Voluntary Control of Task Selection Does Not Eliminate the Impact of Selection History on Attention

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Abstract

■ The human visual system can only process a fraction of the information present in a typical visual scene, and selection is historically framed as the outcome of bottom–up and top–down control processes. In this study, we evaluated how a third factor, an individual's selection history, interacts with top–down control mechanisms during visual search. Participants in our task were assigned to one of two groups in which they developed a history of either shape or color selection in one task, while searching for a shape singleton in a second task. A voluntary task selection procedure allowed participants to choose which task they would perform on each trial, thereby maximizing their top–down preparation. We recorded EEG throughout and extracted lateralized ERP components that index target selection (N_T) and distractor suppression (P_D). Our results showed that selection history continued to guide attention during visual search, even when top–down control mechanisms were maximized with voluntary task selection. For participants with a history of color selection, the N_T component elicited by a shape target was attenuated when accompanied by a color distractor, and the distractor itself elicited a larger P_D component. In addition, task-switching results revealed that participants in the color group had larger, asymmetric switch costs implying increased competition between task sets. Our results support the notion that selection history is a significant factor in attention guidance, orienting the visual system reflexively to objects that contradict an individual's current goals— even when these goals are intrinsically selected and prepared ahead of time. ■

INTRODUCTION

Everyday visual scenes contain far more information than the human visual system can process at a given point in time. Effective functioning despite this limitation requires a system that can flexibly focus its processing on the most relevant parts of a scene. Historically, models of this process have posited that selection is driven by the interaction between bottom–up and top–down influences. Bottom–up processes are based on the physical properties of a stimulus, biasing selection toward things like bright, flashing lights and loud, sudden noises. Top–down processes, on the other hand, are based on the internal goals of the individual, biasing selection toward, for example, the red and white hat worn by a friend that you have lost in a crowd. More recently, Awh, Belopolsky, and Theeuwes (2012) suggested that a third factor, selection history, is integrated with both top–down and bottom–up information to guide attention in a visual scene.

Selection history refers to an individual's previous experience of encountering and responding to a stimulus in a given context (Awh et al., 2012), and a range of experiments have provided evidence of its impact on attention. One such example of how selection history impacts on the deployment of attention is demonstrated by intertrial priming. In visual search tasks where target features vary from trial to trial, intertrial priming refers to the observation that participants respond significantly faster to the current target when it matches the features of the target from the preceding trial (Fecteau, 2007; Nakayama, Maljkovic, & Kristjansson, 2004; Wolfe, Butcher, Lee, & Hyle, 2003; Maljkovic & Nakayama, 1994). Notably, features associated with a previous trial's target are primed even in cases where they contradict the current top–down goals of the participant (Maljkovic & Nakayama, 1994). It has also been shown that associating a stimulus with reward can produce increased attentional capture by that stimulus long after the reward has stopped (Wang, Li, Zhou, & Theeuwes, 2018; Donohue et al., 2016; Laurent, Hall, Anderson, & Yantis, 2015; Hickey & van Zoest, 2013). Similarly, subtle statistical regularities in target and distractor location across a task have been demonstrated to produce implicit changes in the efficiency of both target selection and distractor suppression processes (Failing, Wang, & Theeuwes, 2019; Theeuwes, 2018, 2019; Ferrante et al., 2018; Wang & Theeuwes, 2018a, 2018b). Intertrial priming, reward association, and statistical learning all demonstrate the critical role that selection history plays alongside bottom–up and top–down influences on attentional control.

The impact that selection history has on the allocation of attention has also been shown to persist even when

participants are performing a different task. Feldmann-Wüstefeld, Uengoer, and Schubö (2015) demonstrated this using a dual-task paradigm in which participants performed either a categorization task or a search task on each trial. During the categorization task, participants learned to categorize stimuli based on either color or shape, whereas in the search task, they searched for a shape singleton and responded to the rotated line that it contained. Their results showed that, when color distractors were present in the search displays, they caused greater interference for participants who had performed color categorization in the categorization task. This implies that color became more salient as a result of selection history, and follow-up experiments showed that these effects persist when the tasks are performed in separate blocks and on separate days (Kadel, Feldmann-Wüstefeld, & Schubö, 2017).

Additional insight into the effect of selection history on attention has been provided through the measurement of neural indices of attention processing recorded by EEG. One of the predominant components used to study attention is an enhanced negativity recorded at posterior electrode sites contralateral to an attended stimulus, occurring approximately 200 msec after stimulus onset. Referred to as N2pc, this component is generally considered to reflect the deployment of spatially selective attention to the stimulus location (Li, Liu, & Hu, 2018; Grubert & Eimer, 2016; Tan & Wyble, 2015; Luck & Hillyard, 1994a, 1994b) and has been used as an index of attentional capture by relevant stimuli (Berggren & Eimer, 2018; McCants, Berggren, & Eimer, 2018; Kiss, Van Velzen, & Eimer, 2008) and pop-out objects (Holguin, Doallo, Vizoso, & Cadaveira, 2009; Eimer & Kiss, 2007). In their dual-task investigation into the effects of selection history on attention, Feldmann-Wüstefeld et al. (2015) showed that, during search trials, participants who had performed color categorization in the categorization task produced an N2pc to the color distractor, whereas participants who performed shape categorization did not. These data support the suggestion that selection history results in the automatic allocation of attention to stimuli even when they are currently task irrelevant.

Recently, methodological developments have allowed for even more specific measures of attention processing using EEG. Efficient attentional orienting depends on not only efficient mechanisms for identifying and orienting to targets but also the identification and suppression of possible distractors. Distinguishing between these processes using only behavioral measures can be difficult; however, recent research has identified a set of lateralized ERPs that can provide dissociable measures of object selection and suppression. Central to the calculation of the N2pc is the subtraction of any neural activity that is represented equally in both hemispheres. Hickey, Di Lollo, and McDonald (2009) took advantage of this fact to dissociate target and distractor processing.

Participants in their task performed a visual search task in which both a target and a distractor were present, but only one of these objects was lateralized on a given trial. When a target is lateralized and the distractor is on the midline, calculation of lateralized ERPs results in subtraction of all distractor activity and isolation of lateralized target processing. Similarly, when the distractor is lateralized, activity related to distractor processing can be isolated. Results using this approach have identified a lateralized positivity reflecting attentional disengagement from a stimulus in addition to the lateralized negativity indexing the attentional selection of a stimulus (Gaspelin & Luck, 2018; Gaspar & McDonald, 2014; Hickey et al., 2009).

Specific measures of attentional selection and suppression have provided increased specificity of the role that selection history plays in the orienting of attention. In a follow-up experiment, Feldmann-Wüstefeld et al. (2015) adapted their task to allow for the dissociation of target and distractor processing. Their results showed that, for participants who categorized based on color in the categorization task, the presentation of a colored distractor in the search task elicited an N_D (a lateralized negativity to distractors) followed by a relatively large P_D (a lateralized positivity to distractors). This implies that, for these participants, the color distractor captured attention in the search task (reflected by N_D) and therefore required increased subsequent suppression (reflected by increased P_D). Participants who had learned to categorize based on shape, however, did not show this effect. The color distractor in their case elicited no N_D during search trials and a small P_D, indexing a lack of attentional capture and decreased distractor suppression, respectively.

An open question remains as to whether increased top–down control can be used to attenuate or eliminate the effects of selection history on attention. To investigate this, Kadel et al. (2017) adapted the dual-task paradigm introduced by Feldmann-Wüstefeld et al. (2015) that allowed for increased top–down control throughout the experiment. In the original version, the two tasks were randomly interleaved and participants did not know which of the two tasks they would perform until the task display was shown. Kadel et al. (2017) ran a version of the task in which participants were cued ahead of the task display and therefore had the opportunity to prepare for the task they were about to perform. Their results showed that the effect of selection history persists, even in a cued version of the task, and therefore, they concluded that increased top–down control cannot be used to override the effects of selection history.

However, recent work in the task-switching literature has suggested that cued task switching may be insufficient for allowing participants to optimally engage top–down control before the trial begins (Kiesel et al., 2010). The primary measure of interest in task-switching

paradigms is switch cost, that is, the slowed RTs after a task switch relative to a task repetition. Although switch costs do appear to be reduced in cued task switching (Ruthruff, Remington, & Johnston, 2001; Sohn & Anderson, 2001), it has also been known for some time that they are still affected by bottom–up factors like residual activation of prior task sets (Alport, Styles, & Hsieh, 1994) and priming of previous task sets (Koch & Allport, 2006; Waszak, Hommel, & Allport, 2003). A novel approach to increasing top–down attentional control in dual tasks is the voluntary task-switching paradigm developed by Arrington and Logan (2004). In this version of the task, participants are not cued as to what trial type will be performed, but rather, they are given the choice of which trial type they would like to perform next. Evidence suggests that the voluntary task-switching paradigm allows for stronger proactive control over performance of each task (Kang, DiRaddo, Logan, & Woodman, 2014; Arrington & Logan, 2005).

Evidence that voluntary task-switching procedures enable greater top–down control comes from a range of behavioral and electrophysiological findings. Comparisons to cued task-switching procedures showed reduced switch costs in the voluntary version as well as a lack of any consistent influence by bottom–up factors (Chen & Hsieh, 2015; Gollan, Kleinman, & Wierenga, 2014; Arrington & Logan, 2005). Chen and Hsieh (2015) also extended these effects to show that voluntary task switching allows for participants to adopt different preparatory strategies when stimulus–response mappings were manipulated, an ability that was not observed for those doing cued task switching. A prominent signature of the different control processes engaged during cued and voluntary task-switching procedures comes from EEG activity recorded during the preparatory period before task onset. Whereas cued task switching has typically been associated with a P3-like posterior positivity (see Karayanidis et al., 2010, for a review), recordings from participants engaged in voluntary switching are dominated by a fronto-central negativity (Chen & Hsieh, 2015; Poljac & Yeung, 2014; Vandamme, Szmalec, Liefooghe, & Vandierendonck, 2010). This component, typically referred to as the contingent negative variation (CNV), has been associated with preparatory task-response mapping and has been used to demonstrate the increased top–down control that is engaged during voluntary task switching. Kang et al. (2014) directly compared preparatory EEG activity between cued and voluntary task-switching tasks within the same participants and confirmed that, whereas cues elicited posterior positivity, voluntary choices were associated with a large CNV.

