

Free-choice saccades and their underlying determinants: Explorations of high-level voluntary oculomotor control

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Models of eye-movement control distinguish between different control levels, ranging from automatic (bottom-up, stimulus-driven selection) and automatized (based on well-learned routines) to voluntary (top-down, goal-driven selection, e.g., based on instructions). However, one type of voluntary control has yet only been examined in the manual and not in the oculomotor domain, namely free-choice selection among arbitrary targets, that is, targets that are of equal interest from both a bottom-up and top-down processing perspective. Here, we ask which features of targets (identity- or location-related) are used to determine such oculomotor free-choice behavior. In two experiments, participants executed a saccade to one of four peripheral targets in three different choice conditions: unconstrained free choice, constrained free choice based on target identity (color), and constrained free choice based on target location. The analysis of choice frequencies revealed that unconstrained free-choice selection closely resembled constrained choice based on target location. The results suggest that free-choice oculomotor control is mainly guided by spatial (location-based) target characteristics. We explain these results by assuming that participants tend to avoid less parsimonious recoding of target-identity representations into spatial codes, the latter being a necessary prerequisite to configure oculomotor commands.

Introduction

Efficient eye-movement control is a key requirement for many types of interaction with our environment as it provides the basis for tasks such as visual orienting, social interaction, or reading. Oculomotor control is usually assumed to be driven by both bottom-up (stimulus-driven) and top-down (goal-driven) processes, sometimes also referred to as exogenous and endogenous control, respectively. The efficiency of basic eye-movement control processes on these different hierarchical levels of processing can be systematically assessed (e.g., Leigh & Kennard, 2004), for example, in order to precisely localize potential control impairments associated with deficits underlying visual cognition in diverse contexts (dyslexia, substance abuse, attention deficit disorders, schizophrenia, etc.). However, one level of behavioral control that has been studied outside the oculomotor-research domain, namely free-choice behavior, has received surprisingly little attention as yet. Here, we conceptualize free-choice behavior as action resulting from a self-generated goal, that is, a particular goal that is not already specified by instruction or other environmental demands. Usually, such goals result from more or less extensive deliberation by considering several behavioral options from which to choose. The absence of oculomotor research on such free-choice behavior is

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particularly surprising given that deliberate-choice behavior is a core component of human cognition and behavior and even though saccadic decision making has already been suggested as a role model to understand choice behavior in general (Glimcher, 2003). For example, impairments of deliberate choice were assumed to underlie addictive behavior and executive-control deficits. The present study is, therefore, designed to provide first steps toward an understanding of free-choice oculomotor control and its underlying determinants.

As outlined above, a significant part of oculomotor behavior is guided by features of our visual environment. Models of bottom-up control typically refer to visual saliency (based on physical features, such as color, luminance, and orientation contrast) of potential eye-movement targets as an explanatory concept for selection (e.g., Itti & Koch, 2001). Bottom-up processing has also been considered central to orient attention toward suddenly occurring information (e.g., Huestegge & Koch, 2010), a phenomenon termed “attention capture” (Theeuwes, 1992) or—when eye movements are involved—oculomotor capture (see Theeuwes, 2010, for a review).

However, bottom-up control only explains one part of fixation location (or saccade-target selection) variance. Contingent upon current task goals, it is often important to look at targets that are not very salient but potentially fulfill current information needs. This type of top-down processing based on different task goals or instructions has a long research tradition (Yarbus, 1967), and some researchers have argued that top-down processing even plays a role in (presumably low-level, saliency-driven) attention-capture phenomena (contingent capture; see Bacon & Egeth, 1994; Folk, Remington, & Johnston, 1992). According to this research line, attentional control settings determine what kind of (bottom-up) features can capture attention. Top-down control can be very strong and is assumed to potentially override bottom-up processing (Castelhano, Mack, & Henderson, 2009; Huestegge & Koch, 2012; Huestegge & Radach, 2012). The interaction of bottom-up and top-down processing is captured in many models of spatial attention and fixation distribution (e.g., Nuthmann, Smith, Engbert, & Henderson, 2010; Wolfe, Cave, & Franzel, 1989). In between this continuum from top-down to bottom-up control, other additional sources of influence have been assumed, including selection determined by previous selection targets (i.e., based on selection history), by reward contingencies associated with targets (i.e., reward history; see Awh, Belopolsky, & Theeuwes, 2012; Hickey & van Zoest, 2012, for a review), or by other types of anticipation of effects associated with eye movements (Huestegge & Kreutzfeldt, 2012; Pfeuffer,

Kiesel, & Huestegge, 2016; Riechelmann, Pieczykolan, Horstmann, Herwig, & Huestegge, 2017).

Apart from the aforementioned stimulus-related sources of influence on spatial attention and fixation distribution, there is also ample evidence for general spatial biases. For example, it has been proposed that the lower and the upper visual fields serve different functional goals and thereby can exert a bias on saccade-target selection (Previc, 1990). Other studies report a tendency toward making initial saccades on a display to the left (vs. right), which has been attributed to a right-hemispheric dominance for visuospatial attention (Nuthmann & Matthias, 2014; Ossandón, Onat, & König, 2014). This leftward bias has been shown to be more pronounced for the lower visual field (Thomas & Elias, 2011). Furthermore, there is a center bias in scene viewing, defined as a tendency of observers to fixate central (vs. peripheral) positions more frequently (e.g., Clarke, Stainer, Tatler, & Hunt, 2017; Clarke & Tatler, 2014). Finally, it has also been proposed that visual scanning habits might play a role, such as, for example, a tendency to repeat a scan path over repeated exposures to identical or similar displays (Foulsham et al., 2012; Noton & Stark, 1971; but see Foulsham & Kingstone, 2013).

A model of eye-movement control that aimed at capturing different levels of control has been developed by Findlay and Walker (1999). Specifically, they distinguish between automatic, automatized, and voluntary control levels (the model does not explicitly focus on other types of influence, such as general spatial biases). Automatic control is assumed to be determined by bottom-up processing (e.g., eye movements toward suddenly occurring, highly salient objects in the periphery). Automatized control is assumed to be mainly determined by overlearned routines. For example, although eye movements in reading are known to be additionally guided by current processing demands, a large portion of control is assumed to be based on highly automatized routines, thus ensuring efficient text decoding (see Rayner, 2009, for a review). Finally, the voluntary control level involves situations in which, for example, despite high saliency of a peripheral target, a saccade is instructed to be generated in the opposite direction (antisaccade paradigm; Hallett, 1978; Massen, 2004; Walker, Husain, Hodgson, Harrison, & Kennard, 1998). Although some errors (erroneous prosaccades) typically occur in this type of task, participants are, by and large, able to follow such instructions, demonstrating that bottom-up processing can be overridden by instructions (see also related tasks requiring delayed, memory-guided, or countermanding saccades). In sum, voluntary eye-movement control in this model, thus, comprises situations in which a saccade target (location) is generated by means of instruction.

