor and vocal system we even observed an (albeit non-significant) tendency towards smaller switch costs when switching (from a manual context response) towards an oculomotor vs. towards a vocal response. Finally, note that the exceptional role of oculomotor responses cannot be explained in the same way as in Study C, since there is no reason to assume the occurrence of withheld responses here.

Thus, this discrepancy speaks against the account that the mechanisms underlying effector system prioritization as demonstrated in dual tasking with temporal task overlap (cf. Study A, B, C, Huestegge & Koch, 2013; Pieczykolan & Huestegge, 2014) can be readily transferred to the concept of effects of task dominance in task switching (e.g., Allport & Wylie, 1999; Meuter & Allport, 1999; Monsell et al., 2000; Yeung & Monsell, 2003). The present results rather point towards different underlying prioritization or dominance mechanisms in multitasking control for situations with and without temporal task overlap.

One alternative explanatory approach is the assumption that task switching situations involving oculomotor responses are special. This idea is supported by the observed effects of greater vocal than manual switch costs (and therefore in the only comparison without any oculomotor task requirements investigated in the present study) which are in line with previous findings regarding dominant vs. non-dominant tasks. Furthermore, the lack of task dominance effects in task switching when one task involves oculomotor responses resembles a finding by Stephan et al. (2013) who did not observe any IOMC effects (cf. e.g., Hazeltine et al., 2006; see Section 1.3.2) when combining oculomotor and manual responses triggered by visual and auditory stimuli, which was interpreted as an indication for shielding of oculomotor responses.

In conclusion, an alternation of the executing effector system in task switching yielded mixing and switch costs similar to those typically observed in task switching situations. Therefore, this setting can be considered as inducing switching between different effector system-specific task sets. This strongly suggests that effector systems are an integral component for defining a task set. However, regarding differences in performance decrements caused by an effector system switch as a function of effector system identities we did not observe cost asymmetries that consistently followed a similar pattern as effector system prioritization in paradigms involving simultaneous task initiation (e.g., Study A). While we were able to replicate previous observations of greater switch costs for vocal over manual tasks, potentially indicating vocal-over-manual dominance, we found no indication of oculomotor dominance (over vocal or manual tasks) in task switching. Therefore, our results indicate that underlying mechanisms of multitasking control should be differentiated among specific situations of task requirements (i.e., e.g., regarding task overlap). Consequently, temporal task overlap was shown to be an important requirement to evoke typical effects of (at least oculomotor) effector system prioritization.

6. General Discussion

6.1 Summary: General Theoretical Implications of the Presented Studies

This work represents an approach to systematically examine task processing differences based on effector systems in the three to date most important multitasking paradigms in cognitive psychology. Therefore, we examined multitasking performance in situations involving the simultaneous presentation of two cross-modal stimuli (Study A), simultaneous intra-modal stimulation for the specific combination of vocal and manual responses (Study B), sequential stimulation of two (cross-modal) stimuli with a short temporal delay in the PRP paradigm (Study C), and lastly switching between different task sets in the task switching paradigm (Study D). Correspondingly, different kinds of multitasking decrements were used as markers to uncover processes of effector system prioritization: asymmetries in dual-task costs, differences in PRP effects (as a marker of the extent of task prioritization based on stimulus presentation order), and mixing/switch costs. Thereby, the present work aimed at gaining detailed insight into mechanisms underlying effector system prioritization in general and specifically into the role of temporal task overlap in multitasking control.

The results of Study A indicated a robust ordinal prioritization pattern among effector systems when two tasks are triggered simultaneously and therefore with no externally suggested task order. This pattern illustrated an overall prioritization of oculomotor responses over pedal, vocal, and manual responses, while pedal responses were prioritized over vocal as well as manual responses, and vocal responses were prioritized over manual responses (oculomotor > pedal > vocal > manual, indicating decreasing prioritization). Crucially, this pattern did not follow the same pattern as single task response times, ruling out overall task processing speed as an explanation (see Section 2.9).

This prioritization pattern was supported by data regarding direct comparisons within pairwise combinations of effector systems in six experiments as well as in four separate across-experiment analyses comparing dual-task costs between effector systems of a focus task when combined with a fixed context task. The consistency of the prioritization pattern was not compromised by any reversals in the hierarchy nor was it substantially altered by the assignment of the two stimulus modalities to the effector systems. However, in the pairwise combination of vocal and manual responses, results of Study A (Experiment 6, see Section 2.7) were not as clear as regarding all other combinations. Moreover, although a prioritization of vocal over manual responses was already demonstrated by Huestegge and Koch (2013), it had to be considered possible that – especially regarding this combination – IOMC effects may have influenced previous observations of vocal-over-manual task prioritization.

IOMC effects are usually interpreted in terms of a particular good fit of some input modalities to specific output modalities (namely visual stimuli to manual responses and auditory stimuli to vocal responses rather than vice versa). As a consequence, it might be easier to activate input-output modality compatible task sets than input-output modality incompatible task sets (cf. e.g., Halvorson et al., 2013; Hazeltine et al., 2006; Stelzel et al., 2006; Stephan et al., 2013). Possible explanations that have been discussed to date refer to the similarity of produced sensual after-effects of responses to certain stimuli (as vocal responses produce auditory effects while manual operations can often be registered visually) or to learning experience in interaction with the outer world (e.g., in everyday conversations we normally have to react verbally to the utterance of our communication partner which we just perceived aurally; see also Section 1.3.2, for more details).

In Study B, we provided further evidence for vocal-over-manual task prioritization when using exclusively auditory as well as exclusively visual stimulation. The observation of smaller vocal than manual dual-task costs under *both* stimulus modality conditions ruled out the possibility that vocal-over-manual prioritization holds exclusively for auditory stimulation conditions based on a better fit of auditory stimuli to vocal responses than to manual responses. Moreover, it further strengthened the assumption of the ordinal effector system prioritization hierarchy proposed in Study A.

Furthermore, we also demonstrated evidence for vocal-over-manual prioritization for situations with sequential stimulus presentation when using the PRP paradigm (and therefore with an externally suggested task order; Study C). We observed a significantly smaller PRP effect for vocal than for manual responses when both were executed after a fixed oculomotor Task 1, irrespective of the respective stimulus-to-response modality assignment. Note that here the size of the PRP effect can be interpreted as a marker of the extent to which Task 1 (triggered first) is prioritized over Task 2 based on stimulus presentation order. This finding is of special theoretical relevance as it shows that well-known and -examined effects of task prioritization based on task order can be modulated by effector system prioritization. Moreover, this is an additional example of a prioritization of the overall slower (vocal) over the overall faster (manual) task.

At first sight it might seem surprising (and a potential restriction in generalisability) that we did not observe any evidence for oculomotor prioritization in the PRP paradigm. However, as discussed above (see Section 4.4), this was probably caused by a tendency to withhold (usually substantially faster) oculomotor responses when instructed to execute them after a (usually substantially slower) manual or vocal response. This explanatory account is strengthened by untypically high oculomotor error rates after a vocal Task 1 (for short SOAs) and by the impression of the experimenter that participants complained more frequently about subjectively unjustified order-related error feedback in the oculomotor-vocal combination when oculomotor responses should be executed second.

Besides this evidence for effector system-based task prioritization when executing two temporally overlapping tasks at the same time, in Study D we examined whether similar effector system-related performance costs arise in the task switching paradigm, that is, without any actual temporal task overlap. Interestingly, we did not observe any asymmetries in performance decrements between oculomotor compared to vocal or manual responses in the task switching paradigm. However, we did observe switch cost asymmetries between vocal and manual responses in line with previous preliminary research: Vocal responses were associated with significantly greater switch costs than manual responses. This finding does not only represent a conceptual replication of similar observations of Philipp and Koch (2011), but is also in line with the assumption that the concept of dominant (well-trained) tasks can be readily transferred to prioritized tasks. The fact that vocal responses, which are assumed to be relatively prioritized, were associated with significantly greater switch costs than manual responses could be interpreted in terms of strong persistent inhibition of the vocal effector system (cf. e.g., Allport et al., 1994; Meuter & Allport, 1999; Monsell et al., 2000; Yeung & Monsell, 2003).