Another advantage of voluntary task selection procedures is that they allow us to measure choice processes and could therefore provide insight into how choice is affected by selection history. In previous use of voluntary task selection, research has shown systematic patterns in task selection when participants are instructed

to perform the two tasks in a random order. Participants typically show a repetition bias in their task choices (Arrington & Logan, 2004), which is exacerbated by shorter intertrial intervals (Vandierendonck, Liefooghe, & Verbruggen, 2010; Arrington & Logan, 2005) and typically involves a preference for performing the difficult task more frequently (Millington, Poljac, & Yeung, 2013; Yeung, 2010). A number of previous studies have also shown that the availability of a stimulus to the cognitive system can impact task choice (Arrington, Weaver, & Pauker, 2010; Yeung, 2010; Mayr & Bell, 2006). For example, when participants choose to perform either size or animacy judgments about words, they were more likely to choose the size judgment if they had performed a size judgment on that word previously and more likely to choose the animacy judgment if they had performed an animacy judgment on that word previously (Arrington et al., 2010). Similarly, there are consistent biases in judgment choice across participants. Particular words, for instance "aspirin," are more likely to elicit a size judgment, whereas other words are more likely to elicit an animacy judgment (Arrington et al., 2010). In other voluntary selection tasks, repetition of a target's location has increased the likelihood of a participant repeating their previous choice (Yeung, 2010; Mayr & Bell, 2006), and individual switch rates correlated strongly with the cost of a task switch (Mayr & Bell, 2006). These findings suggest that previous history influences the ease with which a particular task is performed and, therefore in turn, impacts task choice in a voluntary selection paradigm.

In this study, we adapted the design of Feldmann-Wüstefeld et al. (2015) to a voluntary task-switching paradigm to investigate the relationship between top–down control and selection history. By allowing participants to determine whether they would perform search or categorization on the next trial, participants would be able to proactively engage the task set for the upcoming trial and exercise maximal top–down control. We also recorded EEG during their performance of the task and leveraged the procedure of Hickey et al. (2009) to allow for the isolation of target and distractor activity. This approach provides specific measures of target selection, distractor capture, and distractor suppression during the task and therefore provides a fine-grained understanding of how top–down control interacts with selection history during attentional orienting. If increased top–down control can eliminate the effects of selection history, then we would expect to see that distractor costs in the search task are similar regardless of whether participants were assigned to the shape or color group in the categorization task. We would also expect that group assignment would not have differential effects on the lateralized ERP components elicited by stimuli in the search task. On the other hand, if top–down control cannot be used to override selection history effects, then the effect of categorization group assignment on distractor costs

and ERP component amplitudes during search should remain.

METHODS

Participants

Twenty-seven participants with normal or corrected-to-normal vision (tested using an Oculus Binoptometer 3) participated in the task for either payment or course credit. All participants gave written and informed consent before the start of the experiment. Participants were randomly assigned to either the shape group (ages ranging from 21 to 31 years, $M = 24.5$ years, $SD = 2.8$) or the color group (ages ranging from 19 to 25 years, $M = 22.5$ years, $SD = 1.7$). Each group had one left-handed participant, and all other participants were right-handed. One participant did not reach suitable performance during the practice session and was therefore excluded from the experiment.

Experimental Procedure

Participants came in for two separate sessions (performed on consecutive days) and performed two different tasks within each session, a categorization task and a search task (described in detail below). Session 1 was a practice session in which participants were familiarized with the two tasks by performing them in separate blocks; the order of these blocks was counterbalanced across participants. This was designed to train participants on both tasks but was separated from the testing session to avoid fatigue interfering with the EEG session. In Session 2, EEG was recorded and the full task began where participants chose at the start of each trial whether they would perform a categorization or search trial. Participants were seated in a comfortable chair in a dimly lit room with their eyes 100 cm away from the screen (LCD-TN Samsung Syncmaster 2233). An Erogodex DX1 response pad was placed on their lap with six keys arranged so that participants could use the index and middle fingers of each hand (in a resting position) to respond to the task, whereas the thumb on each hand could be used to perform task selection between trials. Each task was performed with one hand (index and middle fingers responded to the task display, whereas the thumb was used to select that task at the start of the trial), and task-to-hand assignment was counterbalanced across participants. Stimulus presentation and response collection were controlled by E-Prime 2.0 (Psychology Tools, Inc), and audio feedback was presented by two stereo speakers (Logitech Z120 2.0) placed behind the screen.
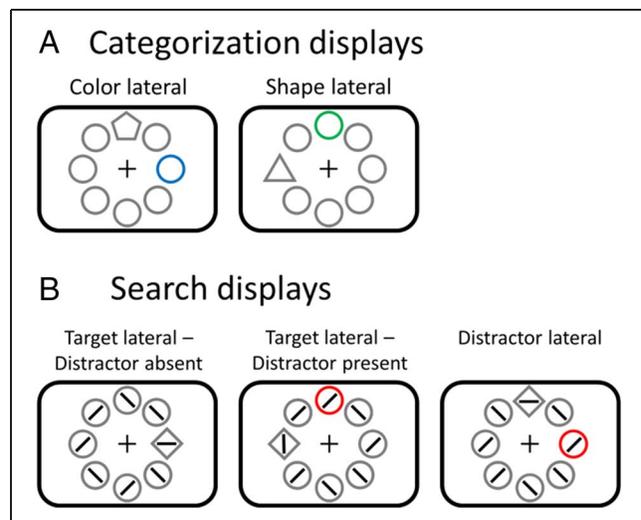
Stimuli

Each stimulus presented during the categorization and search trials was presented on a dark gray background

(RGB: 60, 60, 60) and subtended 2.3° of visual angle. A fixation cross (0.6°) was located in the center of the screen throughout the experiment to help participants maintain central fixation. The physical luminance of the gray (RGB: 110, 110, 110), green (RGB: 48, 171, 48), blue (RGB: 48, 48, 171), and red (RGB: 171, 48, 48) stimulus colors was balanced using a luminance meter (Konica Minolta LS-100).

Categorization Trials

Categorization trials began with a 500-msec fixation cross in the center of the screen. Eight stimuli were then presented simultaneously in a circular arrangement with a radius of 6.3° of visual angle for 200 msec (see Figure 1A). Six of these objects were unfilled gray circles, one was an unfilled colored circle (either blue or green, randomly selected on each trial), and one was an unfilled gray shape singleton (either pentagon or triangle, selected randomly on each trial). The color singleton and the shape singleton were constrained to appear in only four of the eight possible locations along either the vertical or horizontal midline. In half of the categorization trials (288 trials), the shape singleton was presented on one of the vertical midline positions, whereas the color singleton was presented on one of the lateral positions on the horizontal midline. In the other half of categorization trials, the color singleton was on the vertical midline, whereas the shape singleton was lateralized (see Figure 1A). Participants had two response keys for the categorization task, and after selecting one of these keys, they were given feedback informing them whether they had selected the

Figure 1. Example task displays for the categorization (A) and search (B) tasks. In each display, one singleton is lateralized and the other is on the midline to allow for the calculation of EEG activity elicited by the lateral stimulus. Participants performed 1152 trials in total; 50% of these were required to be categorization trials (half of each display type), and 50% were required to be search trials (one third of each display type).

correct response. At the beginning of the task, participants were not told the correct stimulus–response pairing and instead had to learn which key was correct for a given display. For half of the participants (the color group), the correct response was based on the color singleton (e.g., Key 1 when blue was shown, Key 2 when green was shown). For the other half (the shape group), the correct response was based on the shape singleton (e.g., Key 1 when a pentagon was shown, Key 2 when a triangle was shown). The trial would end when participants made their response, up to a maximum of 2000 msec.

Search Trials

Search trials began with a 500-msec fixation cross in the center of the screen. Next, eight stimuli were presented in a circular arrangement with a radius of 6.3° of visual angle for an interval of 200 msec (see Figure 1B). Six of these were always unfilled gray circles; one was the target, that is, an unfilled gray diamond; and one was either another unfilled gray circle (in the target-only condition) or an unfilled red circle (in the distractor-present condition). Each of these stimuli contained a line of varying orientations, and participants were required to indicate whether the line contained by the target diamond was oriented horizontally or vertically. The trial would end when participants made their response, up to a maximum of 2000 msec. One third of the search trials (192 trials) were target-only trials with seven gray circles and one gray diamond target. The other two thirds of the search trials were distractor-present trials in which one of the circles was colored red. In half of these distractor-present search trials (192 trials), the target diamond was placed on the vertical midline and the colored distractor was lateralized to either the left or right (chosen randomly on each trial) along the horizontal midline. In the remaining trials (192 trials), the colored distractor was placed on the vertical midline and the target diamond was lateralized to either the left or right (chosen randomly on each trial) on the horizontal midline (see Figure 1B).

Task Selection

In Session 2, every trial began with a task selection screen where participants had to indicate, using either their left or right thumb, whether they would like to perform a categorization or search trial. This screen stayed on until the participant's response. Participants were asked to try to ensure that they distributed their choices evenly between the two options and to try and make their choice random and unpredictable. Participants were required to perform 576 of each trial type, and after every block of 32 trials, they were shown a pictorial display indicating how many of each trial type was left for them to perform as well as some feedback about RTs and accuracy. Examples of the

full trial procedure and a between-block feedback display are shown in Figure 2.

EEG Recording

EEG activity was recorded continuously at 1000 Hz using Brain Products 64-channel actiCAP Ag–AgCl electrodes. The electrodes were arranged according to the modified combinatorial nomenclature for the 10–10 system. The online reference was FCz, and the COM sensor was located on the z axis between FCz and Cz. EEG activity was pre-amplified by the active electrodes and then passed to aBrain Products BrainAmp amplifier with 16-bit A/D conversion, an input impedance of 10 MΩ, and an antia-liasing filter with a 1000-Hz low-pass cutoff. Impedances were kept below 5 kΩ, and active shielding was used throughout for attenuating common mode noise.

