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Rethinking Volitional Control over Task Choice in Multitask Environments: Use of a Stimulus Set Selection Strategy in Voluntary Task Switching

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Abstract

Under conditions of volitional control in multitask environments, subjects may engage in a variety of strategies to guide task selection. The current research examines whether subjects may sometimes use a top-down control strategy of selecting a task-irrelevant stimulus dimension, such as location, to guide task selection. We term this approach a stimulus set selection strategy. Using a voluntary task switching procedure, subjects voluntarily switched between categorizing letter and number stimuli that appeared in two, four, or eight possible target locations. Effects of stimulus availability, manipulated by varying the stimulus onset asynchrony between the two target stimuli, and location repetition were analyzed to assess the use of a stimulus set selection strategy. Considered across position condition, Experiment 1 showed effects of both stimulus availability and location repetition on task choice suggesting that only in the 2-position condition, where selection based on location always results in a target at the selected location, subjects may have been using a stimulus set selection strategy on some trials. Experiment 2 replicated and extended these findings in a visually more cluttered environment. These results indicate that, contrary to current models of task selection in voluntary task switching, the top-down control of task selection may occur in the absence of the formation of an intention to perform a particular task.

Keywords

cognitive control; task selection; volitional behavior; voluntary task switching

Volitional behavior is often associated with the will or intent to perform some action and as such is frequently contrasted with stimulus-driven behavior (Devaine, Waszak, & Mamassian, 2013; Waszak, Wascher, Keller, Koch, Aschersleben, et al., 2005). In reality most human behavior lies along a continuum from internally- to externally-driven behaviors

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(Haggard, 2008; Logan & Gordon, 2001). The act of reaching down to pick up a toy from the floor may be triggered both by the intent to straighten the house and having just stepped on the toy. The interplay between internal and external, or top-down and bottom-up, control has long been studied in many cognitive domains (Bargh & Chartrand, 1999; Neely, 1977; Yantis, 2000). More recently, cognitive neuroscientists studying the selection of action have made a similar distinction between neural systems that are engaged when selection is internally- vs. externally-driven. Stimulus-driven behaviors engage a parietal-premotor circuit involving the lateral surface of the frontal lobe; while intentional or volitional behaviors involve medial frontal cortex (see for review Kriehoff, Waszak, Prinz, & Brass, 2011). These lateral and medial systems are highly interconnected suggesting that the balance between externally- and internally-guided behavior may result from interactions between these two systems (Forstmann, Brass, Koch, & von Cramon, 2006; Haggard, 2008). Multitask environments that include complex stimuli affording multiple tasks allow for the flexibility in responding that is needed to investigate the interplay between these two modes of guiding behavior. The current study considers the top-down strategies used in volitional task selection in a multitask paradigm that may alter the balance between internally- and externally-driven behavior.

In both cognitive psychology and cognitive neuroscience, the task switching paradigm has become widely used in the past twenty years to address questions surrounding cognitive control mechanisms such as those thought to underlie volitional behavior (for recent reviews see Kiesel, Steinhauser, Wendt, Falkenstein, Jost, et al., 2010; Vandierendonck, Liefoghe, & Verbruggen, 2010). The paradigm involves sequential performance of two or more tasks with the current task typically specified by a cue or pre-set sequence of tasks. Because the target stimuli afford multiple tasks, the currently appropriate behavior is not fully determined by the external target stimulus and must be paired with internal information about which task is currently relevant. This internal information is generally thought to involve the representation of a task set that includes properties of both the task-relevant stimulus features and the associated responses (Meiran, 2000) and can be represented in both declarative working memory and the subordinate systems that carry out the task-related processes (Logan & Gordon, 2001). Throughout a run of task switching trials the current task set must be updated frequently resulting in a situation where competition can arise between the current and recent task sets. The behavioral results nearly ubiquitous in this paradigm are response time (RT) and accuracy switch costs associated with slower and less accurate performance on trials where the task switches. The theoretical accounts for these switch costs include both active processes associated with establishing a new task set and passive processes associated with interference between sequentially activated task sets (Kiesel, et al., 2010; Vandierendonck, et al., 2010). While this literature has provided a wealth of information about the process involved in the preparation and execution of tasks, there has been relatively little consideration of the question of how a particular task set comes to be the task set currently driving task behavior. In standard task switching paradigms, the currently relevant task is generally determined by the interpretation of an external cue (Sudevan & Taylor, 1987) or the retrieval of a particular task from a memorized sequence (Rogers & Monsell, 1995), making the paradigm ill-suited to address questions of how the intent to perform a task arises in unconstrained multitask environments, such as real

world multitasking environments where the ordering of a sequence of tasks is typically determined by the individual acting within the environment rather than an external indicator of which task to perform.