However, the premise of similar underlying mechanisms being responsible for multitasking cost asymmetries in situations with and without temporal task overlap would have predicted highest switch costs for the oculomotor system. As this was clearly not reflected in the data, results of Study D overall rather point towards different underlying mechanisms in dual-task and task switching control. Probably, attentional switches between task sets differing in output systems are responsible for effector system-based switch cost differences in manual-vocal task switching (rather than parallel allocation policies as in temporally overlapping tasks).

One formerly open issue that – amongst others – motivated this work was the question of whether effector system prioritization can be observed in typical dual-task situations when both tasks are triggered by two different stimuli or two independent aspects of a stimulus in a similar way as in dual-response compounds studied by Huestegge and Koch (2013; cf. also Fagot & Pashler, 1992; Pieczykolan & Huestegge, 2014, 2017, 2018). Especially the results of Study A and Study B, but also of Study C confirm this assumption, as the proposed ordinal prioritization of oculomotor over vocal over manual responses was not violated in any of these studies. Especially Study A yielded consistent results regarding the relation of the three formerly investigated effector systems and strongly strengthened the assumption of ordinality by readily integrating pedal responses as a fourth effector system in this pattern. Study B and Study C provided additional evidence for vocal-over-manual prioritization in different dual-task conditions that share the requirement of two separate response selection processes for the two tasks.

On the other hand, results of the present work also highlight the importance of separately investigating resource allocation in typical dual-task settings (with two independent response selection processes) and situations requiring dual-response compounds, as we observed notable differences to the findings of previous research using the latter paradigm. Specifically, in all studies presented here we observed typical multitasking performance decrements throughout all task combinations. The dual-response setting implemented by Huestegge and Koch (2013), in contrast, yielded substantial dual-response costs associated with vocal responses in combination with oculomotor but not with manual responses. That is, in the combination of vocal and manual responses (Experiment 2 in Huestegge & Koch, 2013), vocal dual-response costs were virtually zero. Because this previous study used the same aspect of one (auditory) stimulus to trigger both responses, it did not involve any cases in which the two responses were spatially incongruent. Thus, vocal response selection might have been performed by simply copying the spatial code from the manual response (which was usually executed first). Note that in the subsequent study of Pieczykolan and Huestegge (2014), instructions implied to execute one response spatially congruent and one spatially incongruent to one and the same stimulus. Therefore, in this study both responses were *always* spatially incongruent to each other, but still, response selection of both responses cannot be assumed to be independent as one correct response consistently contained all information needed to successfully perform the respective other response. In contrast, the present approaches required participants to select appropriate responses independently, which eventually resulted in more substantial dual-task costs (particularly for vocal responses).

6.2 Implications for Existing Multitasking Frameworks

Interestingly, to date none of the existing theoretical frameworks can fully explain the main findings of the present work. Nevertheless, there already are some frameworks regarding dual-task control mechanisms including assumptions about how resources can be differentially allocated among tasks. Some of these accounts should be discussed here, as they include specific proposals regarding the principal relevance of modalities in these processes.

First, Wickens' *four-dimensional multiple resources model* (1984; see also Wickens, 2008; Wickens & Hollands, 2000) accounts for input as well as output modalities. Specifically, Wickens proposed four categorical, dichotomous dimensions to characterize dual-task performance. These are: stages of processing, codes of processing, perceptual modalities, and visual channels. Within the dimension of processing codes the model also differentiates between separate effector system domains (manual and vocal) on the output side of processing (i.e., at the final processing stage that is related to response selection and execution) in that manual responses are mainly spatially coded while vocal responses are mainly verbally coded. However, the four-dimensional resources model does not provide any (a priori) mechanism of prioritized resource scheduling among different effector systems. Therefore, to account for our observed effects of effector system prioritization, additional corresponding assumptions regarding different processing weights among output modalities would need to be established.

Second, the *EPIC (executive-process interactive control)* architecture of Meyer and Kieras (1997a) includes assumptions about input and output modalities. The EPIC model is composed of three separate processing subsystems to emulate functional parts of the human information-processing system. There is a perceptual processor subserving information from different input modalities, a cognitive processor with a declarative working memory and a motor processor that prepares and produces responses. While in this model the motor processor can differentiate between specific effector system units such as an ocular motor processor, a manual motor processor, and a vocal motor processor, EPIC does not specify whether and how respective effector system characteristics could influence resource scheduling regarding the cognitive processor. Therefore, this model is also not able to explain effector system-based task processing priorities without further assumptions.

Generally, it could be considered to extend these models by taking a broader range of effector systems into account. Regarding Wickens four-dimensional multiple resource model (Wickens, 1984), one could add the oculomotor as well as the pedal system to the processing codes dimension. Although both of them can be considered as primarily spatial (similar to manual responses), the present data clearly indicate to further differentiate among their specific characteristics. Regarding the EPIC architecture (Meyer & Kieras, 1997a), in principle it should be possible to add a pedal processor to the motor processing system. Nevertheless, these additions would still not explain effector system-based task prioritization.

The most promising account to integrate effector system-based prioritization policies appears to be the *executive control theory of visual attention (ECTVA)* framework of Logan and

Gordon (2001). The ECTVA framework combines the theory of visual attention (TVA) by Bundesen (1990) and Nosofsky and Palmeri's (1997) exemplar-based random walk (EBRW) model as subordinate processes to provide a theory of executive control that could explain phenomena that arise in dual-task situations such as task interference (and other situations requiring executive control). Importantly, ECTVA provides the possibility of parallel or serial processing depending on strategic reasons and assumes specific parameters at the stage of TVA and EBRW that determine task performance. Via these parameters, it in principle offers the possibility to allow for task prioritization. Interestingly, while ECTVA, for instance, includes a rate parameter υ that allows for a computation of the probability of choosing a specific categorization for a specific object or an evidence parameter η that is determined by the stimulus properties of the object to categorize and the subject's history with members of the requested category, until now there is no specific parameter regarding involved effector systems. However, it should be possible to expand this framework by including a mechanism for effector system weighting, for example, by adding separate response weighting parameters (cf. TVA's attention weight parameters; Bundesen, 1990).

A first approach to mathematically describing such weighting processes might be to simply define weighting parameters based on the relative means regarding cost differences among effector systems observed in the present work. Based on the data of Study A (averaged across S-R modality mappings), one could, for example, assume that when combining oculomotor and vocal responses, oculomotor responses are processed with a priority factor of 2.36, thereby resulting in 2.36 times higher vocal (than oculomotor) dual-task costs. This rationale would further lead to a priority factor of 1.39, and 3.04 in favor of the oculomotor system when combined with pedal and manual tasks, respectively, and of 1.38 and 1.89 in favor of the pedal system when combined with vocal and manual tasks, respectively. Lastly, for the combination of vocal and manual tasks the data of Study A would, according to this approach, suggest a vocal priority factor of 1.12. However, as soon as we compare this suggestion with data of Study B, it becomes obvious that this is an oversimplified approach that cannot directly account for a broader range of dual-task situations. In the rather similar setting of Study B (using either only auditory or only visual stimulation), the same approach would yield a suggested priority parameter of 1.31 in visual stimulation conditions and 1.55 in auditory stimulation conditions. Therefore, it appears evident that such factors generated based on just one specific experimental design lack generalizability. As a consequence, it would be advisable to conduct more experimental studies involving a systematic variation of effector systems prior to constructing a model with specific weighting parameters. Nevertheless, taken together, our data highlight the substantial influence of effector system characteristics on task performance and therefore generally suggest that such an approach is reasonable.

6.3 Functional Significance and Explanatory Accounts

While empirical results regarding mechanisms of effector system prioritization in varying multitasking situations including temporal task overlap paint a consistent and rather clear picture, crucially, its functional significance and underlying causes, such as whether effector system prioritization is based on a voluntary strategy or rather based on automatic processes still remain elusive. Although this key question cannot be answered with the present data and possible explanations must thus remain speculative, in the following some promising ideas are discussed.

First, it would be plausible to provide an especially high amount of resources for the selection of ballistic responses (such as saccades) to minimize the risk of false decisions. This refers to the observation that the oculomotor system is suggested to be prioritized over all other effector systems while at the same time it holds the specific and unique feature that saccades cannot be stopped or altered after initiation (cf. e.g., Westheimer, 1954). Optimal performance thus requires great care already at early stages of response-related processing. However, while this approach could explain our observations of oculomotor prioritization, it is not suited to explain other prioritization relations among the remaining effector systems (e.g., the prioritization of pedal over vocal tasks).