EEG Processing

EEG data were processed using the EEGLAB toolbox in MATLAB (The MathWorks). For the extraction of lateralized components (N_T and P_D), data were first segmented into 700-msec epochs (−200 to 500 msec around each search or categorization display) and baselined so that the average of the prestimulus period was set to zero for each event. For artifact rejection, a horizontal EOG channel was created by taking the voltage difference between the electrodes on the outer canthi of each eye, and a vertical EOG was created by taking the voltage difference between the electrodes above and below the left eye. These channels were filtered using a low-pass value of 35 Hz to reduce false positives, and then trials containing either ±35 mV in the horizontal EOG channel (within 300 msec after stimulus presentation) or ±80 mV in the vertical EOG channel were removed. Trials containing ±80 mV in the channels of interest (PO3, PO7, PO4, and PO8) were also removed, and the data were referenced to the average of all channels. Left hemisphere channels (PO3, PO7) were averaged together, and right hemisphere channels (PO4, PO8) were averaged together so that contralateral and ipsilateral ERPs could be calculated for each condition.

Comparison between Voluntary and Cued Task Switching

A central premise in the logic of this study is that the voluntary task-switching paradigm affords participants greater top–down control than a cued task-switching procedure. As described above, evidence supporting this claim has come primarily from analysis of preparatory activity in the task-switching literature. This work has shown that task cues result in a smaller frontal negativity (CNV) and a larger posterior positivity during the preparatory phase when compared to voluntary task selection. However, there are several differences in the tasks used

Figure 2. (A) Trial procedure. Participants started each trial by selecting which of two tasks they would perform next. After a 500-msec delay, their chosen task display was presented. In the case of a categorization display, they would categorize either the shape or color singleton (depending on group assignment), whereas in the search task, all participants would respond to the orientation of the line within the shape singleton. (B) An example of the feedback display shown to participants between blocks, which provides information about the percentage of trials left for each task, as well as the number of blocks completed, average accuracy for each task, and average RT for each task.
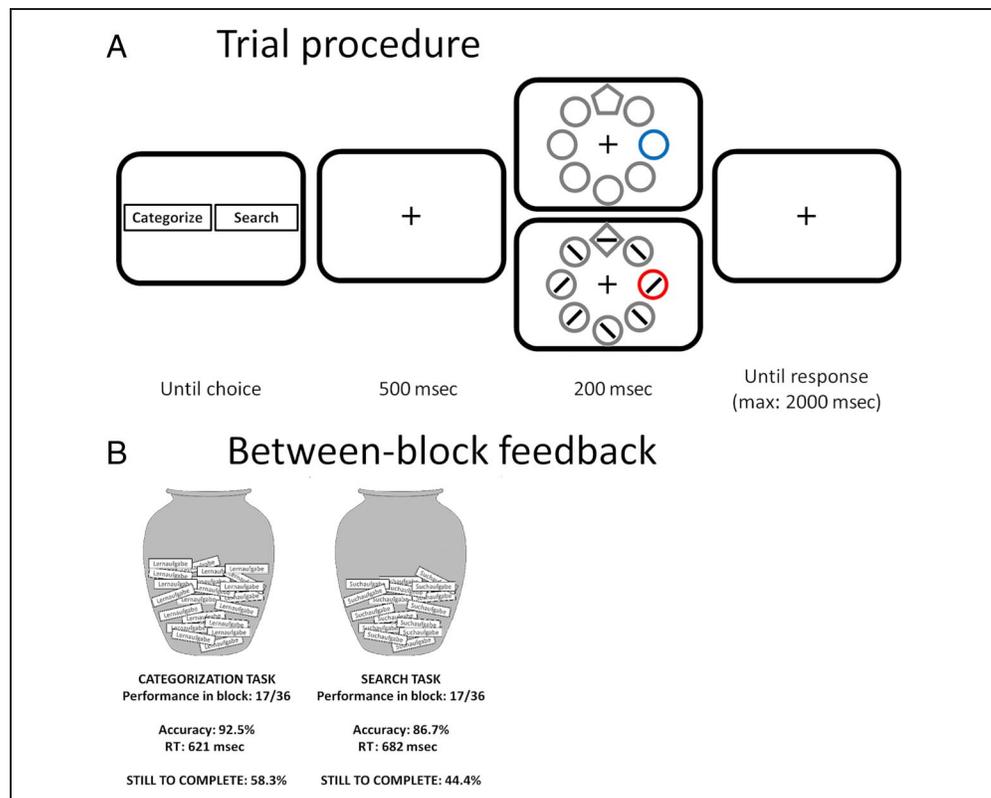
in that literature when compared to the search tasks used here. To confirm that the voluntary task design is similarly effective at improving top–down control in our context, we sought to compare the preparatory activity in our task to the preparatory activity in a cued version of our task. In Experiment 1 of their article, Kadel et al. (2017) performed exactly this task; their analyses, however, focused exclusively on poststimulus activity. We acquired the data of Kadel et al. (2017) and analyzed the prestimulus activity that had been not been processed previously. We extracted the CNV and posterior positivity elicited by task cues and compared them to the CNV and posterior positivity elicited by voluntary task choices in our experiment.

Details of the procedure used by Kadel et al. (2017) can be found in their methods section; however, we provide a brief description of the most relevant points here. In their experiment, participants performed either a learn or search task on each trial (the details of which are identical to the tasks used in our experiment). Trials began with a fixation cross, presented for 500 msec, which indicated whether the upcoming display was a categorization or search trial. Participants then performed the task, and after their response, the next trial began. This procedure allows for a direct comparison of the 500-msec preparatory period after the cue to the 500-msec fixation period after a voluntary choice in the present experiment.

For the analysis of preparatory activity, we followed the EEG processing procedures used by previous investigations of cued and voluntary task switching. Data were rereferenced to the average of the mastoids and segmented into 1600-msec epochs around stimulus onset. The epochs start 800 msec before the task display onset and extend 800 msec after task display. The 500-msec period before task display onset corresponds to the presentation of a fixation cross after either a cued (in the cued task) or the participant's choice (in the voluntary task). A baseline period of −700 to −500 msec was used, corresponding to the 200 msec preceding the cue or choice. Data were filtered using a low-pass value of 35 Hz, and epochs were rejected if they contained activity exceeding ±200 mV in any channel, ±75 mV in EOG channels, or improbable data (based on EEGLAB's pop_jointprob function with a 6-SD threshold). Trials where participants responded incorrectly were also excluded. A frontocentral cluster of electrodes (F3, Fz, F4, FC3, FCz, FC4, C3, Cz, C4) and a posterior cluster of electrodes (CP3, CPz, CP4, P3, Pz, P4, POz, O1, O2) were then created based on the channels used by Poljac and Yeung (2014), and we extracted component amplitudes by averaging the 300-msec period directly preceding stimulus onset.

Statistical Analysis

All statistical analyses were performed in Version 1.1.463 of RStudio (RStudio Team, 2016) using R (Version 3.5.2; R Core Team, 2018). Data processing and visualization were performed using the *tidyverse* set of packages (Wickham, 2017), and statistical tests were performed

using the *afex* package (Singmann, Bolker, Westfall, & Aust, 2019). Where necessary, calculations for comparing unequal groups were therefore performed automatically by the *afex* package. This article was produced in R using the *papaja* package (Aust & Barth, 2018).

Voluntary Task Selection

To evaluate the choice processes in our task, we used both switch rates and switch costs. For all of these analyses, we applied the same rejection criteria as we used in the behavioral analyses presented above. Switch rate was calculated simply as the percentage of trials in which a participant chose to switch between the two tasks. Switch costs were calculated as the average RT difference between switch trials and repetition trials.

Selection History

Behavioral analyses. For behavioral analyses, we first calculated the switch rate for all participants, calculated as the percentage of trials on which a participant chose to switch tasks from the previous trial. We removed any participant whose switch rate was below 0.2 (resulting in the removal of three participants) on the basis that these participants were not following the instructions of randomly distributing their choices. At this point, there were 12 participants remaining in the color group and 11 participants in the shape group. For the remaining participants, we removed trials with abnormally long RTs (greater than 2.5 *SD*s above the mean, calculated separately for each participant and each task), resulting in the removal of an average of 2.32% of trials in each task. For analyses with RT as the dependent variable, we also removed trials with incorrect responses, resulting in the removal of a further 4.86% of the total categorization trials and 4.51% of the total search trials.

ERP analyses. In the categorization task, four participants had to be excluded because fewer than 70% of the trials were left in the categorization task (equivalent to an average of 202 trials remaining in each condition) or because their switch rate between the tasks was less than 0.2. As a result, 11 participants were remaining in each group. Our analyses focused on two components of interest, the N_T and P_D. To determine the time range for the N_T, a grand-averaged ERP of all participants was created for lateralized predictor trials (color singleton for color group participants and shape singleton for shape group participants). The peak negativity that occurred later than 200 msec post stimulus was defined as the N_T, and a 50-msec time window was centered on this time point producing a window from 206 to 256 msec. For the P_D component, we created a grand-averaged ERP for lateralized nonpredictor trials (the shape singleton for the color group and the color singleton for the shape group), identified the peak positivity that occurred later than

200 msec post stimulus, and centered a 50-msec window on this time point, which produced a window from 238 to 288 msec.

In the search task, five participants were excluded because less than 85% of trials remained after artifact rejection (equivalent to an average of 163 trials remaining in each condition), or their switch rate between the tasks was less than 0.2. As a result, 10 participants remained in the color group, and 11 participants remained in the shape group. We again focused analyses on the N_T and P_D components. To select the N_T time window, we created a grand average of all participants for trials with a lateralized target, identified the peak negativity that occurred later than 200 msec post stimulus, and centered a 50-msec window on this time point. This produced a time range of 227–277 msec after stimulus onset. For the P_D component, we created a grand-averaged ERP for trials with a lateralized distractor, identified the peak positivity that occurred later than 200 msec post stimulus, and centered a 50-msec window on this time point, which produced a window from 264 to 314 msec.