The idea that voluntary eye-movement control is essentially characterized by such an instruction-driven, top-down weighting of potential targets is widely shared across several strands of research on target selection. Note, however, that this view of voluntary control still implies that potential target objects (or locations) differ in their associated priority (due to their relation with respect to current instructed task goals). Typical paradigms (e.g., reading, scene perception, and visual search), thus, usually involve situations in which potential targets differ with respect to their (top-down or bottom-up) associated priority (coded on a general priority map; see Belopolsky, 2015; Zelinsky & Bisley, 2015), eventually resulting in response selection that is focused on the most attractive (prioritized) target when summing up both (bottom-up and top-down) sources of processing (e.g., Wolfe, 2007; Wolfe et al., 1989). However, one type of voluntary eye-movement control has not yet received much attention, namely free-choice control. Here, we define free-choice control as a choice between targets of equal overall attractiveness, that is, targets that differ with respect to neither their bottom-up saliency nor their differential correspondence with specific instructed task goals.

The issue of free-choice behavior has already been addressed in the manual action-control domain by focusing on actions driven by self-chosen (instead of externally instructed) goals (e.g., Brass & Haggard, 2008; Herwig, Prinz, & Waszak, 2007; Keller et al., 2006; Passingham, Bengtsson, & Lau, 2010; Waszak et al., 2005). Forced- and free-choice tasks were already compared by Berlyne (1957). In typical forced-choice tasks, each stimulus (e.g., a tone of a certain frequency or a visual stimulus, such as a certain letter or object shape) is unambiguously mapped (via instructions) to one specific response (e.g., usually one out of two possible key-press responses); thus, only one response is correct. Free-choice tasks require an arbitrary decision among a set of response alternatives (Berlyne, 1957), for example, pressing one out of two response keys. Still, free-choice tasks usually involve the presentation of a stimulus serving as a starting point for the response-time (RT) interval. A robust finding is that responses are faster in forced- than in free-choice tasks, either because two different “action-control systems” handle stimulus- versus goal-driven actions or because free-choice tasks require an additional process dedicated to target specification (e.g., Astor-Jack & Haggard, 2005; Brass & Haggard, 2008; Janczyk, Nolden, & Jolicoeur, 2015; Naefgen, Dambacher, & Janczyk, 2018; Obhi & Haggard, 2004).

One study in the manual action-control domain is of particular interest for the present oculomotor free-choice study. Herbort and Rosenbaum (2014) have shown that, in manual free choice, that is, in situations in which participants aim at one of two objects with either the

right or left hand, choice of hand (action-based selection) precedes target choice. Specifically, they asked participants to aim for one of two target objects (one blue and one green) with either the left or right hand (free choice of action). They then compared the choice pattern (proportion of responses executed with left or right hand toward the green or blue object) made in this free condition with constrained-choice patterns when either the hand (but not the target) or the target (but not the hand) was specified. As a main result, they found that a model assuming similar selection processes in the hand-specified and free conditions provided the best account for the data (action selection, not selection based on target identity). This result was further corroborated in RT analyses (unconstrained choice RTs were more similar to the condition involving hand prespecification) and questioned the claim that stimulus processing (in terms of target selection) always precedes action selection, an assumption at the core of many stage-based information-processing theories (e.g., Sternberg, 1969, for a strictly serial model or Spivey, 2007, for a cascaded model).

Here, we address a related question in the oculomotor-control domain by developing a novel methodological approach (based on Herbort & Rosenbaum, 2014) to examine free-choice behavior in oculomotor control. Specifically, we asked which target features (identity- or location-related) are used to determine oculomotor free-choice behavior by comparing free target choice under completely unconstrained conditions (freely select one out of four targets) with target choice under constrained (freely select one out of two) conditions (either constrained by target color or by target location). We reasoned that, for example, similar choice behavior under unconstrained conditions and location-constrained conditions indicates that the location-based constraint did not substantially alter behavior, most likely indicating that unconstrained free choice is also based on location information (vice versa for color-based choice, see Herbort & Rosenbaum, 2014, for a similar reasoning). Note that we did not expect the participants’ choices to be free from any priors in the form of target-selection biases. On the contrary, our approach to compare unconstrained choice patterns with models based on two types of constrained choice presupposes that participants adopt certain idiosyncratic biases in each condition (as opposed to showing fully random choice behavior), for example, based on left/right or upper/lower visual field preferences (see above). Only on this premise are we able to individually fit an individual’s choice pattern in unconstrained choice with the two models based on patterns in the constrained-choice condition.

Overall, we considered location-based free-choice selection more likely: It represents a more parsimonious strategy because oculomotor commands eventually

need to be coded in spatial terms anyway. Beside choice frequencies, we additionally analyzed RT distributions under unconstrained- and constrained-choice conditions to search for further support for a selection strategy (e.g., more similar RT levels between unconstrained choice and location-based choice).

Experiment 1a

In Experiment 1a, participants were asked to respond to a central cue with a saccade toward one of four possible targets in the periphery. Two targets (identity defined by color: one blue, one green) were displayed at two spatial locations (upper and lower position) on the right of fixation, and the other two targets (one blue, one green) were located on the left side. Target identity information (e.g., whether the upper left target was blue or green) was available with central cue onset. Across blocks, we varied three task conditions: In the color-constrained condition, the cue involved the letters “B” (for blue) or “G” (for green), requiring participants to freely choose a saccade to the left or right (to one of the two targets prespecified by the color cue). In the location-constrained condition, the cue involved the letters “L” (for left) or “R” (for right), requiring participants to freely choose a saccade to the green or blue target (on the side prespecified by the location cue). The unconstrained free-choice condition only involved one cue (“I” for German *irgendein*, equivalent to “any target”), and participants could freely decide for one of the four target objects.

Method

Participants

Eighteen participants (15 female, mean age = 21 years, $SD = 1.9$, range: 18–25) took part in the experiment and received course credit for participation. All had normal or corrected-to-normal vision and gave informed consent.

Apparatus

Eye movements were recorded using a high-speed (1,000 Hz sampling rate) infrared reflection system (Eyelink 1000, SR Research, Mississauga, ON, Canada). A chin rest was used to minimize head movements. Participants were seated 77 cm in front of a 20-in. CRT screen (100 Hz, resolution: $1,024 \times 768$). Participants used the space bar of the keyboard to start the experiment after a visual instruction was presented. Experiments were programmed using Experiment Builder software (SR Research).