Second, it is also possible that resources are allocated among tasks according to a mechanism that takes variability in complexity or difficulty among tasks into account. Overall task difficulty could be determined by effector systems despite otherwise constant task requirements in terms of overall comparable selection demands (e.g., basic, spatially S-R congruent, left/right decisions as used in all of the present studies), independent of associated overall response speed. This appears plausible since the execution of some responses are well trained in everyday life, while others are highly unfamiliar. For example, manual key presses are executed frequently in daily life in a similar way as in our experimental setup, namely when typing on a keyboard. Contrastingly, most of our participants are not familiar with the deliberate execution of a saccade into a pre-defined direction.

This idea is also supported by first evidence provided by the previously introduced study of Pieczykolan and Huestegge (2014). In this study, performance costs in a cross-modal dual-response situation with high response-related conflict were shown to be modulated by the allocation of this conflict. Specifically, in this setting in which participants were instructed to execute one of two responses to a single stimulus spatially S-R congruent and one incongruent (resulting in spatial response-response conflict), relatively lower dual-response costs (within the same effector system) were observed for responses that were assigned to the S-R incongruent (instead of S-R congruent) mapping. As these responses were potentially associated with higher conflict, this can be interpreted as an indication for the more difficult response receiving a larger portion of cognitive resources. However, this account calls for further research in order to be tested more explicitly (see Section 6.4).

Note that taking these response execution characteristics (the extent to which they are relatively ballistic or complex) into account may result in especially efficient overall task performance (and therefore in a strategic advantage). Consequently, both of these accounts could be implemented by assuming resource allocation policies based on strategic reasons, as already implemented in current flexible resource sharing models (cf. Meyer & Kieras, 1997a; Navon & Miller, 2002; Tombu & Jolicœur, 2003).

From a more global perspective, effector system prioritization could be evolved by being a hereditary evolutionary advantage. In hazardous situations, survival could have been fostered by attaching more importance and therefore prioritized processing to, for instance, gathering potentially life-threatening information with the oculomotor effector system or running away by foot rather than, in contrast, reacting vocally (e.g., by calling for help) or manually. On the other hand, it is also possible that such general prioritization patterns are learned based on experience with the outer world in everyday life (e.g., by using a breaking pedal while driving or the continuous importance of the pedal system in maintaining balance). Again, these potential functional origins of effector system prioritization are so far speculative and certainly future research would be needed to come up with a more substantial answer here.

Irrespective of its functional origin, it can be proposed that the demonstrated empirical effects interpreted in terms of effector system prioritization are rooted in effector system-specific resource allocation policies. Consequently, these allocation policies imply that effector systems – that at first sight only related to the last stage of a classic processing stage logic – already influence central processing. I assume that the mechanism how effector system characteristics can influence resource allocation in the first place must be either based on a relatively early anticipation of effector systems associated with response execution during task processing, or on an effector system-specific response selection or integrative, holistic task processing itself. These potential alternatives to a classic processing stage logic (as well as a schematic illustration of this classic approach itself) are outlined in Figure 6.1.

An early anticipation of effector systems, as schematically illustrated in Figure 6.1B, might operate in a comparable manner as anticipation of action effects assumed in ideo-motor theories (e.g., Badets, Koch, & Philipp, 2016; Pfister, 2019, for reviews). Note moreover, that in Study A, B, and C the assignment of effector systems to stimulus modality (Study A and C) and accordingly stimulus component (in the case of Study B) was only manipulated blockwise, whereby it should have been relatively easy for participants to associate appropriate stimulus characteristics and effector systems. This approach complements the idea discussed above to integrate an additional weighting parameter reflecting effector system relations in existing dual-task control theories such as the ECTVA framework of Logan and Gordon (2001).

An effector system-specific response selection process, on the other hand, would make such a separate anticipation process obsolete. Assuming such an effector system-specific response selection process, this process itself could drag relatively more or less attention in terms of cognitive resources. Although the supplementary analysis included at the end of the results section of Study C (Section 4.3.2) delivered no indication for differences in the response selection *duration* among effector systems, it does not necessarily follow that distinct representation of effector system-specific processing is not possible. In fact, this assumption does not even rely on the logic of three separate processing stages (as assumed by Broadbent, 1958; Pashler, 1994; or Welford, 1952). Rather, we could assume that tasks might be processed in terms of one integral higher-order task set that already includes information about spatial S-R mapping rules, S-R modality mapping, but also subtask order (in dual-task situations) and effector systems, without any necessity to rely on the assumption of discrete processing stages that are passed through chronologically (cf. Figure 6.1C).

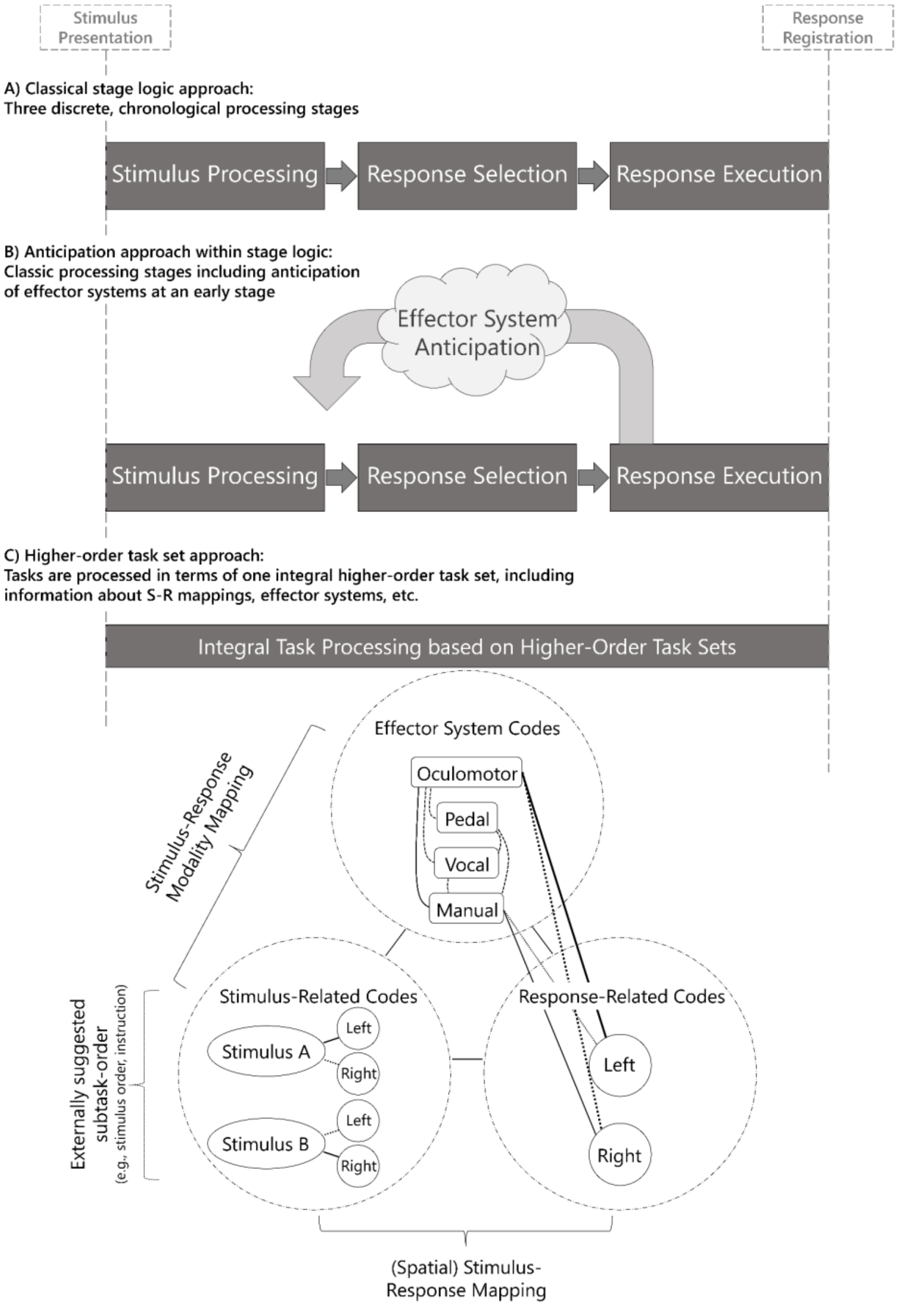

Figure 6.1. Schematic illustration of the classic three stage logic of task processing (A) and two alternatives that might account for an effector system-based influence on resource allocation policies. (B) Effector systems are anticipated at an early stage during task processing. (C) Tasks are processed in terms of one integrative task set including representations of associated effector systems (and other information e.g., regarding S-R modality mapping, spatial S-R mapping rules, or subtask order). An exemplary situation involving a prioritized left oculomotor response and a non-prioritized right manual response is depicted. Note that accounts B and C both are able to cover dual-task situations with and without externally suggested task order (e.g., via instruction or stimulus order).