Comparison between Voluntary and Cued Task Switching

Independent samples *t* tests were used to compare the preparatory activity between the present data and the data from Kadel et al. (2017). One test compared CNV amplitude taken from the frontal electrode cluster, and a second compared amplitudes taken from the posterior electrode cluster. In addition, for each experiment, we decided to perform a 2 × 2 ANOVA to investigate the effect of Task (categorization vs. search) and Transition (switch vs. repetition) on preparatory activity at both frontal and posterior electrode clusters.

RESULTS

Voluntary Task Selection

Task Choice

Participants were asked to keep the task selection balanced at around 50% search and 50% choice trials throughout the experiment. To measure this, we calculated task choice across the task and show that participants typically succeeded in maintaining approximately 50% of each trial across the task (see Figure 3A).

In addition, a 2 × 2 ANOVA was performed to evaluate the effect of Task Transition (repeat vs. switch) and Group (color vs. shape) on the time taken to make a task choice. The results (depicted in Figure 3B) showed no significant main effects of Group, $F(1, 21) = 0.01$, $MSE = 11,339.88$, $p = .909$, $\eta_G^2 = .001$, and Task Transition, $F(1, 21) = 0.08$, $MSE = 428.25$, $p = .777$, $\eta_G^2 = .000$, as well as no significant interaction between Group and Task Transition, $F(1, 21) = 2.24$, $MSE, = 428.25$, $p = 1.50$, $\eta_G^2 = .004$.

Figure 3. (A) Proportion of search trials chosen by each individual across blocks throughout the experiment for participants in the shape group (gray) and color group (green). Lines have been smoothed with a loess function for visualization. (B) Time taken for participants in the color group (green) and the shape group (gray) to make their task selection at the start of each trial. This is depicted separately for trials where they chose to switch task versus those where they chose to repeat the previous task. Thick lines represent the group averages, whereas thin lines represent individual data. Rep. = repeat.
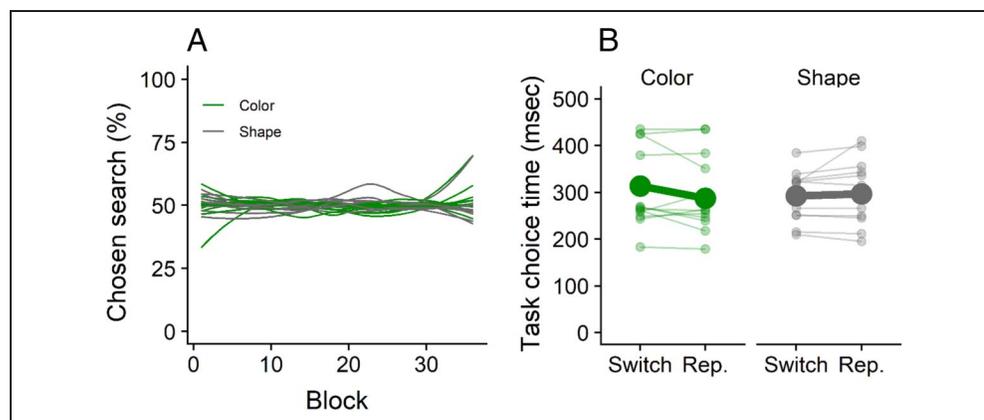
Switch Rates

Participants were encouraged to make their task selections as random as possible, which would produce a switch rate of 50%; however, average switch rate across all participants was 40.49%. Analysis of the voluntary task choice showed that, whereas participants in the shape group showed no significant deviation from a switch rate of 50% ($M = 0.45$, 95% CI [0.38, 0.52]), $t(10) = -1.66$, $p = .128$, participants in the color group showed a significant repetition bias ($M = 0.36$, 95% CI [0.30, 0.43]), $t(11) = -4.56$, $p = .001$. When we directly tested whether switch rates in the color group were lower than the shape group, we also saw a significant difference ($\Delta M = -0.08$, 95% CI $[-\infty, -0.01]$), $t(20.85) = -1.97$, $p = .031$. Switch rates are shown in Figure 4.
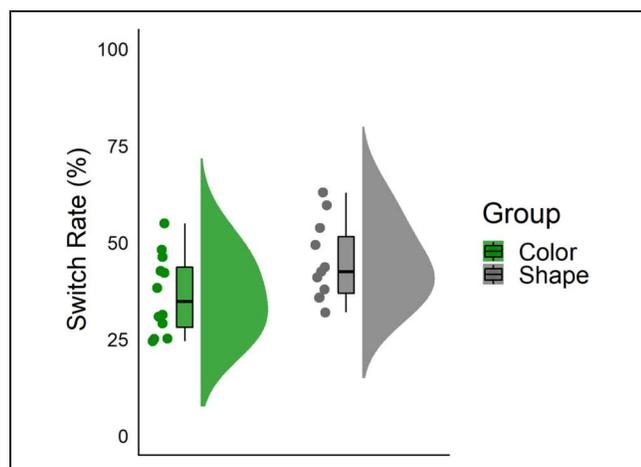
Figure 4. Voluntary switch rates for each individual separated by group assignment. Dots show each individual's switch rate alongside a boxplot and violin plot to display the range and distribution of switch rates. A switch rate of 50% is expected when participants are randomly selecting the task on each trial as instructed.

Switch Costs

Switch costs were calculated by subtracting RTs to repetition trials from RTs to switch trials. We performed a 2 × 2 ANOVA to evaluate the effect of Task (categorization vs. search) and Group (color vs. shape) on the size of these switch costs. Our results showed a significant effect of Task, $F(1, 21) = 9.74$, $MSE = 990.29$, $p = .005$, $\eta_G^2 = .051$, but not Group, $F(1, 21) = 4.06$, $MSE = 7,633.70$, $p = .057$, $\eta_G^2 = .146$; however, these effects were superseded by a significant interaction between Task and Group, $F(1, 21) = 11.03$, $MSE = 990.29$, $p = .003$, $\eta_G^2 = .057$. Follow-up comparisons (visualized in Figure 5) demonstrated that participants in the color group had significantly larger switch costs in the categorization task ($\Delta M = 130.32$ msec, $SE = 3.02$) than the search task ($\Delta M = 70.48$ msec, $SE = 2.18$), $t(21) = -4.66$, $p < .001$, whereas participants in the shape group showed no difference between the categorization ($\Delta M = 47.49$ msec, $SE = 1.47$) and search ($\Delta M = 49.34$ msec, $SE = 1.65$) tasks, $t(21) = 0.14$, $p = .892$. In the categorization task, participants in the color group had significantly larger switch costs than participants in the shape group, $t(26.36) = 3.02$, $p = .006$; however, there was no difference between the two groups in the search task, $t(26.36) = 0.77$, $p = .448$. A set of one-sample t tests confirm that switch costs differ from 0 for both groups in all conditions (all ps < .001).

Selection History

Behavioral Performance

A 2 × 2 ANOVA was carried out to evaluate whether there were effects of Group (shape vs. color) and Task (categorization vs. search) on participant RTs. The results showed that RTs of participants in the shape group ($M = 568.47$ msec, $SE = 2.48$) were not significantly different from participants in the color group ($M = 581.17$ msec,

Figure 5. RTs for switch and repeat (Rep) trials for the color group (green) and the shape group (gray) in each task. For the search task (left), we observed a switch cost (faster responses to repetition trials) for both groups of participants. In the categorization task (right), participants in the color group (green) showed significant switch costs; however, participants in the shape group (gray) showed comparatively small differences.
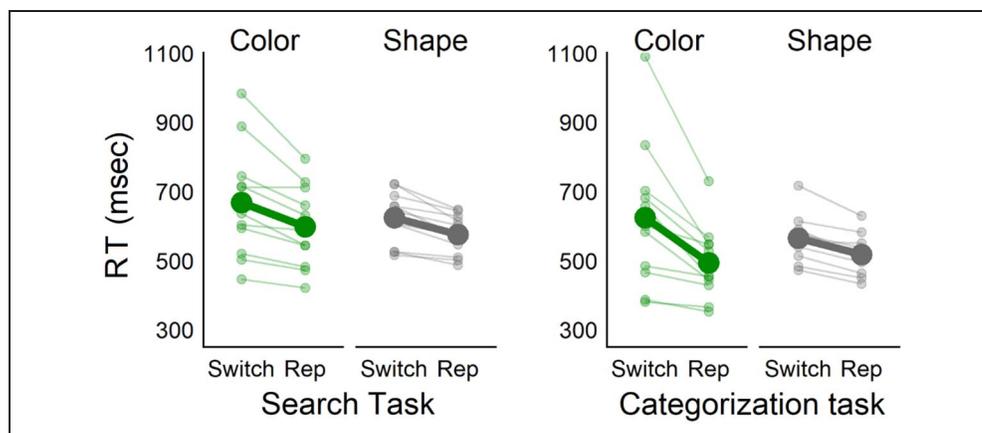
$SE = 3.32$), $F(1, 21) = 0.09$, $MSE = 19,707.80$, $p = .762$, $\eta_G^2 = .004$. However, participants (irrespective of group) performed significantly faster in the categorization task ($M = 539.88$ msec, $SE = 2.11$) than they did in the search task ($M = 610.31$ msec, $SE = 2.07$), $F(1, 21) = 41.92$, $MSE = 1,337.74$, $p < .001$, $\eta_G^2 = .113$. We did not observe a significant interaction between group and task, $F(1, 21) = 1.28$, $MSE = 1,337.74$, $p = .271$, $\eta_G^2 = .004$.