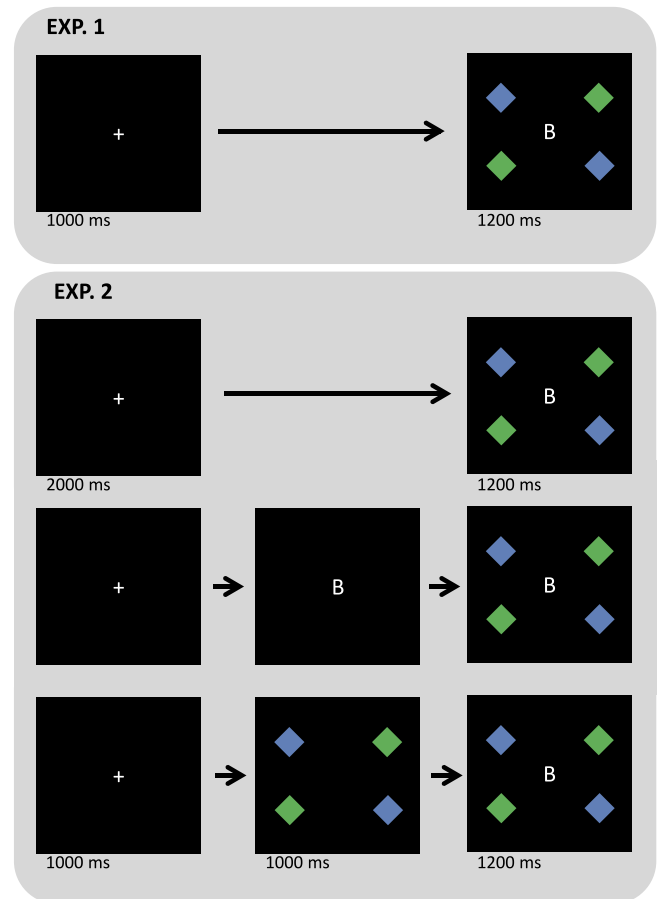


Figure 1. Experimental trial structure in the constrained (color) conditions in Experiment 1a (upper panel) and in the three SOA conditions in Experiment 2 (lower panel from top to bottom: simultaneous, cue-first, and targets-first conditions). The “B” cue shown in the example required participants to saccade toward one of the two (left or right) blue target objects (similarly, “G” required to saccade to a green target; color-based constrained choice). In the location-based constrained choice condition, “L” and “R” required participants to saccade to one of the two left or right targets, respectively. In unconstrained-choice conditions, a letter (e.g., “X”) indicated free choice out of all four targets. Trials never involved the occurrence of two identical targets (e.g., green) on the same side (e.g., left). Experiment 2 additionally involved cue-first and targets-first conditions.

Stimuli and procedure

The stimulus display (black background) consisted of a central cue (letter B/G for blue/green, R/L for right/left, or I for any target) presented in white color (0.8°). To the upper left, lower left, upper right, and lower right (distance to center: 8.6°) of this central letter, four diamond-shaped targets (1.0°) were arranged, one blue and one green square on the right of fixation and one blue and one green square on the left of fixation, resulting in four possible target arrangements (Figure 1). Luminance and saturation of the two colors were subjectively adjusted to be roughly

comparable. A white central fixation cross (size: 0.8°) was presented for 1,000 ms at the screen center prior to the (simultaneous) onset of cue and targets, which remained on screen for 1,200 ms. Short practice blocks (eight trials for each of the three task conditions) were administered at the beginning of the experiment to ensure task comprehension and were not further analyzed. The study adhered to the Declaration of Helsinki.

Design

Task condition (color-based constrained choice, location-based constrained choice, unconstrained choice) was a within-subject independent variable that was manipulated block-wise. Each block consisted of 40 trials. Block sequence was counterbalanced across participants. Each block sequence was repeated three times within each participant, resulting in nine blocks altogether. Dependent variables included target choice frequency, saccade latency, and error rates (for constrained-choice conditions only).

Analyses of choices

To address whether free-choice saccades are primarily governed by location- or identity-related information, we constructed two models that predict choice probabilities in the different tasks. According to the *location-first model* (which assumes priority of spatial information), the selection of the target identity depends on the outcome of the location-selection process. According to the *identity-first model*, the selection of the target location depends on the selected target identity. These models are hierarchical in the sense that first one aspect is determined (location or identity), and then, based on this selection, the second aspect is chosen. Each model contained parameters that represented saccade-selection probabilities for conditions in which participants were instructed to saccade to a left target ($p[G|L]$), to a right target ($p[G|R]$), to a green target ($p[L|G]$), or to a blue target ($p[L|B]$), with which L, R, G, and B, refer to left, right, green, and blue, respectively. According to the location-first model, participants chose a specific target identity based on the selected location regardless of whether the location was selected freely or determined by the task. Choices in the free condition were modeled by adding the parameter $p(L)$, which reflects the probability of leftward saccades in the free-choice conditions. This parameter was then used in conjunction with the parameters $p(G|L)$ and $p(G|R)$ to compute the probabilities of the four possible choices in the free condition.

According to the identity-first model, participants decide whether they saccade to the left or right based on the prior selection of the target identity. The identity-first model contained an additional parameter

$p(G)$, reflecting probabilities for saccades toward green targets in the free condition. The parameters $p(G)$, $p(L|G)$, and $p(L|B)$ were used to compute the probabilities of each of the four saccade types in the free condition. We computed maximum-likelihood estimates of the five parameters of each model for each individual participant. Additionally, the winning hierarchical model was compared with a fully saturated model to check whether additional explanatory power can be gained by assuming a nonhierarchical free-choice process. In the saturated model, the free choices were modeled with three additional parameters that were independent of choice parameters for the conditions in which target color or location was specified. The appendix lists how choice probabilities were computed for each condition in the three models.

Data reduction and analysis

For analyses, we only considered (error-free) trials with minimum latencies of 70 ms (to rule out anticipatory saccades), and trials in which at least the second saccade after target onset was target directed (i.e., had an amplitude of 2° minimum and landed within a radius of 2.15° around one of the four target centers). Saccade latencies exceeding $\pm 3 SD$ within each participant were not included in mean latency computations. In sum, these procedures resulted in 92.5% valid trials.¹

Results and discussion

Choice frequency analysis

Figure 2a shows the relative frequency of choices in the different conditions and the predictions of the different models. Figure 2b shows scatterplots of the empirical and predicted relative-choice frequencies of both models. The location-first model generally provided a close fit to the data. By contrast, the identity-first model showed systematic deviations from the data in most conditions.² Accordingly, the participant-wise fit of the location-first model as expressed by the negative log likelihood (*NLL*: $M = 16.1$, $SD = 1.3$) was better than that of the identity-first model (*NLL*: $M = 22.8$, $SD = 7.5$), $t(17) = -3.335$, $p = 0.004$, $d_z = 0.786$. To compare the direction-first and the saturated model with a likelihood-ratio test, we used the sums of the participant-wise *NLLs* of the direction-first and the saturated model (*NLL*: $M = 15.1$, $SD = 0.9$). The fit of the saturated model was not better than could have been expected based on its higher flexibility, $\chi^2(36) = 36.356$, $p = 0.452$. Thus, the direction-first model provided a better fit than the identity-first model. Moreover, this model is sufficient in the sense that a saturated model does not provide a significantly better fit.