This idea is in line with previous theories assuming that cognitive processes are not completely abstract but also represent bodily systems (embodied cognition; e.g., Anderson, 2003; Mahon & Caramazza, 2008; Markman & Brendl, 2005; Wilson, 2002), and that tasks could be represented by rather complex higher-order task sets, which integrate information about effector systems, but also relations of subtasks such as subtask order (cf. e.g., Hirsch et al., 2017; Hirsch et al., 2018; Kübler et al., 2018). Moreover, this approach is also in line with the crosstalk model introduced by Huestegge and Koch (2010) for the case of simultaneously executed oculomotor and manual responses to a single stimulus. While this model still includes three processing stages (perceptual processing, parallel mapping selection, and response execution), crucially, the central stage of mapping selection is not assumed to consist of two separated individual response selections of tasks, but rather represents a parallel, holistic mapping of spatial codes to respective modality codes. Thereby, relevant effector system codes and mappings of stimulus and effector system codes are implied to be held active in working memory (i.e. at a central processing stage). Note further, that our interpretation of Study D already implies that effector systems should be assumed as integral task set components (cf. also Philipp & Koch, 2011) and therefore mentally represented during the whole task processing. Taken together, allocation policies regarding central resources could therefore be correspondingly adjusted either due to the representation of the effector system in an integrative task set from the onset of processing or based on early anticipatory mechanisms.

6.4 Outlook: Open Issues and Future Research

As discussed above, the functional significance of effector system prioritization is an important open issue which should be empirically addressed. This can be done, on the one hand, on a specific task-related level, and, on the other hand, on a broader level that focuses more on a potential evolutionary advantage of prioritizing specific tasks.

First, it would be interesting to consider the possibilities that effector system prioritization is the outcome of an evolutionary advantage or of longstanding training in everyday life. The former could be rooted, for instance, in the high relevance of gathering information with the oculomotor system that might promote survival chances (in hazardous situations), while the second view could, for example, account for pedal/vocal over manual prioritization by assuming a high priority of the pedal system for maintaining balance/driving or verbal responses in our highly civilized, language-based society (compared to the manual system). Here, further insights could be derived by studying resource allocation in participants with a different learning history regarding responses in specific effector systems. For instance, in the combination of manual-vocal dual tasks, this could be professional piano players or people who learned vocal language later in their life than sign language (e.g., as a result of cochlear implant surgery). If learning is a driving factor, one would expect that in these groups the relation of the vocal and the manual system regarding resource allocation differs from a control group. If we take the present data as a baseline one might expect to observe effects of manual-over-vocal (instead of vocal-over-manual) prioritization.

Next, as discussed above, one promising account to explain underlying mechanisms of resource allocation based on effector system characteristics refers to different response control difficulties among them. This account calls for further specification regarding exact determinants of difficulty in order to be tested more explicitly in the future. Future research could examine whether the observed dual-task costs asymmetries in Study A and B could be modulated by manipulating task demands regarding spatial S-R congruency. This could be realized by using the exact same setting as described here, apart from simply instructing participants to give a spatially congruent response according to one but a spatially incongruent response to the other stimulus (or stimulus component when using intra-modal stimulation as in Study B). Thus, we could examine whether it is possible to conceptually replicate the observations of Pieczykolan and Huestegge (2014) in a more typical dual-task setting. However, it should be mentioned that the observation of Pieczykolan and Huestegge (2014) on which these considerations are grounded were not actually in the focus of this previous study, but should rather be considered as an incidental observation. Therefore, it could also be reasonable to first test whether a modulation of effector system prioritization in dual-response compounds in the form of relatively lower dual-response costs for S-R incongruent compared to S-R congruent responses can be replicated.

If both approaches yield consistent results, then the next step would be to further investigate which aspects of and to what extent responses executed by different effector systems differ a priori in their difficulty. Regarding this account it should be mentioned that a first pilot study conducted in our lab failed to demonstrate asymmetrical dual-task costs when responding to both the word identity and the print colour of stroop stimuli (Stroop, 1935; see e.g., MacLeod, 1991, for a review). Note that while this manipulation was assumed to affect task difficulty, it probably relates more to the complexity of stimulus processing. In future research, it might be more relevant to focus on the manipulation of task difficulty in relation to central (response selection) or late (task execution) processes.

Besides this crucial question of underlying mechanisms actually causing the empirically observable effects of effector system prioritization, two more experimental settings that would be suitable to uncover and further expand the present insights are outlined below. The first one refers to the findings of Study C, in which we were not able to demonstrate a modulation of the PRP effect by effector system prioritization when oculomotor Task 2 responses were compared to vocal or manual Task 2 responses after a controlled (manual or vocal) Task 1. As already discussed above (see Section 4.4), we do not interpret this as an indication against oculomotor effector system prioritization under task requirements involving sequential stimulus presentation. Instead, it was supposed that oculomotor responses (which can be executed extremely fast in relation to responses executed by other effector systems) were artificially withheld due to our rather strict design regarding response order reversals. Consequently, it would be interesting to address whether a modulation of PRP effects by effector system prioritization in the comparison of oculomotor vs. vocal or manual Task 2 performance can be observed in a setting without any restrictions or feedback regarding response order reversals. This might even be implemented without any external instruction to stick to stimulus presentation order (cf. e.g., Bratzke et al., 2007; Bratzke et al., 2008).

Second, in Study D no evidence for oculomotor effector system prioritization in the context of task switching was observed. However, here the interpretation was quite different, as we assumed different processes to be responsible for multitasking control in situations with and without temporal task overlap. In the first type of task requirements cognitive resources have to be shared among overlapping task processing, while in the latter performance asymmetries are rather associated with differences in the extent of inhibitory mechanisms. On the other hand, to date we cannot rule out that the lack of oculomotor effector system prioritization effects in task switching can rather be explained by unique characteristics of the oculomotor system. The latter idea would be in line with arguments of Stephan and colleagues (Stephan et al., 2013), as they observed no typical IOMC effects in a task switching setting involving oculomotor responses. The first option, in contrast, is supported by the observations of Philipp and Koch (2011), who found no systematic differences when switching between vocal and pedal or between pedal and manual responses. Therefore, it would be important to conduct one or two further experiments that would explicitly address whether or not pedal responses are associated with systematically greater switch costs compared to vocal and manual responses. If they are not, this could conclusively rule out the idea that systematic differences in the size of switch costs among effector systems when oculomotor responses were involved were merely not observable due to unique characteristics of the oculomotor system, and could constitute further evidence supporting the assumption of different underlying control mechanisms in multitasking situations with and without temporal task overlap.

Finally, I want to refer to a recent approach of Miller and colleagues to address the question of resource allocation among tasks by actively instructing participants to maximize priority for one task ("prioritized-processing paradigm"; developed by Miller & Durst, 2014; see also Miller, 2017; Miller & Durst, 2015; Mittelstädt & Miller, 2017). In this paradigm, participants are instructed to attend to a primary and a background task and to maximize priority for the primary task in the sense that they should only respond to the background task in trials in which the primary task requires no response. This recently introduced paradigm combines similarities of all three multitasking paradigms used here, but also features relevant distinctions. While in each trial two stimuli are presented simultaneously, as in the simultaneous onset paradigm, an external task prioritization is defined by instruction as in the PRP paradigm. Furthermore, in the prioritized-processing paradigm two distinct stimuli are presented in each trial, while only one response is required (task switch or an alternation), similar to the task switching paradigm.