The voluntary task switching paradigm (Arrington & Logan, 2004) has been used to examine factors influencing task choice in simple multitask environments. In most respects voluntary task switching is similar to other task switching paradigms except that subjects freely choose which task to perform on each trial with only global instructions on how to perform the tasks (e.g. equally often or in a random order). In these studies, the focus is generally on measures of task choice rather than performance and they address questions related to why subjects select to perform a given task on the current trial when it is not uniquely specified by the characteristics of the experimental environment. Task choice is influenced by many factors including preparation time (Arrington & Logan, 2005), concurrent working memory load (Demanet, Verbruggen, Liefoghe, & Vandierendonck, 2010; Weaver & Arrington, 2010; Weywadt & Butler, 2013), stimulus repetition (Mayr & Bell, 2006), task difficulty (Liefoghe, Demanet, & Vandierendonck, 2010; Orr, Carp, & Weismann, 2011; Yeung, 2010), and individual differences in executive control (Arrington & Yates, 2009). Looking across these various studies, it is apparent that task choice involves both internally- and externally-driven processes. Furthermore the degree to which task choice is externally driven may fluctuate with changes in the strength of internal top-down goals as well as the availability and salience of external stimuli affording specific tasks.

Of particular relevance to the current study, the balance between top-down and bottom-up factors in voluntary task switching was considered in a study examining the roles of preparation time and stimulus availability on task choice (Arrington, 2008). Subjects viewed displays containing two stimuli, S1 and S2. The stimuli were a letter and a number, affording consonant-vowel and even-odd judgments. Stimulus availability was manipulated through the stimulus onset asynchrony (SOA). Subjects instructed to select the tasks randomly showed a systematic bias, performing the task associated with S1 with a probability, $p(S1)$, greater than 0.5. The $p(S1)$ bias increased with the increasing SOA. Additionally, as the response-to-stimulus interval (RSI) between trials increased, allowing for greater preparation for the upcoming trial, the $p(S1)$ decreased. These results demonstrate both stimulus-driven and goal-directed processes involved in voluntary task switching. Arrington (2008) framed these results within Logan and Gordon's (2001) executive control of Bundesen's theory of visual attention (ECTVA), which provides a formal model of executive control in dual-task situations.

Logan and Gordon (2001) define a task set as those parameters necessary to program the subordinate processes that perform a task. Within their model these parameters include both those under the control of the executive and those determined by the stimulus environment, making it a well-suited model for accounting for the combination of effects in Arrington (2008). The parameters under the control of the executive are represented in working memory at both task and parameter levels. The task-level representation is accessible to conscious awareness and associated with task goals. The parameter-level representation is derived from the task-level, transmitted from working memory to the subordinate systems, and combines with parameters determined by the environment to guide task performance.

The process of selecting and categorizing an object is conceived of as a race with the winner determined by the processing rates for all possible categorizations. In its simplest form, the processing rate in ECTVA includes three components. The first component is an evidence parameter, η , which is driven by the external stimulus and represents the similarity between the object and a representation of the category in memory. The second component is a bias parameter, β , which represents the subject's bias to respond with a particular categorization. The third component is a priority parameter, π , which represents the attentional weight of a particular object. The three parameters combine multiplicatively such that β and π can be thought of as gain controls on the processing of evidence for a particular categorization of an object. Critical for the current research, the β and π values are under the control of the executive and can loosely be thought of in terms of specifying the response set and stimulus set components, respectively, of the task set for a particular task (Logan, 2002; Meiran, 2000). As applied to dual-task environments, Logan and Gordon modeled a task switch in terms of resetting β values to instantiate the responses associated with the categorizations for the new task and an object switch in terms of resetting π values to increase the attention weights for the currently relevant object. While we focus here on the ECTVA model to motivate the current study and frame the predictions, it is worth noting that other theories similarly involve control of behavior through intentional weighting of particular task components, for example work by Hommel and colleagues on the Event Coding Theory (Hommel, 2009; Hommel, Müsseler, Aschersleben, & Prinz, 2001).

Arrington (2008) focused on the η and β parameters in explaining the effects of stimulus availability and preparation time on task choice. The increase in $p(S1)$ as a function of SOA was described in terms of the advantage in the race that results from the onset of S1 prior to S2. In an externally-driven fashion, the onset of a stimulus establishes the η values for that stimulus and allows the accumulation of evidence for the response associated with that stimulus to begin. When SOA is greater than 0, the likelihood that the response associated with S1 will win the race increases, resulting in a $p(S1)$ greater than 0.5. The interaction between SOA and RSI (i.e. stimulus availability and preparation time) arises from the multiplicative relationship between the η and β values. Establishing an internally-driven goal to perform a task results in the representation of a response set, where β values are set high for responses for one task and low for the responses for the other task. The formation of a task-level representation of the selected task in working memory, the generation of the parameter-level representation, and transmission of the parameters to the subordinate system all take time. As the RSI increases, the likelihood that β values are set prior to the onset of S1 increases. When β values are set high for one task and low for the other, the accumulation of evidence for the response associated with the intended task will be so rapid as to overcome the advantage that S1 has in the race. In short, when a response set has been established by the executive based on the intent to perform a particular task, the impact of the stimulus environment is diminished.