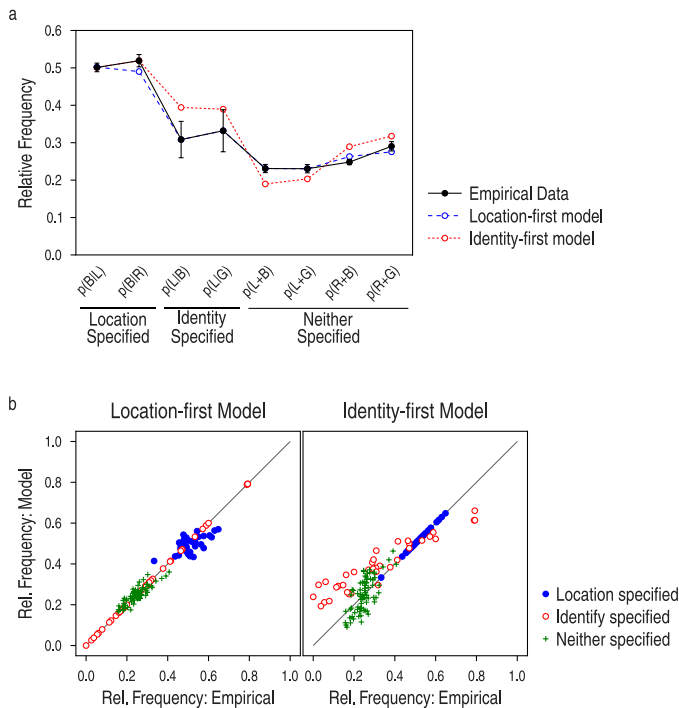


Figure 2. Choices and model fits in Experiment 1. (a) The black circles show the empirical, mean relative frequency of the possible saccades in Experiment 1. Error bars show 1 SEM. The open circles show the average predictions of the two models. (b) The scatterplots compare model predictions and empirical data for both models. The scatterplots comprise the values displayed in panel a for each individual participant.

Latency and error analyses

There was a significant main effect of task condition on mean saccade latencies, $F(2, 34) = 89.43, p < 0.001, \eta_p^2 = 0.86$. Mean latencies were much larger for color cues (436 ms, $SE = 19.6$) than for location cues (319 ms, $SE = 11.4$), and shortest latencies were observed for unconstrained-choice cues (234 ms, $SE = 12.9$), $p < 0.001$, for all three post hoc comparisons (see Figure 3).

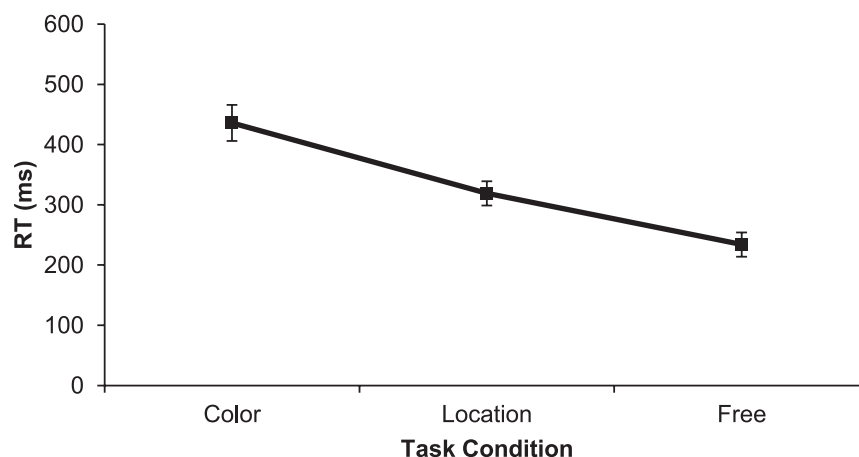


Figure 3. RTs in Experiment 1a (error bars represent SEM).

Error rate was higher for color cues (15.6%, $SE = 2.6$) than for location cues (5.5%, $SE = 1.0$), $t(17) = 4.67, p < 0.001$.

Thus, all three conditions exhibited significantly different RT levels. Although the shorter RTs in the location (vs. color) condition can, at first sight, be interpreted as indicating an advantage for processing based on spatial (location-based) response codes (in line with our choice-frequency results), there are also other viable explanations for the RT results. Specifically, given the block-wise manipulation of fast RTs in the unconstrained-choice condition may be due to full preselection of the target location prior to cue onset. Such a processing strategy is not possible in the other two conditions in which response options are constrained based on cue identity (blue/green or left/right). Second, the RT difference between location and color cues can also be explained by a simple assumption: Location-based choice should be finished faster because participants do not need any time to process the target information in the periphery to come up with a saccade-target decision (because targets always appear at the exact same four locations). For example, after processing a left cue, they can immediately decide to saccade to the upper left position regardless of the actual identity of the target (blue/green) at that location. In contrast, when decisions are based on a color cue, participants need to process the color of the peripheral targets (in addition to cue processing) in order to know the potential two target locations, which should take some extra time. This additional processing demand in the color condition may also account for the higher error liability in this condition.

The following two experiments address two open issues. First, Experiment 1b is based on a comment by a reviewer who suggested that the task involving color cues in Experiment 1a could be represented in terms of a left/right decision (e.g., execute saccade to left or right green target), and the task involving spatial cues could

be represented in terms of an upward/downward decision (e.g., execute saccade to upper or lower target on the left side). Assuming that left/right decisions might differ in speed from upward/downward decisions, this might additionally contribute to the observed behavioral differences between the two constrained-choice conditions. Thus, in Experiment 1b, we explicitly tested whether the same diagonal saccades differ in speed when coded (instructed) as left/right versus upward/downward. Second, to rule out the possibility that participants already predecide (prior to cue onset) on a target location in unconstrained conditions (as indicated by relatively fast RTs in this condition), we conducted Experiment 2 in which we used a mixed (instead of blocked) design.

Experiment 1b

As noted by one reviewer, the task in Experiment 1a could be reframed by the participants in the following manner: The color cue lets participants choose between a left versus a right target option, and the spatial cue lets participants choose between an upper versus a lower target option. Because all targets eventually require comparable diagonal saccades (upper left, upper right, lower left, lower right), their difficulty in terms of physical characteristics of saccade programming should be comparable. However, it is still possible that, on a cognitive level, it is, for example, easier to select a target based on a horizontal (left/right) mental representation dimension than on a vertical (upper/lower) mental representation dimension, which would potentially undermine our interpretation of the results (e.g., the task involving color cues could then be considered easier). To rule out this possibility, we set up a new experiment involving trials showing a similar display as those used in Experiment 1a but with only two (instead of four) diagonal targets of the same color (either upper left and lower right or upper right and lower left).

Method

Participants

Twelve new participants (no overlap with participants in the other experiments) were tested (three male, mean age = 25 years, $SD = 3.6$).