A 2 × 2 ANOVA carried out on participant accuracy showed neither a significant difference in accuracy between the shape group ($M = 95.73\%$, $SE = 0.57$) and the color group ($M = 94.73\%$, $SE = 0.6$), $F(1, 21) = 0.39$, $MSE = 29.11$, $p = .538$, $\eta_G^2 = .016$, nor any significant difference on the categorization task ($M = 95.02\%$, $SE = 0.42$) and the search task ($M = 95.4\%$, $SE = 0.42$), $F(1, 21) = 0.54$, $MSE = 3.74$, $p = .470$, $\eta_G^2 = .003$. There was also no significant interaction between Group and Task on accuracy, $F(1, 21) = 3.53$, $MSE = 3.74$, $p = .074$, $\eta_G^2 = .019$.
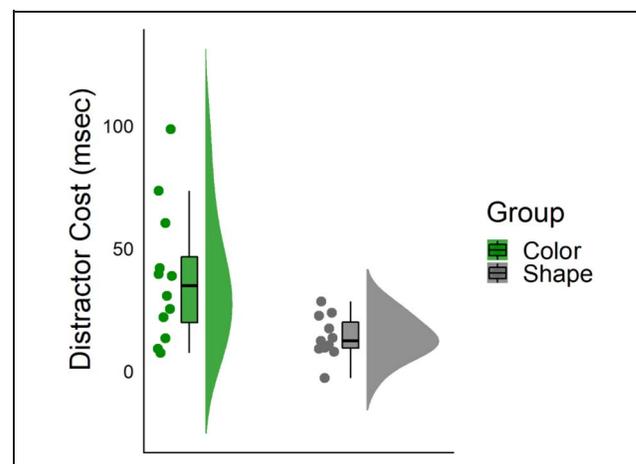
Search task distraction. For the search task, we used a mixed 2 × 2 ANOVA where Trial type (target only vs. target and distractor) was the within-participant factor and Group (color vs. shape) was the between-participant factor. This was performed once with RT as the dependent variable and once with accuracy as the dependent variable.

Across both trial types, the color group's RTs ($M = 615.93$ msec, $SE = 3.17$) did not differ significantly from participants in the shape group ($M = 595.05$ msec, $SE = 2.39$), $F(1, 21) = 0.26$, $MSE = 19,190.88$, $p = .615$, $\eta_G^2 = .012$; however, participants (irrespective of group) responded significantly faster in the distractor-absent trials ($M = 592.64$ msec, $SE = 1.97$) than in the distractor-present trials ($M = 619.25$ msec, $SE = 2.13$), $F(1, 21) = 36.11$, $MSE = 216.20$, $p < .001$, $\eta_G^2 = .019$. An interaction between Trial Type and Group demonstrates that distractor presence had a significantly larger effect on participants in the color group ($\Delta M = 38.36$ msec, $SE = 1.51$) than those in the shape group ($\Delta M = 13.8$ msec, $SE = 0.89$), $F(1, 21) = 8.00$, $MSE = 216.20$, $p = .010$, $\eta_G^2 = .004$. This effect of group assignment on distractor cost is shown in Figure 6.

When it comes to search task accuracy, we did not observe any differences between the shape group ($M = 95.02\%$, $SE = 0.58$) and the color group ($M = 95.03\%$, $SE = 0.61$), $F(1, 21) < 0.01$, $MSE = 34.64$, $p = .998$, $\eta_G^2 < .001$, or differences between the target-only trials ($M = 95.03\%$, $SE = 0.43$) and target and distractor trials ($M = 95.02\%$, $SE = 0.42$), $F(1, 21) < 0.01$, $MSE = 0.95$, $p = .949$, $\eta_G^2 < .001$. There was also no interaction between Group and Trial Type on accuracy, $F(1, 21) = 0.61$, $MSE = 0.95$, $p = .445$, $\eta_G^2 = .001$.

ERP Results

Categorization task. In the categorization task, our ERP analyses focused on the lateralized response to each object (either the shape singleton or the color singleton). For each ERP, there were two time windows of interest,

Figure 6. RT cost (RT in distractor-present trials minus RT in distractor-absent trials) caused by the presence of a colored distractor in the search task. Participants assigned to respond to color in the categorization task (shown in green) had significantly higher costs during the search task than participants assigned to respond to shape in the categorization task (shown in gray). Individual RT costs are depicted as dots alongside a boxplot and violin plot to visualize the range and distribution of costs for each group.

the N_T time window (206–256 msec) and the P_D time window (238–288 msec), as depicted in Figure 7. We performed a set of mixed 2 × 2 ANOVAs with Electrode Laterality (contralateral vs. ipsilateral) as the within-participant factor and Group (color vs. shape) as the between-participant factor, performed for both components (N_T and P_D) elicited by each of the lateralized stimuli (color and shape singletons).

Lateral color singleton, midline shape. In displays with the color singleton lateralized and the shape singleton on the midline, voltages in the N_T time window did not differ between participants in the color group ($M = -0.65$ μV, $SE = 0.5$) and participants in the shape group ($M = -1.8$ μV, $SE = 0.44$), $F(1, 20) = 1.21$, $MSE = 11.97$, $p = .284$, $\eta_G^2 = .056$, nor was there any difference between the contralateral electrode site ($M = -1.23$ μV, $SE = 0.33$) and ipsilateral electrode site ($M = -1.23$ μV, $SE = 0.34$), $F(1, 20) < 0.01$, $MSE = 0.18$, $p = .960$, $\eta_G^2 < .001$. We did, however, observe a significant interaction between Group and Electrode Laterality, $F(1, 20) = 18.43$, $MSE = 0.18$, $p < .001$, $\eta_G^2 = .014$. For participants performing color categorization, a lateralized color singleton elicited a more negative voltage at contralateral electrode sites ($M = -0.93$ μV, $SE = 0.5$) than ipsilateral electrode sites ($M = -0.37$ μV, $SE = 0.5$), $t(20) = -3.07$, $p = .006$, whereas for participants performing shape lateralization, a lateralized color singleton elicited a more positive voltage at contralateral electrode sites ($M = -1.53$ μV, $SE = 0.43$) than ipsilateral electrode sites ($M = -2.08$ μV, $SE = 0.44$), $t(20) = 3.00$, $p = .007$.

When evaluating the P_D time range, we observed no main effects of Group, $F(1, 20) = 2.30$, $MSE = 12.70$, $p = .145$, $\eta_G^2 = .102$, or Electrode Laterality, $F(1, 20) = 2.80$, $MSE = 0.20$, $p = .110$, $\eta_G^2 = .002$, and no interaction
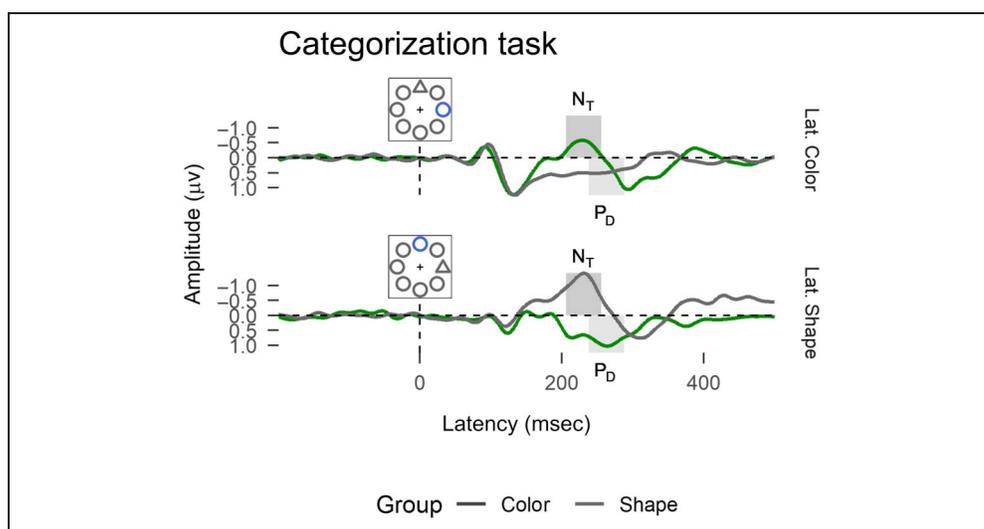
between Group and Electrode Laterality, $F(1, 20) = 3.56$, $MSE = 0.20$, $p = .074$, $\eta_G^2 = .003$.

Lateral shape singleton, midline color. In displays with the shape singleton lateralized and the color singleton on the midline, voltages in the N_T time window did not differ between participants in the color group ($M = -0.93$ μV, $SE = 0.49$) and participants in the shape group ($M = -1.53$ μV, $SE = 0.47$), $F(1, 20) = 0.32$, $MSE = 12.32$, $p = .577$, $\eta_G^2 = .015$, nor was there any difference between the contralateral electrode site ($M = -1.41$ μV, $SE = 0.34$) and the ipsilateral electrode site ($M = -1.06$ μV, $SE = 0.34$), $F(1, 20) = 3.17$, $MSE = 0.41$, $p = .090$, $\eta_G^2 = .005$. We did, however, observe a significant interaction between Group and Electrode Laterality, $F(1, 20) = 26.15$, $MSE = 0.41$, $p < .001$, $\eta_G^2 = .041$. For participants performing shape categorization, a lateralized shape singleton elicited a more negative voltage at contralateral electrode sites ($M = -1.26$ μV, $SE = 0.5$) than ipsilateral electrode sites ($M = -0.61$ μV, $SE = 0.5$), $t(20) = 2.36$, $p = .029$, whereas for participants performing color lateralization, a lateralized shape singleton elicited a more positive voltage at contralateral electrode sites ($M = -0.87$ μV, $SE = 0.47$) than ipsilateral electrode sites ($M = -2.2$ μV, $SE = 0.45$), $t(20) = -4.88$, $p < .001$.

When evaluating the P_D time range, we observed no main effects of Group, $F(1, 20) = 2.27$, $MSE = 0.17$, $p = .148$, $\eta_G^2 = .087$, or Electrode Laterality, $F(1, 20) = 1.54$, $MSE = 0.03$, $p = .229$, $\eta_G^2 = .012$, and no interaction between Group and Electrode Laterality, $F(1, 20) = 0.99$, $MSE = 0.03$, $p = .331$, $\eta_G^2 = .008$.