Note that this paradigm involved an even stronger instructed task prioritization than implied by stimulus presentation order (and often instruction) in the PRP paradigm. While we already demonstrated a modulation of task order-based prioritization in the PRP paradigm (in Study C), it could be an interesting future issue to which extent task prioritization rooted in this kind of explicit instruction is affected by associated effector systems. Indeed, the findings of Miller and Durst (2014) already indicated that while participants were not able to fully prioritize one task over the other in the sense of achieving a single-task focus, some tasks might be easier to prioritize than others (as suggested by an interaction of task emphasis and the relevant stimulus dimension to which a response was required). Taken together, I hypothesize that tasks associated with prioritized effector systems should be easier to prioritize based on conscious control when participants are explicitly instructed to do so based on task definition compared to tasks associated with relatively non-prioritized effector systems. This should result in a modulation of instructed task prioritization by different effector systems (i.e., an interaction of task emphasis and effector system) in the prioritized-processing paradigm when varying effector systems are involved.

6.5 General Conclusion

I want to draw three major conclusions from the present work. First, in a setting including simultaneous task initiation, effector systems follow a consistent, ordinal prioritization pattern: oculomotor > pedal > vocal > manual (indicating decreasing prioritization). This pattern occurs for cross-modal as well as for intra-modal stimulation conditions, and was not qualitatively affected by stimulus modality or by the specific combination of input and output modalities. Crucially, overall response speed can be ruled out as an alternative explanation for the observed data pattern. Rather, it is assumed that response selection is affected by effector system-specific task characteristics. More precisely, effector systems are either anticipated or already represented in a higher-order task set at an early state of task processing, and therefore, limited resources are shifted unevenly among tasks based on the suggested hierarchy among effector systems.

Second, when using sequential task initiation in the PRP paradigm the typical observation of task prioritization based on task order as reflected in PRP effects is not cancelled out by effector system prioritization, but is consistently observable for all investigated effector system combinations and task orders. However, these task order-based prioritization processes can be modulated by effector system prioritization. The observed prioritization of vocal over manual responses in form of a smaller PRP effect in vocal (vs. manual) responses after an oculomotor Task 1 is in line with the well-replicable relation of vocal and manual responses in the processing hierarchy. Also this modulation of the PRP effect was not compromised by any influence of stimulus modality or its assignment to effector systems. This indicates a similar influence of effector system prioritization in dual-task situations involving simultaneous and sequential stimulus presentation, which both imply temporal task overlap.

Third, in the case of multitasking without actual temporal task overlap (task switching), the relation of vocal and manual responses at first sight appears to be in line with the assumption of vocal-over-manual prioritization. Specifically, this might be due to an especially strong inhibition of the prioritized task, similar to previous interpretations regarding task dominance effects in task switching. However, we could not demonstrate typical effects of oculomotor effector system prioritization in task switching. This either indicates a potential uniqueness of oculomotor responses when it comes to task switching, or (probably more likely) different underlying mechanisms responsible for task control in temporally overlapping dual tasks and in non-overlapping task switching situations.

To conclude, the present work supports flexible resource sharing models of dual-task control and strongly underlines the importance of specific effector systems and effector system combinations in multitasking. The present results suggest that effector system characteristics are represented or anticipated and thereby influence dual-task processing at a relatively early stage during task processing. As this issue has widely been neglected in previous research, the results of the present work emphasize the need to take effector system characteristics into account in future research on multitasking as well as in corresponding theories..

References

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

Allport, A., & Wylie, G. (1999). Task-switching: Positive and negative priming of task-set. In G. W. Humphreys, J. Duncan, & A. Treisman (Eds.), *Attention, space, and action: Studies in cognitive neuroscience* (pp. 273–296). New York, NY, US: Oxford University Press.

Anderson, M. L. (2003). Embodied Cognition: A field guide. *Artificial Intelligence*, *149*(1), 91–130. https://doi.org/10.1016/S0004-3702(03)00054-7

Arrington, C. M., & Logan, G. D. (2004). The cost of a voluntary task switch. *Psychological Science*, *15*(9), 610–615. https://doi.org/10.1111/j.0956-7976.2004.00728.x

Arrington, C. M., Reiman, K. M., & Weaver, S. M. (2014). Voluntary Task Switching. In J. A. Grange & G. Houghton (Eds.), *Task switching and cognitive control* (pp. 117–136). New York, NY, US: Oxford University Press. https://doi.org/10.1093/acprof:osobl/9780199921959.003.0006

Badets, A., Koch, I., & Philipp, A. M. (2016). A review of ideomotor approaches to perception, cognition, action, and language: Advancing a cultural recycling hypothesis. *Psychological Research*, *80*(1), 1–15. https://doi.org/10.1007/s00426-014-0643-8

Beurskens, R., & Bock, O. (2012). Age-related deficits of dual-task walking: A review. *Neural Plasticity*, *2012*, 1–9. https://doi.org/10.1155/2012/131608

Beurskens, R., Haeger, M., Kliegl, R., Roecker, K., & Granacher, U. (2016). Postural control in dual-task situations: Does whole-body fatigue matter? *PloS One*, *11*(1), e0147392. https://doi.org/10.1371/journal.pone.0147392

Beurskens, R., Helmich, I., Rein, R., & Bock, O. (2014). Age-related changes in prefrontal activity during walking in dual-task situations: A fNIRS study. *International Journal of Psychophysiology*, *92*(3), 122–128. https://doi.org/10.1016/j.ijpsycho.2014.03.005

Bratzke, D., Rolke, B., Ulrich, R., & Peters, M. (2007). Central slowing during the night. *Psychological Science*, *18*(5), 456–461. https://doi.org/10.1111/j.1467-9280.2007.01921.x

Bratzke, D., Ulrich, R., Rolke, B., Schröter, H., Jentzsch, I., & Leuthold, H. (2008). Motor limitation in dual-task processing with different effectors. *Quarterly Journal of Experimental Psychology*, *61*(9), 1385–1399. https://doi.org/10.1080/17470210701536856

Broadbent, D. E. (1958). *Perception and communication*. Elmsford, NY, US: Pergamon Press. https://doi.org/10.1037/10037-000

Bundesen, C. (1990). A theory of visual attention. *Psychological Review*, *97*(4), 523–547. https://doi.org/10.1037/0033-295X.97.4.523

Colavita, F. B. (1974). Human sensory dominance. *Perception & Psychophysics*, *16*(2), 409–412. https://doi.org/10.3758/BF03203962

Colavita, F. B. (1982). Visual dominance and attention in space. *Bulletin of the Psychonomic Society*, *19*(5), 261–262. https://doi.org/10.3758/BF03330251

Colavita, F. B., & Weisberg, D. (1979). A further investigation of visual dominance. *Perception & Psychophysics*, *25*(4), 345–347. https://doi.org/10.3758/BF03198814

Cooper, R. (1998). Visual dominance and the control of action. In M. A. Gernsbacher & S. J. Derry (Eds.), *Proceedings of the 20th Annual Conference of the Cognitive Science Society* (pp. 250–255). Mahwah, NJ: Erlbaum.

De Jong, R. (1995). The role of preparation in overlapping-task performance. *The Quarterly Journal of Experimental Psychology Section A*, *48*(1), 2–25. https://doi.org/10.1080/14640749508401372

Durst, M., & Janczyk, M. (2018). The motor locus of no-go backward crosstalk. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *44*(12), 1931–1946. https://doi.org/10.1037/xlm0000565

Durst, M., & Janczyk, M. (2019). Two types of backward crosstalk: Sequential modulations and evidence from the diffusion model. *Acta Psychologica*, *193*, 132–152. https://doi.org/10.1016/j.actpsy.2018.11.013

Egeth, H. E., & Sager, L. C. (1977). On the locus of visual dominance. *Perception & Psychophysics*, *22*(1), 77–86. https://doi.org/10.3758/BF03206083

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*(4), 1058–1079. https://doi.org/10.1037/0096-1523.18.4.1058

Fintor, E., Poljac, E., Stephan, D. N., & Koch, I. (2018). Modality compatibility biases voluntary choice of response modality in task switching. *Psychological Research.* Advance online publication. https://doi.org/10.1007/s00426-018-1040-5

Fintor, E., Stephan, D. N., & Koch, I. (2018). Emerging features of modality mappings in task switching: Modality compatibility requires variability at the level of both stimulus and response modality. *Psychological Research*, *82*(1), 121–133. https://doi.org/10.1007/s00426-017-0875-5