Apparatus, stimuli, procedure, and design

The apparatus was the same as in Experiment 1a. As stimuli, we used the same displays as those in Experiment 1a but with only two (instead of four)

diagonal targets: These two targets were either located at the upper left and lower right positions or at the upper right and lower left positions. Unlike in Experiment 1a, both targets had the same color. In two different experimental parts (each involving two blocks of 50 trials each), we either instructed participants to move the eyes to the upper or lower targets (by presenting one of two corresponding letters “O”/“U” at central fixation, German initials for upper/lower) or to the left or right targets (by presenting the letters “L”/“R” at central fixation, German initials for left/right). Note that both experimental parts (upper/lower vs. left/right instructions) involved (diagonal) saccades toward the same physical locations. The sequence of these experimental parts was counterbalanced across participants.

Results and discussion

Mean RTs amounted to 356 ms ($SE = 25.5$) in the left/right condition and 353 ms ($SE = 20.4$) in the upper/lower condition. Thus, we found support for the assumption that RTs toward the same (diagonally arranged) targets did not vary as a function of instruction type (upper/lower vs. left/right) with a Bayes factor of 3.48 in favor of H_0 . Thus, the mental representation of the (same) targets as either upper/lower or left/right did not substantially affect performance. Although a Bayes factor between three and four may not represent highly compelling evidence for a true null effect, the corresponding mean absolute RT difference of 3 ms between conditions renders it very unlikely that such an effect could explain any of the large performance differences between the corresponding conditions in Experiment 1a.

Experiment 2

In Experiment 2, we aimed at a generalization of the findings from Experiment 1a to a mixed (instead of a blocked) design. Note that, in a mixed design (unlike in Experiment 1a), participants cannot already predecide (prior to cue onset) on a target location in the unconstrained condition because they do not know in advance whether the next trial will represent an unconstrained-choice trial. Additionally, we here made the cue conditions more comparable by using two different cues (with the same meaning) instead of only one cue in the unconstrained condition. To further examine the processing time course, we additionally manipulated the temporal interval between the onset of cue and targets by introducing three stimulus onset asynchrony (SOA) conditions (block-wise): The cue

was either presented 1,000 ms prior to, at the same time as (similar to Experiment 1a), or 1,000 ms after the onset of the four targets.

Note that the “cue-first” SOA condition involved two subconditions (“location” and “free choice”) that are difficult to interpret in a theoretically informative manner because participants can already select a target location based on the cue alone (i.e., without the need to wait for the target stimuli). Therefore, we expected that these two conditions should yield the fastest RTs. Nevertheless, we decided against removing these conditions from the design to avoid anticipation effects based on an uneven distribution (nonorthogonal manipulation) of experimental conditions.

Apart from replicating the evidence for location-based free-choice behavior from Experiment 1a, an additional hypothesis was that preparing for the task condition (in conditions in which the color cue was presented prior to target-stimuli onset) should facilitate target choice (as evidenced by shorter saccade latencies) relative to the condition with simultaneous onset of cue and stimuli. Conversely, we tested whether prior information regarding the target stimuli is used to speed up selection when the cue eventually defines potential selection constraints.

Method

Participants

Eighteen new participants (10 female, mean age = 24.3 years, $SD = 3.7$, range: 20–32) took part in the experiment and received course credit or reimbursement for participation. All had normal or corrected-to-normal vision and gave informed consent.

Apparatus, stimuli, procedure, and design

Most aspects of this experiment were the same as in Experiment 1a. Unlike in Experiment 1a, we used two letters (“X” and “Y,” both signaling unconstrained choice) instead of the single “I” to equate the number of cues across task conditions. Unlike in Experiment 1a, task condition was now mixed (randomized order) within blocks, and the additional independent variable SOA was manipulated block-wise (sequence counter-balanced across participants). Each SOA block consisted of 73 trials, and each sequence of three blocks was repeated three times within each participant.

Results and discussion

As in Experiment 1a, only error-free trials were selected involving saccade latencies above 70 ms and meeting the criterion that at least the second saccade

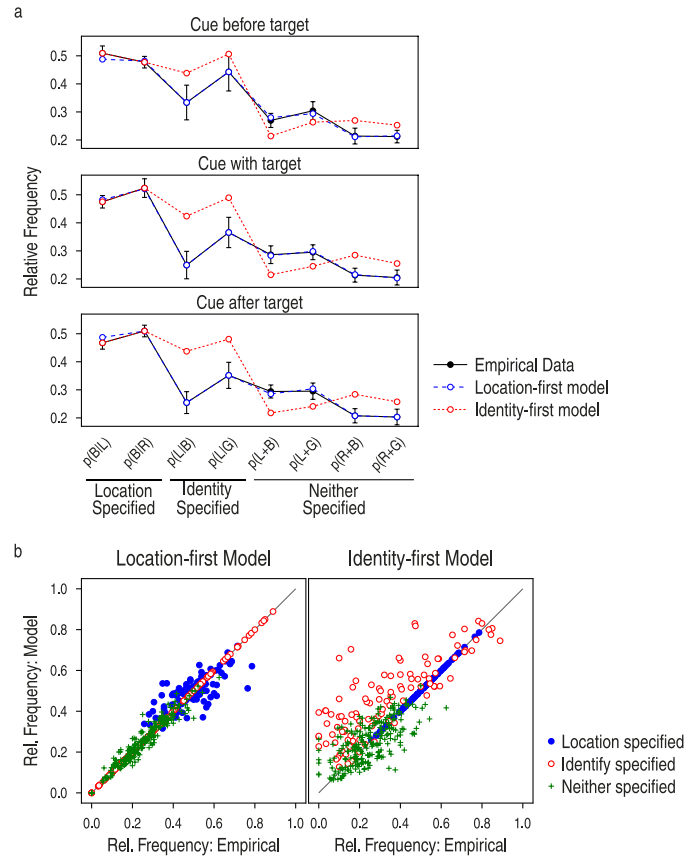


Figure 4. Choices and model fits in Experiment 2. (a) The black circles show the relative frequency of the possible choices by task and SOA in Experiment 2. Error bars show 1 *SEM*. The open circles show the average predictions of the two models. (b) The scatterplots compare model predictions and empirical data for both models. The scatterplot comprises the values displayed in panel a for each individual participant.

after target onset was target directed (i.e., that had an amplitude of 2° minimum and landed within a radius of 2.15° around one of the four target centers). Saccade latencies exceeding ± 3 *SD* within each participant were excluded. In sum, these procedures resulted in 88.6% valid trials.