Search task. Next, we focused on the lateralized response to targets and distractors in the search displays as a function of group assignment. Evidence for the effect

Figure 7. ERP difference waves showing the lateralized response to displays in the categorization task. The top depicts the different neural responses elicited by a lateralized color singleton for participants responding to the color singleton (shown in green) versus those tasked with responding to the shape singleton (shown in gray). The bottom depicts the different neural responses elicited by a lateralized color singleton, again separated by those in the color group (green) and those in the shape group (gray). We see an N_T (206–256 msec) elicited by whichever stimulus was the target (lateralized color

singleton for the color group, lateralized shape singleton for the shape group), but not otherwise. The nontarget stimulus elicited a lateralized positivity in the N_T time window and no significant differences in the P_D time window. Lat. = lateralized.

of selection history would come from the interaction between group and lateralized ERP activity. We performed a set of mixed 2×2 ANOVAs with Electrode Laterality (contralateral vs. ipsilateral) as the within-participant factor and Group (color vs. shape) as the between-participant factor. This was performed for mean amplitudes in the N_T time window elicited by each of the display types (target lateralized, distractor absent; target lateralized, distractor on the midline; and distractor lateralized, target on the midline) as well as the P_D time window in the case of a lateralized distractor (see Figure 8).

Target response: distractor-absent trials. In the target-only displays, the contralateral response ($\Delta M = -2.94$ μV, $SE = 0.35$) was more negative than the ipsilateral response ($\Delta M = -1.34$ μV, $SE = 0.36$), $F(1, 19) = 63.21$, $MSE = 0.42$, $p < .001$, $\eta_G^2 = .085$. Neither the main effect of Group, $F(1, 19) = 0.01$, $MSE = 14.48$, $p = .906$, $\eta_G^2 = .001$, nor the interaction between Group and Hemisphere reached significance, $F(1, 19) = 1.19$, $MSE = 0.42$, $p = .288$, $\eta_G^2 = .002$.

Target response: distractor-present trials. When the target was lateralized in the presence of a midline distractor, we observed no significant main effect of Group, $F(1, 19) = 0.25$, $MSE = 13.97$, $p = .625$, $\eta_G^2 = .013$; however, there was a significant main effect of Electrode Laterality, $F(1, 19) = 52.69$, $MSE = 0.33$, $p < .001$, $\eta_G^2 = .060$, indicating the presence of an N_T ($\Delta M = -1.31$). This main effect was superseded by an interaction between group and electrode laterality, which showed that the voltage difference between contralateral and ipsilateral electrode sites was significantly larger for participants in the shape group ($\Delta M = -1.7$ μV, $SE = 0.31$) than those in the color group ($\Delta M = -0.87$ μV, $SE = 0.2$), $F(1, 19) = 5.61$, $MSE = 0.33$, $p = .029$, $\eta_G^2 = .007$.

Distractor response: distractor-present trials. For the lateralized distractor response, results of the N_T time range showed neither an effect of Group, $F(1, 19) = 0.57$, $MSE = 14.55$, $p = .458$, $\eta_G^2 = .029$, nor of Electrode Laterality, $F(1, 19) = 0.01$, $MSE = 0.17$, $p = .922$, $\eta_G^2 = .000$, nor an interaction between Group and Electrode Laterality, $F(1, 19) = 0.73$, $MSE = 0.17$, $p = .403$, $\eta_G^2 = .000$.

Results of the P_D time window showed no significant main effect of Group, $F(1, 19) = 1.09$, $MSE = 18.69$, $p = .309$, $\eta_G^2 = .054$; however, there was a significant main effect of Electrode Laterality, $F(1, 19) = 10.90$, $MSE = 0.29$, $p = .004$, $\eta_G^2 = .009$, indicating the presence of a P_D ($\Delta M = 0.53$). A significant interaction between Group and Electrode Laterality, $F(1, 19) = 6.32$, $MSE = 0.29$, $p = .021$, $\eta_G^2 = .005$, revealed that a significant P_D was elicited for participants in the color group ($\Delta M = 0.96$, 95% CI [0.46, 1.47]), $t(19) = 4.02$, $p = .001$; however, the difference between the contralateral and ipsilateral electrodes did not reach significance for the shape group ($\Delta M = 0.13$, 95% CI [-0.35, 0.61]), $t(19) = 0.57$, $p = .575$.

Comparison between Voluntary and Cued Task Switching

Comparison of the preparatory activity in the present experiment to the preparatory activity recorded by Kadel

Figure 8. Subtracted ERPs showing the lateralized response for each group across the three different search display conditions. The top shows equivalent N_T components (227–277 msec) elicited by both groups when a target is presented without distraction. The center shows an attenuated N_T for participants in the color group when a target was presented alongside a color distractor. The bottom shows the P_D component (264–314 msec) elicited by lateralized color distractors for participants in the color group but not the shape group.
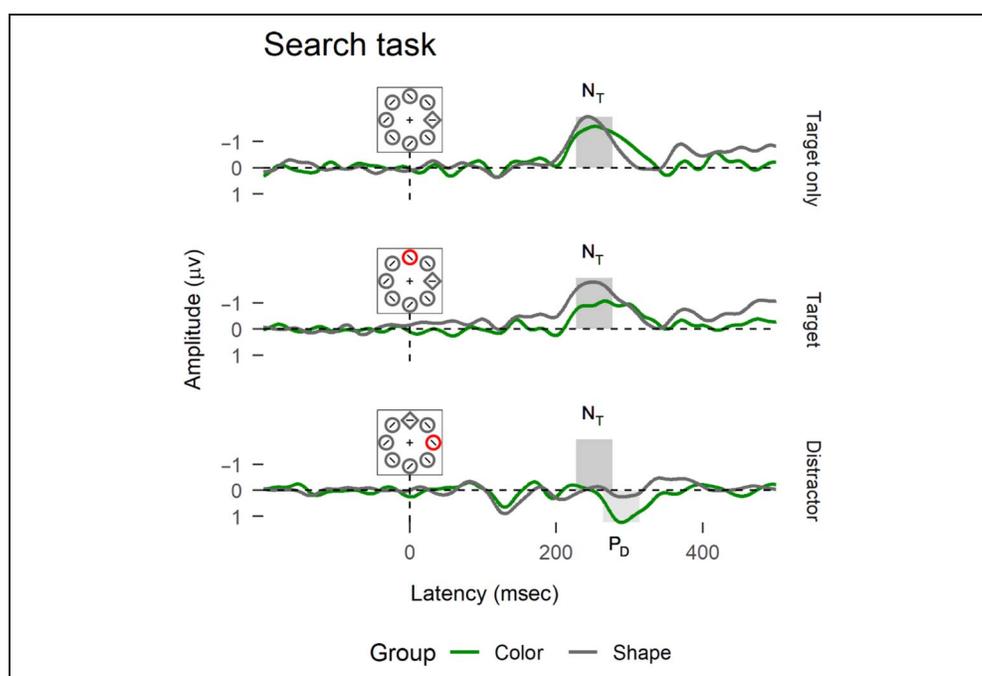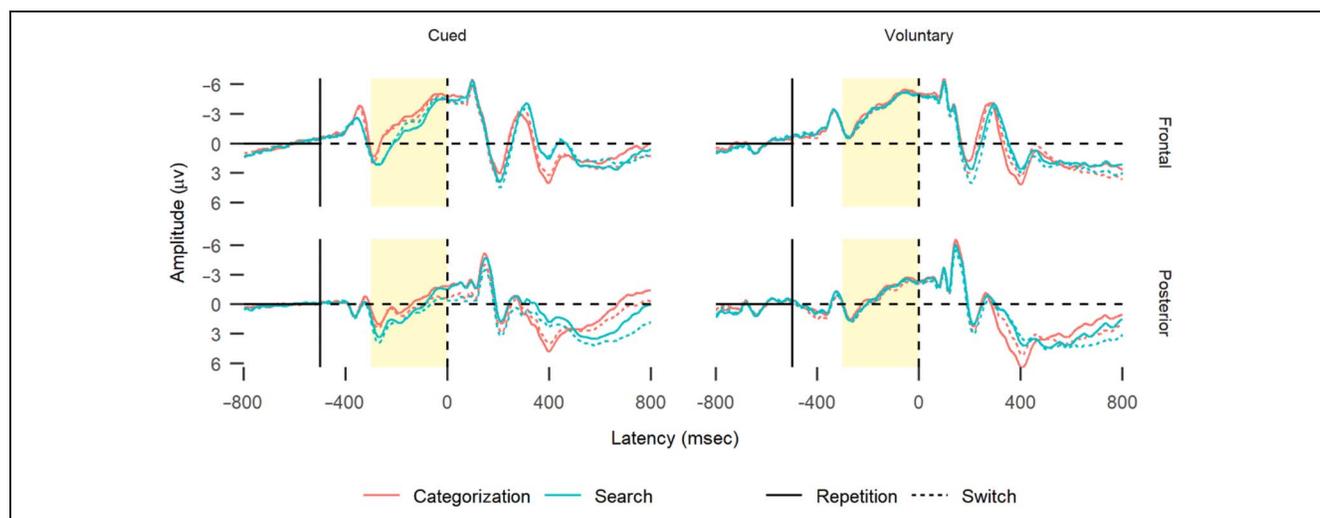
Figure 9. Preparatory activity in the voluntary task selection procedure, compared to the preparatory activity in a cued version of our task carried out in Kadel et al. (2017). (A) ERP activity centered on the task display onset taken from a cluster of fronto-central electrodes to measure the CNV and a cluster of posterior electrodes to measure the posterior positivity. The solid vertical line indicates the onset of the fixation cross preceding the task display on each trial. In the cued task, this fixation indicated which task participants would be presented with; in the voluntary task, this fixation started after participants had selected the task they would like to perform in the upcoming trial. The vertical dotted line shows the onset of the task display, and the component window used to measure preparatory activity is highlighted in yellow. (B) Scalp distribution of ERP activity within the time window of interest, plotted separately for the two experiments. We observe a larger fronto-central negativity typical of voluntary task-switching paradigms and indicative of enhanced top–down control relative to the cued task paradigm.
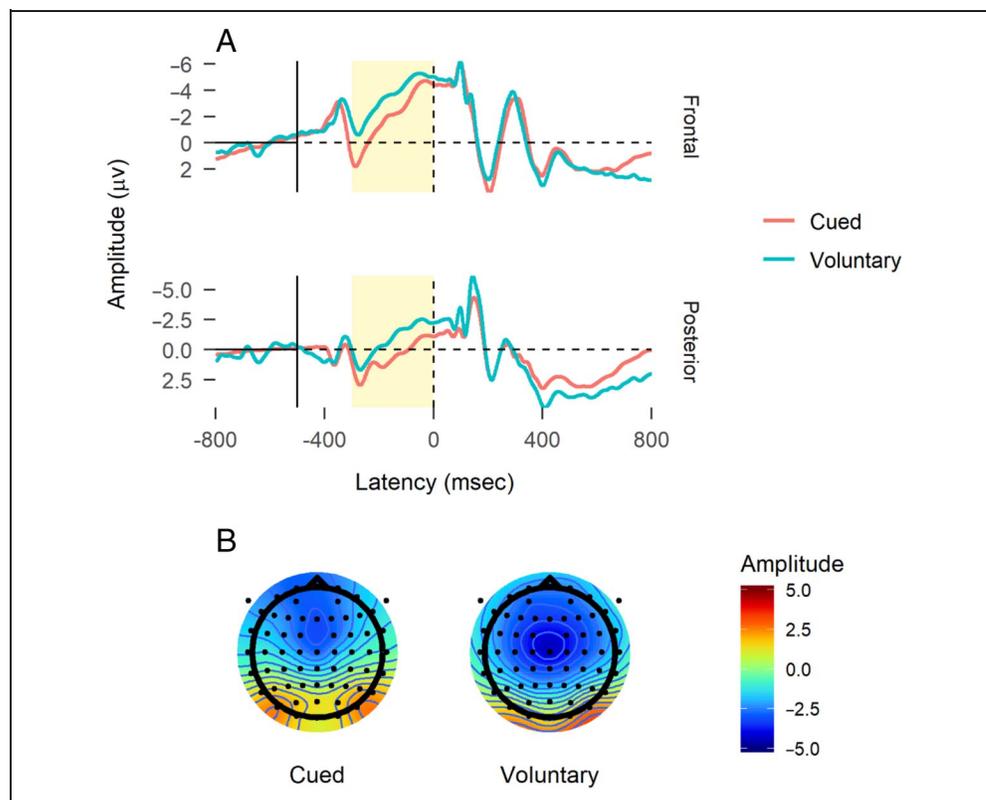
et al. (2017) is shown in Figure 9. We saw a significantly larger CNV at fronto-central electrodes in our voluntary task-switching procedure ($\Delta M = -1.51$, 95% CI [-1.80, -1.23]), $t(552.32) = -10.40$, $p < .001$. We also saw a significantly larger positivity at posterior electrodes in