Fintor, E., Stephan, D. N., & Koch, I. (2019). The interplay of crossmodal attentional preparation and modality compatibility in cued task switching. *Quarterly Journal of Experimental Psychology*, *72*(4), 955–965. https://doi.org/10.1177/1747021818771836

Fischer, R., & Plessow, F. (2015). Efficient multitasking: Parallel versus serial processing of multiple tasks. *Frontiers in Psychology*, *6*, 1366. https://doi.org/10.3389/fpsyg.2015.01366

Fröber, K., & Dreisbach, G. (2017). Keep flexible - Keep switching! The influence of forced task switching on voluntary task switching. *Cognition*, *162*, 48–53. https://doi.org/10.1016/j.cognition.2017.01.024

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. https://doi.org/10.1016/j.cognition.2016.02.003

Granacher, U., Muehlbauer, T., & Gruber, M. (2012). A qualitative review of balance and strength performance in healthy older adults: Impact for testing and training. *Journal of Aging Research*, *2012*, 708905. https://doi.org/10.1155/2012/708905

Greenwald, A. G. (1972). On doing two things at once: Time sharing as a function of ideomotor compatibility. *Journal of Experimental Psychology*, *94*(1), 52–57. https://doi.org/10.1037/h0032762

Greenwald, A. G. (2003). On doing two things at once: III. Confirmation of perfect timesharing when simultaneous tasks are ideomotor compatible. *Journal of Experimental Psychology: Human Perception and Performance*, *29*(5), 859–868. https://doi.org/10.1037/0096-1523.29.5.859

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*(2), 413–432. https://doi.org/10.1037/a0029475

Halvorson, K. M., & Hazeltine, E. (2015). Do small dual-task costs reflect ideomotor compatibility or the absence of crosstalk? *Psychonomic Bulletin & Review*, *22*(5), 1403–1409. https://doi.org/10.3758/s13423-015-0813-8

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*(4), 291–345. https://doi.org/10.1016/j.cogpsych.2005.11.001

Hibberd, D. L., Jamson, S. L., & Carsten, O. M. J. (2010). Managing in-vehicle distractions – evidence from the Psychological Refractory Period paradigm. In A. K. Dey (Ed.), *Proceedings of the 2nd International Conference on Automotive User Interfaces and Interactive Vehicular Applications* (pp. 4-11). New York, NY: ACM. https://doi.org/10.1145/1969773.1969775

Hirsch, P., Declerck, M., & Koch, I. (2015). Exploring the functional locus of language switching: Evidence from a PRP paradigm. *Acta Psychologica*, *161*, 1–6. https://doi.org/10.1016/j.actpsy.2015.07.010

Hirsch, P., Nolden, S., & Koch, I. (2017). Higher-order cognitive control in dual tasks: Evidence from task-pair switching. *Journal of Experimental Psychology: Human Perception and Performance*, *43*(3), 569–580. https://doi.org/10.1037/xhp0000309

Hirsch, P., Nolden, S., Philipp, A. M., & Koch, I. (2018). Hierarchical task organization in dual tasks: Evidence for higher level task representations. *Psychological Research*, *82*(4), 759–770. https://doi.org/10.1007/s00426-017-0851-0

Hoffmann, M. A., Pieczykolan, A., Koch, I., & Huestegge, L. (under review). Two sources of task prioritization: The interplay of effector-based and task order-based capacity allocation in the PRP paradigm.

Hoffmann, M. A., Pieczykolan, A., Koch, I., & Huestegge, L. (2019). Motor sources of dual-task interference: Evidence for effector-based prioritization in dual-task control. *Journal of Experimental Psychology: Human Perception and Performance.* Advance online publication. https://doi.org/10.1037/xhp0000677

Hoffmann, M. A., Westermann, M., Pieczykolan, A., & Huestegge, L. (under review). Effects of input modality on vocal effector prioritization in manual-vocal dual tasks.

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). Amsterdam, North-Holland: Elsevier. https://doi.org/10.1016/S0166-4115(08)61959-7

Hommel, B. (1998). Automatic stimulus–response translation in dual-task performance. *Journal of Experimental Psychology: Human Perception and Performance*, *24*(5), 1368–1384. https://doi.org/10.1037/0096-1523.24.5.1368

Hommel, B., & Eglau, B. (2002). Control of stimulus-response translation in dual-task performance. *Psychological Research*, *66*(4), 260–273. https://doi.org/10.1007/s00426-002-0100-y

Huestegge, L., & Hazeltine, E. (2011). Crossmodal action: Modality matters. *Psychological Research*, *75*(6), 445–451. https://doi.org/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*(2), 352–362. https://doi.org/10.1037/a0013897

Huestegge, L., & Koch, I. (2010). Crossmodal action selection: Evidence from dual-task compatibility. *Memory & Cognition*, *38*(4), 493–501. https://doi.org/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*(3), 633–637. https://doi.org/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. https://doi.org/10.1016/j.actpsy.2014.07.001

Huestegge, L., Pieczykolan, A., & Janczyk, M. (2018). Backward crosstalk and the role of dimensional overlap within and between tasks. *Acta Psychologica*, *188*, 139–147. https://doi.org/10.1016/j.actpsy.2018.06.004

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

Janczyk, M. (2016). Sequential modulation of backward crosstalk and task-shielding in dual-tasking. *Journal of Experimental Psychology: Human Perception and Performance*, *42*(5), 631–647. https://doi.org/10.1037/xhp0000170

Janczyk, M., Augst, S., & Kunde, W. (2014). The locus of the emotional Stroop effect: A study with the PRP paradigm. *Acta Psychologica*, *151*, 8–15. https://doi.org/10.1016/j.actpsy.2014.05.011

Janczyk, M., & Huestegge, L. (2017). Effects of a no-go Task 2 on Task 1 performance in dual-tasking: From benefits to costs. *Attention, Perception & Psychophysics*, *79*(3), 796–806. https://doi.org/10.3758/s13414-016-1257-6

Janczyk, M., & Kunde, W. (2010). Does dorsal processing require central capacity? More evidence from the PRP paradigm. *Experimental Brain Research*, *203*(1), 89–100. https://doi.org/10.1007/s00221-010-2211-9

Janczyk, M., Pfister, R., Hommel, B., & Kunde, W. (2014). Who is talking in backward crosstalk? Disentangling response- from goal-conflict in dual-task performance. *Cognition*, *132*(1), 30–43. https://doi.org/10.1016/j.cognition.2014.03.001

Janczyk, M., Renas, S., & Durst, M. (2018). Identifying the locus of compatibility-based backward crosstalk: Evidence from an extended PRP paradigm. *Journal of Experimental Psychology: Human Perception and Performance*, *44*(2), 261–276. https://doi.org/10.1037/xhp0000445

Jersild, A. T. (1927). Mental set and shift. *Archives of Psychology*, *14*(89), 5–82.

Jurczyk, V., Fröber, K., & Dreisbach, G. (2018). Increasing reward prospect motivates switching to the more difficult task. *Motivation Science.* Advance online publication. https://doi.org/10.1037/mot0000119

Kahneman, D. (1973). *Attention and effort*. Englewood Cliffs, NJ: Prentice Hall.