Choice frequency analysis

Individual models were fit for each participant and each SOA. Figure 4a shows the relative frequency of choices for the different tasks and SOAs as well as the predictions of the location- and identity-first models. Figure 4b shows scatterplots of the empirical and predicted relative choice frequencies of both models. As in Experiment 1, the location-first model provided the closer fit to the data, irrespective of SOA. To compare the models, we submitted the fits in terms of *NLL* to a repeated-measures ANOVA with factors of model (location- vs. identity-first) and of SOA (cue before

SOA	Location first		Identity first		Saturated model		Location first vs. saturated model	
	<i>M</i>	(<i>SD</i>)	<i>M</i>	(<i>SD</i>)	<i>M</i>	(<i>SD</i>)	$\chi^2(36)$	<i>p</i>
Cue before target	12.9	(1.9)	19.0	(8.9)	12.0	(1.7)	33.764	0.575
Cue with target	14.0	(1.9)	24.1	(12.7)	12.9	(1.3)	39.362	0.322
Cue after target	13.9	(1.5)	22.4	(9.2)	13.2	(1.1)	24.714	0.922

Table 1. NLLs of the models and results of likelihood ratio tests.

target, cue with target, cue after target).³ Table 1 shows mean and standard deviations of the NLLs. The location-first model fitted the data better than the identity-first model, $F(1, 17) = 11.875$, $p = 0.003$, $\eta_p^2 = 0.411$. The SOA affected the model fits. Numerically, the fits tended to be better in the cue-before-target SOA than in the other SOAs, $F(1.889, 32.114) = 4.571$, $p = 0.019$, $\eta_p^2 = 0.212$, $\varepsilon = 0.945$. Both factors did not interact, $F(1.899) = 32.283$, $p = 0.160$, $\eta_p^2 = 0.103$, $\varepsilon = 0.949$. We compared the location-first and the saturated model with likelihood-ratio tests for each SOA based on the sums of the participant-wise NLLs (Table 1). In all cases, the better fit of the saturated model could be attributed to the higher number of free parameters. Again, the data show that the direction-first model describes the data better than the identity-first model and has no less explanatory power than a saturated model.

Latency analysis

A 3×3 ANOVA revealed a significant main effect of SOA, $F(2, 16) = 129.13$, $p < 0.001$, $\eta_p^2 = 0.942$; a significant main effect of task condition, $F(2, 16) = 24.877$, $p < 0.001$, $\eta_p^2 = 0.757$; and a marginally significant interaction, $F(4, 14) = 2.75$, $p = 0.071$, $\eta_p^2 = 0.440$ (see Figure 5). As noted above, we already expected the shortest RTs in cue-first conditions, especially when the cue indicated location or free choice, because participants in these conditions can

already fully select a saccade-target location based on the cue alone and simply wait for target onset as a “go” signal to execute their predefined saccade. In the color cue conditions, participants can also preselect a response (e.g., to target the left green object), but still need to wait for target onset in order to specify whether the preselected (e.g., left green) object appears at the upper or lower position prior to saccade onset. Thus, all cue-first conditions allow for either full or at least substantial preselection of the target. In line with this reasoning, the cue-first SOA conditions yielded much faster RTs than any other SOA condition, suggesting that participants indeed benefitted from the early selection opportunities.

A separate post hoc analysis of only the cue-first SOA condition revealed a significant main effect of task condition, $F(2, 24) = 11.15$, $p < 0.001$, $\eta_p^2 = 0.396$. Post hoc contrasts showed that RTs in the color condition (236 ms) were slower than those in both the location condition (189 ms, $p < 0.001$) and the unconstrained condition (210 ms, $p = 0.043$). RTs in the unconstrained condition were significantly slower than those in the location condition ($p = 0.044$). As noted above, in the unconstrained condition and in the location condition, saccade-target location can be fully specified prior to target onset, whereas, in the color condition, saccade-target location can only be fully specified when the targets are presented, and thus, the two positions of the color indicated by the cue are revealed.

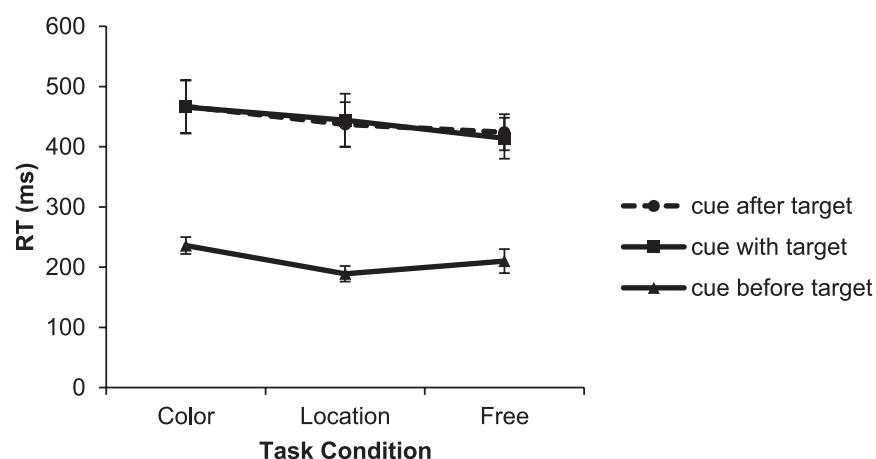


Figure 5. RTs in Experiment 2 (error bars represent SEM).

A corresponding post hoc one-way ANOVA of the SOA = 0 condition only revealed a significant task condition effect, $F(2, 34) = 11.09$, $p < 0.001$, $\eta_p^2 = 0.395$. RTs in the color condition (466 ms) were marginally greater than in the location condition (444 ms, $p = 0.057$) and significantly greater than in the unconstrained condition (414 ms, $p < 0.001$). RTs in the location condition were longer than in the unconstrained condition ($p = 0.023$). Note that, unlike in Experiment 1a (also involving SOA = 0), participants here are not able to preselect their target location in the unconstrained-choice condition due to the mixed design (i.e., participants could not know in advance whether the next trial would be an unconstrained-choice trial), which explains why the RT advantage for the unconstrained condition here is much less pronounced than that in Experiment 1a.

Finally, a post hoc one-way ANOVA of the target-first SOA condition revealed a significant effect of task condition, $F(2, 34) = 19.78$, $p < 0.001$, $\eta_p^2 = 0.712$. RTs in the color condition (467 ms) were significantly longer than those in the location condition (437 ms, $p = 0.018$) and also significantly longer than those in the unconstrained condition (424 ms, $p < 0.001$). However, RTs in the location condition did not significantly differ from those in the unconstrained condition ($p = 0.190$).

Visual inspection of Figure 5 indicates that corresponding data points did not differ across the SOA = 0 and the target-first SOA conditions. In line with this visual impression, there were no significant post hoc contrasts between corresponding data points in the color ($p = 0.934$), location ($p = 0.480$), and unconstrained ($p = 0.480$) conditions.

Similar to Experiment 1a, the general RT advantage of location- over color-based selection across SOA conditions can be explained in terms of the advantage of not having to process target identity in the location condition to specify the saccade target. Interestingly, there was still an advantage of the unconstrained condition over the location condition in the SOA = 0 condition although both conditions are similar in that they do not require any target-object processing. This effect potentially reflects general residual costs of constrained choice (in terms of a process associated with ruling out which target location options are removed). Finally, the relatively long RTs associated with conditions involving cue presentation after the targets might also partially be explained by low-level phenomena: The onset of a central cue at the central fixation location might make it harder for participants to disengage their gaze toward one of the targets, relative to the condition in which the cue is present prior to target onset (cf. Findlay & Walker, 1999).