the cued task-switching procedure used by Kadel et al. (2017; $\Delta M = 1.45$, 95% CI [1.66, 1.25]), $t(589.46) = 13.81$, $p < .001$.

In addition, for each experiment, we decided to perform a 2 × 2 ANOVA to investigate the effect of Task

Figure 10. Preparatory activity in the cued task-switching experiment (left) and the voluntary task-switching experiment (right) separated by the task performed (categorization vs. search) and task transition (switch vs. repetition) from the previous trial. The solid vertical line indicates the onset of the fixation cross preceding the task display on each trial. In the cued task, this fixation indicated which task participants would be presented with; in the voluntary task, this fixation started after participants had selected the task they would like to perform. The vertical dotted line shows the onset of the task display; the component window used to measure preparatory activity is highlighted in yellow.

(categorization vs. search) and Transition (switch vs. repetition) on preparatory activity at both frontal and posterior electrode clusters (Figure 10). In the cued task-switching experiment, CNV amplitude at frontal electrodes showed a significant main effect of Task, $F(1, 27) = 25.06$, $MSE = 1.18$, $p < .001$, $\eta_G^2 = .033$, no significant main effect of Transition, $F(1, 27) = 0.01$, $MSE = 0.48$, $p = .944$, $\eta_G^2 < .001$, and a significant interaction between Task and Transition, $F(1, 27) = 6.56$, $MSE = 0.41$, $p = .016$, $\eta_G^2 = .003$. Follow-up contrasts showed that the CNV is larger for categorization trials than search trials preceding a switch ($\Delta M = -0.72$, 95% CI $[-1.20, -0.24]$), $t(43.60) = -3.02$, $p = .004$, and that this effect is even more pronounced for a repetition ($\Delta M = -1.34$, 95% CI $[-1.82, -0.86]$), $t(43.60) = -5.61$, $p < .001$. We did not see any difference between switch and repetition in categorization trials ($\Delta M = -0.30$, 95% CI $[-0.66, 0.06]$), $t(53.59) = -1.68$, $p = .099$, nor any difference between switch and repetition in search trials ($\Delta M = 0.32$, 95% CI $[-0.04, 0.68]$), $t(53.59) = 1.78$, $p = .080$. When we perform this analysis using data from the posterior cluster of electrodes in the cued task-switching experiment, we see a significant main effect of Transition where switch trials have a significantly larger posterior positivity than repetition trials, $F(1, 27) = 19.37$, $MSE = 0.38$, $p < .001$, $\eta_G^2 = .016$. We also see a main effect of Task in which the posterior positivity is larger for the search task than the categorization task, $F(1, 27) = 20.21$, $MSE = 0.89$, $p < .001$, $\eta_G^2 = .039$. There is no significant interaction between Transition and Task, $F(1, 27) = 0.21$, $MSE = 0.24$, $p = .653$, $\eta_G^2 < .001$.

In the voluntary task-switching experiment, CNV amplitude at frontal electrodes showed no significant effect of Transition, $F(1, 21) = 1.76$, $MSE = 0.36$, $p = .199$, $\eta_G^2 = .001$, no significant effect of task, $F(1, 21) = 0.36$, $MSE = 0.78$, $p = .553$, $\eta_G^2 = .001$, and no interaction between them, $F(1, 21) = 1.43$, $MSE = 0.14$, $p = .246$, $\eta_G^2 < .001$. Analysis at the posterior cluster of electrodes showed that ERP amplitude was significantly more positive in switch trials than in repetition trials, $F(1, 21) = 5.32$, $MSE = 0.29$, $p = .031$, $\eta_G^2 = .006$; however, there was no significant effect of Task, $F(1, 21) = 0.24$, $MSE = 0.16$, $p = .630$, $\eta_G^2 = .000$, and no interaction between Transition and Task, $F(1, 21) = 3.79$, $MSE = 0.14$, $p = .065$, $\eta_G^2 = .002$.

DISCUSSION

Previous research has established that an individual's selection history biases their attention during visual search, even when that selection history is task irrelevant and impairs search performance. In this study, we investigated whether the effects of selection history on attention guidance are eliminated in situations where top–down control is maximized. To this end, we used a voluntary task selection design that allowed participants to decide which task they would like to perform on each trial. The results showed that selection history continues to bias attention during visual search, leading to impaired target selection and an increased need for distractor suppression. These effects were reflected both in RTs as increased distractor costs and in lateralized ERP components as simultaneous attenuation of attention deployed to the target (reflected in the N_T component) and increased need for distractor suppression (reflected as an increase in the P_D component).

This pattern of results is consistent with the results of Feldmann-Wüstefeld et al. (2015) who used a version of this task that allowed for only limited top–down control. In their experiment, participants were also randomly assigned to either a color categorization or shape categorization group and asked to perform two tasks. In the categorization task, their responses depended on group assignment (categorizing either the color or shape singleton), and in the search task, all participants had to search for and respond to a line within a shape singleton. In their version of the task, the two tasks were randomly intermixed, and participants had no way of knowing whether the upcoming trial would be a categorization trial or a search trial. Their results showed that color categorizers incurred greater RT costs when a color distractor was present in the search display relative to shape categorizers. The fact that we observed the same pattern of results in our task suggests that, even when participants have the maximum opportunity to make deliberate, nonspeeded decisions regarding the upcoming task and use top–down control to switch task sets, selection history's effect on attention guidance remains.

We also observed substantial persistence of previously reported ERP effects in our version of the task. The first component of interest was the N_T, a lateralized negative deflection elicited by attended target stimuli in a search display. In our results, we found that, when participants performed visual search for a shape target while color distractors were absent, then both groups of participants produced equivalent N_T components to the target. This is consistent with the suggestion that, in the absence of a colored distractor, both groups were equally proficient at directing their attention to the shape singleton. An increased N_T amplitude is usually considered to reflect enhanced target selection processes. N_T amplitude was reported to be larger in response to threatening stimuli (Weymar, Gerdes, Löw, Alpers, & Hamm, 2013), highly rewarding stimuli (Kiss, Driver, & Eimer, 2009), and stimuli whose processing has been facilitated by intertrial priming (Töllner, Gramann, Müller, Kiss, & Eimer, 2008; although see Mazza, Turatto, & Caramazza, 2009; Mazza & Caramazza, 2011; Mazza, Pagano, & Caramazza, 2013; and Naughtin, Mattingley, & Dux, 2016, for examples in which the relationship is more complex). In our task, the N_T amplitude to the target was significantly reduced for participants with a history

of color categorization when the target was presented with a color distractor. This is consistent with the idea that a history of color categorization leads to increased attention capture by color singletons and therefore an impaired ability to efficiently direct attention to the shape target.

One difference observed between the results of Feldmann-Wüstefeld et al. (2015) and our study is that they observed a lateralized negativity to distractors in the search task for participants in the color group, whereas we see no such component. A negativity to distractors, referred to as the N_D, has been observed in a number of search tasks and is typically viewed as reflecting attentional selection of the distractor, analogous to the N_T. Feldmann-Wüstefeld et al. (2015) suggested that the N_D was the result of the colored distractor capturing attention in the search task. The fact that we saw no evidence of this capture in our task could be taken as evidence that voluntary selection allowed participants to prevent this initial capture by color distractors. An implication of our results may therefore be that top–down control can prevent initial capture of distractors but that this in itself does not prevent the need for distractor suppression (as indexed by the large P_D). Future investigation will be required to establish the reliability of this effect.