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*(5), 849–874. https://doi.org/10.1037/a0019842

Koch, I. (2008). Mechanismen der Interferenz in Doppelaufgaben. *Psychologische Rundschau*, *59*(1), 24–32. https://doi.org/10.1026/0033-3042.59.1.24

Koch, I., Gade, M., Schuch, S., & Philipp, A. M. (2010). The role of inhibition in task switching: A review. *Psychonomic Bulletin & Review*, *17*(1), 1–14. https://doi.org/10.3758/PBR.17.1.1

Koch, I., Poljac, E., Müller, H., & Kiesel, A. (2018). Cognitive structure, flexibility, and plasticity in human multitasking – An integrative review of dual-task and task-switching research. *Psychological Bulletin*, *144*(6), 557–583. https://doi.org/10.1037/bul0000144

Koppen, C., & Spence, C. (2007a). Audiovisual asynchrony modulates the Colavita visual dominance effect. *Brain Research*, *1186*, 224–232. https://doi.org/10.1016/j.brainres.2007.09.076

Koppen, C., & Spence, C. (2007b). Seeing the light: Exploring the Colavita visual dominance effect. *Experimental Brain Research*, *180*(4), 737–754. https://doi.org/10.1007/s00221-007-0894-3

Kübler, S., Reimer, C. B., Strobach, T., & Schubert, T. (2018). The impact of free-order and sequential-order instructions on task-order regulation in dual tasks. *Psychological Research*, *82*(1), 40–53. https://doi.org/10.1007/s00426-017-0910-6

Kunde, W., Wirth, R., & Janczyk, M. (2018). The role of feedback delay in dual-task performance. *Psychological Research*, *82*(1), 157–166. https://doi.org/10.1007/s00426-017-0874-6

Künstler, E. C. S., Finke, K., Günther, A., Klingner, C., Witte, O., & Bublak, P. (2018). Motor-cognitive dual-task performance: Effects of a concurrent motor task on distinct components of visual processing capacity. *Psychological Research*, *82*(1), 177–185. https://doi.org/10.1007/s00426-017-0951-x

Liepelt, R., Fischer, R., Frensch, P. A., & Schubert, T. (2011). Practice-related reduction of dual-task costs under conditions of a manual-pedal response combination. *Journal of Cognitive Psychology*, *23*(1), 29–44. https://doi.org/10.1080/20445911.2011.448025

Logan, G. D., & Gordon, R. D. (2001). Executive control of visual attention in dual-task situations. *Psychological Review*, *108*(2), 393–434. https://doi.org/10.1037//0033-295X.108.2.393

Lukas, S., Philipp, A. M., & Koch, I. (2014). Crossmodal attention switching: Auditory dominance in temporal discrimination tasks. *Acta Psychologica*, *153*, 139–146. https://doi.org/10.1016/j.actpsy.2014.10.003

MacLeod, C. M. (1991). Half a century of research on the Stroop effect: An integrative review. *Psychological Bulletin*, *109*(2), 163–203. https://doi.org/10.1037/0033-2909.109.2.163

Mahon, B. Z., & Caramazza, A. (2008). A critical look at the embodied cognition hypothesis and a new proposal for grounding conceptual content. *Journal of Physiology-Paris*, *102*(1-3), 59–70. https://doi.org/10.1016/j.jphysparis.2008.03.004

Maquestiaux, F., Ruthruff, E., Defer, A., & Ibrahime, S. (2018). Dual-task automatization: The key role of sensory-motor modality compatibility. *Attention, Perception & Psychophysics*, *80*(3), 752–772. https://doi.org/10.3758/s13414-017-1469-4

Markman, A. B., & Brendl, C. M. (2005). Constraining theories of embodied cognition. *Psychological Science*, *16*(1), 6–10. https://doi.org/10.1111/j.0956-7976.2005.00772.x

McCann, R. S., & Johnston, J. C. (1992). Locus of the single-channel bottleneck in dual-task interference. *Journal of Experimental Psychology: Human Perception and Performance*, *18*(2), 471–484. https://doi.org/10.1037/0096-1523.18.2.471

Meiran, N. (1996). Reconfiguration of processing mode prior to task performance. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *22*(6), 1423–1442. https://doi.org/10.1037/0278-7393.22.6.1423

Meuter, R. F.I., & Allport, A. (1999). Bilingual Language Switching in Naming: Asymmetrical Costs of Language Selection. *Journal of Memory and Language*, *40*(1), 25–40. https://doi.org/10.1006/jmla.1998.2602

Meyer, D. E., & Kieras, D. E. (1997a). A computational theory of executive cognitive processes and multiple-task performance: Part I. Basic mechanisms. *Psychological Review*, *104*(1), 3–65. https://doi.org/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*(4), 749–791. https://doi.org/10.1037/0033-295X.104.4.749

Miller, J. (2017). Psychophysiological measurement of backward response activation in the prioritized processing paradigm. *Journal of Experimental Psychology: Human Perception and Performance*, *43*(5), 941–953. https://doi.org/10.1037/xhp0000356

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*(8), 2560–2574. https://doi.org/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*(5), 1420–1441. https://doi.org/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*(3), 273–310. https://doi.org/10.1016/j.cogpsych.2006.08.003

Mittelstädt, V., & Miller, J. (2017). Separating limits on preparation versus online processing in multitasking paradigms: Evidence for resource models. *Journal of Experimental Psychology: Human Perception and Performance*, *43*(1), 89–102. https://doi.org/10.1037/xhp0000277

Mittelstädt, V., Miller, J., & Kiesel, A. (2018). Trading off switch costs and stimulus availability benefits: An investigation of voluntary task-switching behavior in a predictable dynamic multitasking environment. *Memory & Cognition*, *46*(5), 699–715. https://doi.org/10.3758/s13421-018-0802-z

Monsell, S. (1996). Control of mental processes. In V. Bruce (Ed.), *Unsolved mysteries of the mind: Tutorial essays in cognition* (pp. 93–148). Hove, United Kingdom: Psychology Press.

Monsell, S. (2003). Task switching. *Trends in Cognitive Sciences*, *7*(3), 134–140. https://doi.org/10.1016/S1364-6613(03)00028-7

Monsell, S., Yeung, N., & Azuma, R. (2000). Reconfiguration of task-set: Is it easier to switch to the weaker task? *Psychological Research*, *63*(3-4), 250–264. https://doi.org/10.1007/s004269900005

Naefgen, C., Caissie, A. F., & Janczyk, M. (2017). Stimulus-response links and the backward crosstalk effect - A comparison of forced- and free-choice tasks. *Acta Psychologica*, *177*, 23–29. https://doi.org/10.1016/j.actpsy.2017.03.010

Navon, D., & Miller, J. (1987). Role of outcome conflict in dual-task interference. *Journal of Experimental Psychology: Human Perception and Performance*, *13*(3), 435–448. https://doi.org/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*(3), 193–251. https://doi.org/10.1006/cogp.2001.0767

Nosofsky, R. M., & Palmeri, T. J. (1997). An exemplar-based random walk model of speeded classification. *Psychological Review*, *104*(2), 266–300. https://doi.org/10.1037/0033-295X.104.2.266

Pashler, H. (1984). Processing stages in overlapping tasks: Evidence for a central bottleneck. *Journal of Experimental Psychology: Human Perception and Performance*, *10*(3), 358–377. https://doi.org/10.1037/0096-1523.10.3.358

Pashler, H. (1994). Dual-task interference in simple tasks: Data and theory. *Psychological Bulletin*, *116*(2), 220–244. https://doi.org/10.1037/0033-2909.116.2.220

Pashler, H., Carrier, M., & Hoffman, J. (1993). Saccadic eye movements and dual-task interference. *The Quarterly Journal of Experimental Psychology Section A*, *46*(1), 51–82. https://doi.org/10.1080/14640749308401067

Pashler, H., & Johnston, J. C. (1989). Chronometric Evidence for Central Postponement in Temporally Overlapping Tasks. *The Quarterly Journal of Experimental Psychology Section A*, *41*(1), 19–45. https://doi.org/10.1080/14640748908402351

Peterson, L. R. (1969). Concurrent verbal activity. *Psychological Review*, *76*(4), 376–386. https://doi.org/10.1037/h0027443

Pfister, R. (2019). Effect-based action control with body-related effects: Implications for empirical approaches to ideomotor action control. *Psychological Review*, *126*(1), 153–161. https://doi.org/10.1037/rev0000140

Philipp, A. M., & Koch, I. (2005). Switching of response modalities. *The Quarterly Journal of Experimental Psychology Section A*, *58*(7), 1325–1338. https://doi.org/10.1080/02724980443000656

Philipp, A. M., & Koch, I. (2011). The role of response modalities in cognitive task representations. *Advances in Cognitive Psychology*, *7*, 31–38. https://doi.org/10.2478/v10053-008-0085-1

Pick, H. L., Warren, D. H., & Hay, J. C. (1969). Sensory conflict in judgments of spatial direction. *Perception & Psychophysics*, *6*(4), 203–205. https://doi.org/10.3758/BF03207017

Pieczykolan, A., & Huestegge, L. (2014). Oculomotor dominance in multitasking: Mechanisms of conflict resolution in cross-modal action. *Journal of Vision*, *14*(13), 1–17. https://doi.org/10.1167/14.13.18

Pieczykolan, A., & Huestegge, L. (2017). Cross-modal action complexity: Action- and rule-related memory retrieval in dual-response control. *Frontiers in Psychology*, *8*, 529. https://doi.org/10.3389/fpsyg.2017.00529