At first sight, the finding that unconstrained choice (four response options) is faster than constrained choice (two response options) appears to contradict the

intuition that RTs should scale with the number of response alternatives (similar to the classic Hick's law in forced-choice conditions). However, previous research on forced-choice eye movements also indicates that oculomotor control is special in that it is exempt from Hick's law usually found in the manual-response domain (e.g., Kveraga, Boucher, & Hughes, 2002). Thus, our present results regarding free-choice behavior may appear less surprising.

Error analyses

The analysis of error rates does not include unconstrained conditions, in which target-selection errors are not possible. For the constrained conditions, a 2×3 ANOVA revealed a significant main effect of SOA, $F(2, 34) = 11.68$, $p < 0.001$, $\eta_p^2 = 0.407$, and of cue type, $F(1, 17) = 19.83$, $p < 0.001$, $\eta_p^2 = 0.538$, but no interaction, $F < 1$. Post hoc contrasts revealed that cue-first conditions showed the lowest error rates (6.9%, $SE = 1.0$), followed by the targets-first condition (12.8%, $SE = 2.3$), and the SOA = 0 condition (16.3%, $SE = 3.1$). The cue-first condition differed from both the SOA = 0 condition ($p = 0.002$) and the targets-first condition ($p = 0.005$), and the SOA = 0 condition also differed from the targets-first condition ($p = 0.016$). Probably, more simultaneous processing demands are the source of the high error rates in the SOA = 0 condition, whereas the cue-first condition is particularly easy in terms of processing demands due to the possibility of preselection (see above). Mean error rates in the color condition amounted to 16.80% ($SE = 2.8$) and were different from the mean error rate in the location condition ($M = 7.2\%$, $SE = 1.6$, $p < 0.001$), again showing that location choice is less error prone (easier) likely because of the lack of target-processing requirements.

General discussion

The present choice-frequency results across experiments and conditions suggest that voluntary free-choice eye movements are mainly based on spatial target characteristics rather than on features related to target identity (here defined by its color). This preference for spatial features as a main determinant of oculomotor decision processes underlying free target choice could represent an economical (parsimonious) strategy because saccades ultimately need to be coded in terms of spatial codes to be executed (Findlay & Walker, 1999). A selection based on target identity would, thus, involve an additional (potentially resource-consuming) transformation process, namely from an object identity-based target code into a spatial code. Note that this

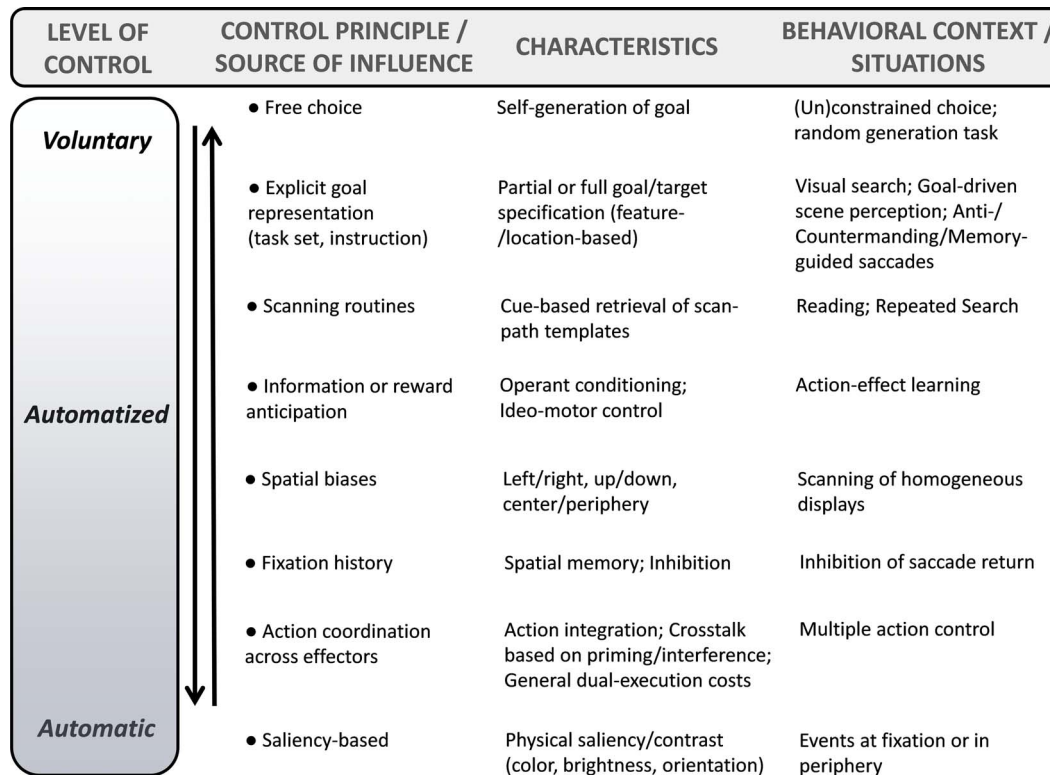


Figure 6. Overview of oculomotor-control levels (see Introduction and Discussion for details and examples regarding individual concepts). Arrows indicate bidirectional interactions between control levels. Control principles are not considered to be ordered along levels in a strict sense (e.g., specific instances of effects of spatial biases or fixation history may differ in their degree of automaticity). Behavioral context/situations comprise examples for tasks or situations in which some aspects of the respective control principles can be observed. Note that free-choice saccades are assumed to be influenced by control principles on lower levels, such as spatial biases, fixation history, scanning routines, etc. (see Introduction and Discussion). Our results suggest that self-generation of goals in free choice is primarily based on specification of target location, not target features (see goal-specification possibilities on subordinate level).

idea is also in line with the longer RTs observed in color- (or identity-) versus location-based choice conditions.

Although the RT data are overall in line with our observations based on choice frequencies (i.e., more similar RT levels between unconstrained and location-based choice than between unconstrained and color-based choice), the individual RT pattern in each experiment and condition can also be explained through specific mechanisms associated with the particular research design. For example, preselection of unconstrained choice due to the blocked design of cue condition may account for the corresponding RT advantage in Experiment 1a. Second, the possibility of target preselection likely explains the low RT levels in the cue-first condition in Experiment 2. Third, advantages associated with the constant target locations across trials (as compared with unpredictable color features of targets at these locations) may generally explain the RT advantage in location over color conditions. Finally, the RT data from Experiment 2 additionally showed that preparation based on target identity does not facilitate performance. This observation is in line with previous

research demonstrating that spatial attention is typically activated earlier than feature-based attention (Liu, Stevens, & Carrasco, 2007).