The final component of interest in our study was the P_D component, a lateralized positivity that has been associated with distractor suppression (Hickey et al., 2009). Evidence that it reflects distractor suppression was initially provided by Hickey et al. (2009), who showed that it was elicited by lateralized distractors but not lateralized targets and therefore referred to it as a positivity to distractors, or P_D. Similar effects have been reported by others (Toffanin, de Jong, & Johnson, 2011; Hilimire, Mounts, Parks, & Corballis, 2009), and the presence of a lateralized positivity to targets in some instances (Burra & Kerzel, 2014; Hilimire & Corballis, 2014; Sawaki, Geng, & Luck, 2012) has led to the suggestion that it reflects a general mechanism for both, preventing capture by distractors (Heuer & Schubö, 2019; Gaspelin, Leonard, & Luck, 2017; Gaspar & McDonald, 2014), and disengaging from stimuli that were initially attended but do not require further processing (Burra & Kerzel, 2014; Hilimire & Corballis, 2014; Sawaki et al., 2012). In our results, we saw a P_D elicited by color distractors during search, but only for the group of participants who performed color categorization in the categorization task. This suggests that, for these participants, successful search entailed the suppression of the color distractor, a process that is not required for participants in the shape group. The fact that this pattern of results persisted when voluntary task selection was used suggests that the selection history effect in our case was the result of an implicit accrual of information about a feature dimension's relevance that biases attention automatically.

A substantial body of work has demonstrated the role that top–down control plays in directing attention to relevant stimuli. Early research showed that top–down control settings could be used to enhance the processing of specific locations (Eriksen & Hoffman, 1972) as well as specific features like color, size, and orientation Ansorge, Horstmann, & Carbone, 2005; Wolfe & Horowitz, 2004; Ansorge & Heumann, 2003; Von Wright, 1970). Recent research has established that abstract top–down control settings are also effective. For example, participants are able to engage control settings that prepare for oddball detection (Bacon & Egeth, 1994; Pashler, 1988), relative features (e.g., "redder" items; Becker, Folk, & Remington, 2013; Becker, 2010), and semantic categories (Wyble, Folk, & Potter, 2013; Wyble, Bowman, & Potter, 2009; Leblanc & Jolicoeur, 2007; Barnard, Scott, Taylor, May, & Knightley, 2004). A large portion of this literature has focused on the interaction between top–down control and bottom–up salience as well as the question of whether top–down control settings prevent capture by salient distractors (Wang & Theeuwes, 2018a, 2018b). Given the relative novelty of selection history as an area of study, its interaction with top–down control remains poorly understood. Previous work using a version of our task in which participants were cued about the task they would perform on the subsequent trial, or performed the tasks in a fixed, predictable order (Kadel et al., 2017), showed the same selection history effects reported here, suggesting that top–down preparation cannot overrule the effect that selection history has on attentional filter settings.

Our study extends on previous work through the use of a voluntary task selection design. Experiments from the task-switching literature have provided a number of ways that top–down control can be improved in tasks like the one used here. Examples include task cuing paradigms in which a cue is presented before the trial to inform participants which task they are about to perform as well as the alternating-runs paradigm where tasks are performed in a predictable sequence, for example, A-A-B-B-A-A-B-B (Kiesel et al., 2010). Both of these procedures allow the participant to switch task sets in preparation for the upcoming trial demands and have been shown to reduce the cost of a task switch as a result. Voluntary task selection is a more recent development along these lines (Chen & Hsieh, 2015; Gollan et al., 2014; Arrington & Logan, 2004, 2005), with behavioral and ERP evidence to show that it results in even greater preparatory reconfiguration processes than the cuing paradigms used previously (Kang et al., 2014; Vandamme et al., 2010; Arrington & Logan, 2005). Although these effects were fairly well established in the task-switching literature, the tasks used in task switching are typically very different to the search style tasks used in the present experiment. Therefore, it was important to verify that the voluntary task selection paradigm used in the present experiment provided an equivalent gain of top–down control when compared to cued versions such as the one used in Kadel et al. (2017).

One of the primary signatures of increased top–down control is the presence of a CNV component that is larger during voluntary task selection than cued task switching (Kang et al., 2014; Vandamme et al., 2010). The CNV component is a fronto-central negativity that gradually builds in anticipation of a target display (Brunia, 2003; Walter, Cooper, Aldridge, McCallum, & Winter, 1964) and is believed to represent top–down preparation of stimulus–response mappings (Leuthold, Sommer, & Ulrich, 2004; Wauschkuhn, van der Lubbe, Jaśkowski, & Trillenberg, 2000). By comparing preparatory activity in the voluntary task selection paradigm used in the present experiment to the preparatory activity in an otherwise identical cued version of this paradigm, we confirm the effects seen in the wider task-switching literature. Namely, our results show that participants in the voluntary task produce a significantly larger CNV compared to those in the cued version. In addition, our results show that the CNV in the cued version of the task is modulated by conditions like the task and the transition that participants are preparing for, whereas in the voluntary version of the task, these effects are mitigated. Taken together, this provides strong support for the suggestion that the present task allowed for a much greater level of top–down preparation than previous tasks, and therefore, we provide the strongest evidence yet that selection history effects are persistent even when top–down preparatory control is maximized.

Another advantage of the voluntary task selection design is that it allows us to measure choice processes. Participants are typically instructed to attempt to distribute their choices as randomly as possible, in which case the probability of switching on a given trial would be 50%. Results from voluntary task-switching experiments have typically shown that participants do not produce switch rates of 50% but instead show a fairly consistent repetition bias (Arrington & Logan, 2004, 2005). Importantly, this does not appear to be a general consequence of asking people to produce random sequences, which has been shown to instead produce the opposite effect—a switching bias (Arrington & Logan, 2004; Nickerson, 2002). Arrington and Logan (2004) suggested that the repetition bias may reflect participants' attempts to avoid the costs of a task switch, and they supported this by showing that the repetition bias is mediated by the length of time preceding a choice. When participants were given more time between trials before they had to make a choice, both switch costs and the magnitude of the repetition bias were reduced.

In our results, we saw that participants in the color group had a repetition bias indicating that they struggled to randomly select between trial types and were instead more likely to repeat the previous trial type than switch. This was different to participants in the shape group who showed no evidence of a bias in their choices. These results imply that participants who performed shape categorization in the categorization task may have incurred

smaller costs when task switching and therefore did not attempt to avoid task switches to the same degree as participants in the color group. This suggestion is also supported by the fact that, when switching to the categorization task, participants in the color group incur larger switch costs than participants in the shape group. Although modest switch costs are present in all conditions for both groups, only the color group show significant increases in costs associated with a switch from search to categorization. Despite the increased top–down control afforded by a voluntary task-switching procedure, the color group's conflicting selection history leads to greater interference in task performance, and presumably as a consequence of this, these participants show a repetition bias in their choices.

An interesting feature of the switch costs described above is the asymmetry observed between the tasks. Switch costs were significantly larger when participants switched from the search task to the categorization task, than in the reverse situation where they switched from categorization to search. This kind of switch cost asymmetry has been described in previous task-switching paradigms where the two tasks differ in difficulty (Arrington, Reiman, & Weaver, 2014). Somewhat paradoxically, it has been shown that switch costs tend to be larger for the easier task, and this is true for general task-switching paradigms (Alport et al., 1994) as well as in various types of voluntary task selection (Millington et al., 2013; Yeung, 2010). Although participant accuracy in our two tasks did not differ significantly, we did see a significant slowing of responses to the search task suggesting that it may have been the more difficult of the two tasks. Larger switch costs in the categorization task are therefore consistent with the finding that switch costs are usually larger for easier tasks.

The main explanation given by previous research for the observation that switch costs are reduced when switching to a difficult task is related to between-task competition (Arrington et al., 2014). In a task-switching procedure, participants have two task sets competing for representation while they perform any given trial. By default, this competition is weighted in favor of the easier task, and performance of the difficult task requires active enhancement of its weaker task set. As a consequence of enhancing the strength of the difficult task set across the experiment, participants find it easier to switch to this task and therefore take reduced switch costs (Arrington et al., 2014). Previous investigations of this effect in voluntary task designs have shown that participants also choose to perform the difficult task more often (Millington et al., 2013; Yeung, 2010) and that this depends on the degree of response overlap between the two tasks (Yeung, 2010) as well as the amount of time taken to make a selection (Millington et al., 2013).

Notably, in our case, this switch cost asymmetry was observed only in the color group, and no such effect

was seen in the shape group. If switch cost asymmetries are the result of between-task competition, then this suggests that between-task competition was reduced for participants in the shape group. Importantly, this is not because of a change in task difficulty between the groups—the shape group's RTs show that they also find the search task more difficult than the categorization task. Although task difficulty remains the same for both groups, the switch cost asymmetry is absent for the shape group whose target is a shape singleton in both tasks. This suggests that between-task competition is modulated not only by response compatibility (as described by Yeung, 2010) but also by the congruency between the attentional templates used in each task. A thorough understanding of the factors that modulate between-task competition will require further investigation. Our results, however, suggest that such work may find utility in expanding on the paradigm used here to control for task difficulty while manipulating between-task competition.

Conclusion

Previous work has managed to establish that a person's selection history can influence his or her deployment of attention during the performance of a visual search task. Our study used a voluntary task selection paradigm to maximize participants' top–down control. The results showed that top–down control could not eliminate the effects of selection history on attention even when maximized. This was evident in both the distractor costs measured from behavior as well as in the lateralized ERP components that dissociated target selection and distractor suppression. Group assignment also affected choice processes and switch costs in voluntary task switching. Switch costs in our task were significantly larger for the categorization task in the color group than in any other condition, which along with the presence of a repetition bias only in the color group, implies the presence of increased between-task competition for those participants. These results support the suggestion by Awh et al. (2012) that selection history represents a third distinct mechanism of attention control, and future research into visual attention would benefit from clarifying the mechanism by which this information is accrued.

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