Pieczykolan, A., & Huestegge, L. (2018). Sources of interference in cross-modal action: Response selection, crosstalk, and general dual-execution costs. *Psychological Research*, *82*(1), 109–120. https://doi.org/10.1007/s00426-017-0923-1

Pieczykolan, A., & Huestegge, L. (2019). Action scheduling in multitasking: A multi-phase framework of response-order control. *Attention, Perception & Psychophysics.* Advance online publication. https://doi.org/10.3758/s13414-018-01660-w

Renas, S., Durst, M., & Janczyk, M. (2018). Action effect features, but not anatomical features, determine the Backward Crosstalk Effect: Evidence from crossed-hands experiments. *Psychological Research*, *82*(5), 970–980. https://doi.org/10.1007/s00426-017-0873-7

Rogers, R. D., & Monsell, S. (1995). Costs of a predictable switch between simple cognitive tasks. *Journal of Experimental Psychology: General*, *124*(2), 207–231. https://doi.org/10.1037/0096-3445.124.2.207

Ruthruff, E., Hazeltine, E., & Remington, R. W. (2006). What causes residual dual-task interference after practice? *Psychological Research*, *70*(6), 494–503. https://doi.org/10.1007/s00426-005-0012-8

Sanders, A. F. (1980). Stage analysis of reaction processes. In G. E. Stelmach & J. Requin (Eds.), *Tutorials in motor behavior* (Vol. 1, pp. 331–354). Amsterdam, North-Holland: Elsevier. https://doi.org/10.1016/S0166-4115(08)61955-X

Sangals, J., Wilwer, M., & Sommer, W. (2007). Localizing practice effects in dual-task performance. *Quarterly Journal of Experimental Psychology*, *60*(6), 860–876. https://doi.org/10.1080/17470210600822720

Schuch, S., Sommer, A., & Lukas, S. (2018). Action control in task switching: Do action effects modulate N - 2 repetition costs in task switching? *Psychological Research*, *82*(1), 146–156. https://doi.org/10.1007/s00426-017-0946-7

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*(2), 101–108. https://doi.org/10.1111/1467-9280.00318

Schweickert, R. (1978). A critical path generalization of the additive factor method: Analysis of a stroop task. *Journal of Mathematical Psychology*, *18*(2), 105–139. https://doi.org/10.1016/0022-2496(78)90059-7

Sinnett, S., Spence, C., & Soto-Faraco, S. (2007). Visual dominance and attention: The Colavita effect revisited. *Perception & Psychophysics*, *69*(5), 673–686.

Sommer, A., & Lukas, S. (2018). Action-effect associations in voluntary and cued task-switching. *Frontiers in Psychology*, *8*, 2233. https://doi.org/10.3389/fpsyg.2017.02233

Soto-Faraco, S. (2000). An auditory repetition deficit under low memory load. *Journal of Experimental Psychology: Human Perception and Performance*, *26*(1), 264–278. https://doi.org/10.1037/0096-1523.26.1.264

Soto-Faraco, S., & Kingstone, A. (2004). Multisensory integration of dynamic information. In B. E. Stein, C. Spence, & G. Calvert (Eds.), *The handbook of multisensory processes* (pp. 49–68). Cambridge, Mass: MIT Press.

Spelke, E., Hirst, W., & Neisser, U. (1976). Skills of divided attention. *Cognition*, *4*(3), 215–230. https://doi.org/10.1016/0010-0277(76)90018-4

Spence, C., & Driver, J. (2004). *Crossmodal space and crossmodal attention*. New York, NY: Oxford Univiversity Press.

Spence, C., Parise, C., & Chen, Y.-C. (2012). The Colavita Visual Dominance Effect. In M. M. Murray & M. T. Wallace (Eds.), *The neural bases of multisensory processes.* (pp. 529-556). Boca Raton, FL: CRC Press.

Stelzel, C., & Schubert, T. (2011). Interference effects of stimulus-response modality pairings in dual tasks and their robustness. *Psychological Research*, *75*(6), 476–490. https://doi.org/10.1007/s00426-011-0368-x

Stelzel, C., Schumacher, E. H., Schubert, T., & D'Esposito, M. (2006). The neural effect of stimulus-response modality compatibility on dual-task performance: An fMRI study. *Psychological Research*, *70*(6), 514–525. https://doi.org/10.1007/s00426-005-0013-7

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*(4), 1075–1081. https://doi.org/10.1037/a0019695

Stephan, D. N., & Koch, I. (2011). The role of input-output modality compatibility in task switching. *Psychological Research*, *75*(6), 491–498. https://doi.org/10.1007/s00426-011-0353-4

Stephan, D. N., & Koch, I. (2015). Tactile stimuli increase effects of modality compatibility in task switching. *Experimental Psychology*, *62*(4), 276–284. https://doi.org/10.1027/1618-3169/a000291

Stephan, D. N., & Koch, I. (2016). Modality-specific effects on crosstalk in task switching: Evidence from modality compatibility using bimodal stimulation. *Psychological Research*, *80*(6), 935–943. https://doi.org/10.1007/s00426-015-0700-y

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*(2), 90–99. https://doi.org/10.1027/1618-3169/a000175

Sternberg, S. (1969). The discovery of processing stages: Extensions of Donders' method. *Acta Psychologica*, *30*, 276–315. https://doi.org/10.1016/0001-6918(69)90055-9

Strobach, T., Becker, M., Schubert, T., & Kühn, S. (2015). Better dual-task processing in simultaneous interpreters. *Frontiers in Psychology*, *6*, 1590. https://doi.org/10.3389/fpsyg.2015.01590

Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology*, *18*(6), 643–662. https://doi.org/10.1037/h0054651

Sudevan, P., & Taylor, D. A. (1987). The cuing and priming of cognitive operations. *Journal of Experimental Psychology: Human Perception and Performance*, *13*(1), 89–103. https://doi.org/10.1037/0096-1523.13.1.89

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

Tombu, M., & Jolicœur, P. (2003). A central capacity sharing model of dual-task performance. *Journal of Experimental Psychology: Human Perception and Performance*, *29*(1), 3–18. https://doi.org/10.1037/0096-1523.29.1.3

Vandierendonck, A., Christiaens, E., & Liefooghe, B. (2008). On the representation of task information in task switching: Evidence from task and dimension switching. *Memory & Cognition*, *36*(7), 1248–1261. https://doi.org/10.3758/MC.36.7.1248

Welford, A. T. (1952). The 'psychological refractory period' and the timing of high-speed performance—A review and a theory. *British Journal of Psychology*, *43*(1), 2–19. https://doi.org/10.1111/j.2044-8295.1952.tb00322.x

Westheimer, G. (1954). Mechanism of saccadic eye movements. *Archives of Ophthalmology*, *52*(5), 710–724. https://doi.org/10.1001/archopht.1954.00920050716006

Wickens, C. D. (1980). The structure of attentional resources. In R. Nickerson (Ed.), *Attention and performance VIII* (pp. 239–257). Hillsdale, NJ: Erlbaum.

Wickens, C. D. (1984). Processing resources in attention. In Parasuraman, R. & Davies, D.R. (Ed.), *Varieties of attention* (pp. 63–102). Orlando, FL: Academic Press.

Wickens, C. D. (2008). Multiple resources and mental workload. *Human Factors*, *50*(3), 449–455. https://doi.org/10.1518/001872008X288394

Wickens, C. D., & Hollands, J. G. (2000). *Engineering psychology and human performance* (3. ed.). Upper Saddle River, NJ: Prentice-Hall.

Wilson, M. (2002). Six views of embodied cognition. *Psychonomic Bulletin & Review*, *9*(4), 625–636. https://doi.org/10.3758/BF03196322

Yeung, N., & Monsell, S. (2003). Switching between tasks of unequal familiarity: The role of stimulus-attribute and response-set selection. *Journal of Experimental Psychology: Human Perception and Performance*, *29*(2), 455–469. https://doi.org/10.1037/0096-1523.29.2.455

Zahn, T. P., Pickar, D., & Haier, R. J. (1994). Effects of clozapine, fluphenazine, and placebo on reaction time measures of attention and sensory dominance in schizophrenia. *Schizophrenia Research*, *13*(2), 133–143. https://doi.org/10.1016/0920-9964(94)90094-9

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