Taken together, the present free-choice saccade paradigm addresses a research gap in the field of oculomotor-control research. Models of oculomotor control usually distinguish between several control levels (see Findlay & Walker, 1999) and even account for choice behavior (Glimcher, 2003) but typically do not differentiate between top-down control (as implemented by instructions that put more weight on specific environmental features) and actual free-choice control, the latter being completely unconstrained by differences in target attractiveness (on a priority map) as defined in a bottom-up or instruction-based (top-down) manner.

Figure 6 represents an overview of oculomotor-control levels and corresponding control principles. We assume a continuum of control levels (from automatic to automatized and voluntary), which are based on comparable distinctions made in previous oculomotor-control models (Findlay & Walker, 1999) as well as in more general (domain-independent) models of behavioral control (e.g., Norman & Shallice, 1986). Control

principles (such as free-choice control; instruction-based, top-down control; and saliency-based, bottom-up control) are loosely ordered along the continuum of control levels. Note, however, that these control principles are not considered to be ordered along control levels in a strict sense. For example, specific instances of effects of spatial biases, fixation history, or saliency-based control may substantially differ in their degree of automaticity.

A central feature of the present model is the assumption of bidirectional interactions between control principles (and control levels). As outlined in the introduction, for example, free-choice behavior appears to be influenced by factors operating on lower levels of control, such as (idiosyncratic) spatial biases, fixation history (in terms of previously chosen targets), scanning routines, etc. Furthermore, participants may also differ in their strategy to come up with a particular target choice, and internal random (target) generation processes (and individual biases in producing random sequences) may play a major role in free-choice control tasks (Naefgen & Janczyk, 2018). Our present results particularly suggest that self-generation of goals in free choice is primarily based on the specification of target location, not target features (see corresponding characteristics of the subordinate level). Despite these various potential sources of influence, the present free-choice saccade paradigm actually indexes a particularly high level of (unconstrained) oculomotor control that has not been addressed previously in the oculomotor domain (but see, e.g., Berlyne, 1957; Brass & Haggard, 2008; Herwig et al., 2007; Keller et al., 2006; Naefgen et al., 2018; Passingham et al., 2010; Waszak et al., 2005, for examples in the manual domain).

In Figure 6, each control principle or source of influence is further characterized, and typical situations or tasks in which these control principles can be observed are briefly outlined. Most of the control principles were already mentioned (see the introduction for details and examples regarding individual concepts). It is debatable whether it is reasonable to assume the possibility of strong automatic control in the sense of responses that cannot be inhibited. Previous research assumed that all saccades can be regarded as being under at least some degree of voluntary control (even those usually labeled as “automatic” or “exogenous,” see Walker, Walker, Husain, & Kennard, 2000). Nevertheless, saccades are known to be impossible to inhibit after they were triggered beyond a certain point of no return, and previous literature also suggests that certain concurrent demands in other effector modalities inevitably affect saccade control (e.g., Huestegge, 2011; Huestegge & Adam, 2011; Huestegge & Hazeltine, 2011; see “action coordination across effectors” in Figure 6).

Open issues

The present study represents a first step toward understanding free-choice oculomotor behavior, that is, saccade generation on the highest possible control level. Two pressing issues need to be resolved in future research. First, our study design was deliberately chosen in a way that the location of targets was fixed from trial to trial. We reasoned that such a setting is realistic because, in daily life, situations usually also involve strong constraints regarding the location of certain objects in space (e.g., Brockmole & Henderson, 2006) although object identity in our visual field varies substantially. In our explanation of the RT data, we reasoned that this design feature of our study at least allows for faster target selection because choices based on location cues can solely be based on the learned and remembered target locations, and actual processing of the targets in the trial is not necessary (unlike in the color-cue conditions). Thus, it would be interesting to conduct a follow-up study using varying target locations from trial to trial to enforce target processing also in the case of location cues.

Second, the present study only involved (unconstrained or constrained) free-choice behavior, but no forced-choice conditions. Thus, it would be interesting to directly compare free- and forced-choice behavior, for example, by adding a condition in which four letters (e.g., “A,” “B,” “C,” “D”) indicate a single saccade target. However, it should be kept in mind that performance in such a forced-choice condition might strongly depend on stimulus type (e.g., it is also possible to use arrows pointing toward the location or to introduce a feature change at one of the four target positions), which complicates the issue of finding perfectly comparable conditions for free- and forced-choice saccades.

Conclusions and implications

In sum, the present study represents a first step toward an understanding of free-choice behavior in the oculomotor domain by successfully transferring an approach introduced by Herbot and Rosenbaum (2014) to the manual domain. The analysis of free-choice saccades may also be relevant for a more complete systematic assessment of (oculo-)motor control abilities, for example, when evaluating oculomotor control after psychopharmacological interventions (e.g., Huestegge, Kunert, & Radach, 2010; Huestegge, Radach, & Kunert, 2009) or in a clinical neuroscience context (patient populations; see Leigh & Kennard, 2004). Regarding the latter, assessments of free-choice saccades may provide a window to the understanding of deliberate choice in contexts such as addiction or

executive functions. Specifically, the (medial) prefrontal cortex has been associated with deliberation and choice (Haggard, 2008), and the anterior cingulate cortex has been shown to be correlated with the what component of decisions (e.g., Müller, Brass, Waszak, & Prinz, 2007), areas that, therefore, might also be involved in controlling saccadic free-choice behavior. In sum, we hope to prompt further research in this direction with the perspective of unraveling the commonalities and differences between principles underlying motor control in different contexts and motor-control systems (Bompas, Hedge, & Sumner, 2017).

Keywords: eye movement control, saccades, free choice, top-down processing, bottom-up processing, control levels

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Footnotes

¹ Keeping trials regardless of saccade latency has a negligible effect on the analyses of the choice frequencies in both experiments and would have led to identical conclusions.

² Note that the perfect fit of the identify-first model in the location-specified condition and of the location-first model in the identity-specified condition is trivial because the predictions of the respective models are derived from parameters that exclusively pertain to these conditions.

³ We report Greenhouse–Geisser corrected *df* and *p* values.

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Appendix

Table A.1 lists the computation of choice probabilities in the location-first, identity-first, and saturated models.

Stimulus	Percentage of saccades to	Location-first model	Identity-first model	Saturated model
B	left	$p(L B)$	$p(L B)$	$p(L B)$
G	left	$p(L G)$	$p(L G)$	$p(L G)$
L	green	$p(G L)$	$p(G L)$	$p(G L)$
R	green	$p(G R)$	$p(G R)$	$p(G R)$
I, X, Y	green, left	$p(G L)p(L)$	$p(L G)p(G)$	$p(G+L)$
	blue, left	$(1-p(G L))p(L)$	$p(L B)(1-p(G))$	$p(B+L)$
	green, right	$p(G R)(1-p(L))$	$(1-p(L G))p(G)$	$p(G+R)$
	blue, right	$(1-p(G R))(1-p(L))$	$(1-p(L B))(1-p(G))$	$1-p(G+L)-p(B+L)-p(G+R)$

Table A1. Computation of choice probabilities in the location-first, identity-first, and saturated models.