Most interpretations of how task selection occurs in voluntary task switching assume that the *intent to perform a particular task* precedes and generally guides task selection (Arrington & Logan, 2005; Vandierendonck, Demanet, Liefoghe, & Verbruggen, 2012). For example, subjects instructed to perform a random sequence of two tasks will maintain a sequence of

tasks in working memory and attempt to select the next task in accordance with some internal representation of a random sequence (Arrington & Logan, 2005). This view is parallel to models of task performance in cued task switching, where the interpretation of a cue indicting a particular task establishes the goal to perform that task and an accompanying reconfiguration of the cognitive system in preparation for performing that task (Arrington, Logan, & Schneider, 2007). Additionally, this view aligns with models of intentional action that suggest that the intention to act involves selecting *what* action to perform (Brass & Haggard, 2008). Thus performance in voluntary task switching (or other real-world, multitask environments) occurs because individuals have formed the intention to perform a particular task, searched through the stimulus environment until finding the target associated with that task, and produced the appropriate response based on a combination of the top-down goal to perform a particular task and the bottom-up evidence from the environment for a specific response. Within ECTVA, the selection of a particular task may be thought of in terms of the formation of a task-level representation of the selected task in working memory (e.g. establishing the intent or goal to perform the number task) and the generation of the parameter-level representation of the response set (e.g. setting β values high for “even” and “odd”) for the selected task.

The current experiments examine whether the top-down control of task selection may occur in the absence of the formation of an intention to perform a particular task. Rather than forming a task-level representation that reflects a choice to perform a particular task, can subjects form a task-level representation that reflects a choice to perform any task associated with a particular stimulus characteristic? For example, rather than choosing to perform the number task, preparing a task set based on high β values for “even” and “odd” responses, and searching for the number target on which to perform that task, can subjects choose a task-irrelevant stimulus characteristic such as location, prepare a task set based on setting high π values for a particular target location, and perform the task appropriate for whichever target matches the stimulus set. We term this approach a *stimulus set selection strategy*. The use of this term follows the terminology of ECTVA, contrasting with a possible response set selection strategy, which would reflect the typical view of how individuals select and prepare to perform a task. A stimulus set selection strategy based on top-down selection of a possible target location and performance of the task afforded by the stimulus occurring at that location would represent a basic filtering mechanism (Bundesen, 1998; Logan, 2002) in visual attention. We consider such a strategy by introducing a manipulation of the number of possible target positions to the basic voluntary task switching environment used in Arrington (2008). Targets appeared in two, four, or eight possible positions. The presence of a stimulus set selection strategy can be assessed by examining the relationship between the number of target positions and the effect of stimulus availability. If subjects select a target position and set the π value high for that position, then the influence of external stimulus availability should decrease because the high π value will act as a gain control for the η values for whichever target appears at that position and overcome the advantage that S1 has in the race.

Two possible patterns of data might arise based on how a stimulus set selection strategy is implemented. First, the $p(S1)$ bias may increase linearly as the number of positions increases. This pattern would occur if the stimulus set selection strategy was used across

position conditions, but with diminished effectiveness as the number of positions increased. Within ECTVA, the probability of selecting a target based on a location-based stimulus set is a function of the attention weight associated with the position in which the target appears relative to the attention weights to all positions. The relative attention weight is calculated as the absolute attention weight for that target divided by the sum of the absolute attention weights for all objects in the display (Logan & Gordon, 2001). Thus, as the number of possible target locations increases the relative attention weight for a given position decreases monotonically as a function of number of locations, diminishing the degree of top-down control afforded by establishing a stimulus set selection strategy. Second, the $p(S1)$ bias may show a more binary pattern with reduced effects at the 2-position condition and equal effects for the 4- and 8-position conditions. If subjects select a possible target position, then the probability that one of the targets will appear in that position decreases as the number of positions increases (i.e. 1.0, 0.5, and 0.25 respectively for the 2-, 4-, and 8-position conditions). Thus given the diminished effectiveness of such a selection strategy with more than two targets, individuals may only implement a selection strategy based on target position in the 2-position condition where it is effective on all trials.

Experiment 1

Method

Participants—Eighteen undergraduates completed the experiment in exchange for partial course credit. All subjects reported normal or corrected-to-normal vision. Data from one participant were excluded due to accuracy below 80%. Data from one participant were excluded due to switches on fewer than 10% of trials.

Tasks and design—The two subordinate-level tasks were even-odd judgments on a single-digit number and consonant-vowel judgments on a letter. The stimulus availability was manipulated through the SOA, which was either 0 or 100 ms presented randomly across trials. The position condition was manipulated by having two, four, or eight possible target positions. Position condition was manipulated across sessions and the session order was counterbalanced across subjects.

Stimuli and apparatus—Stimulus presentation and response recording were made using E-prime software on Dell Dimension computers with 17" CRT monitors. Responses were made on a standard QWERTY keyboard using the *d*, *f*, *j*, and *k* keys. Viewing position was not constrained. Eight possible stimulus positions were configured around a central fixation cross. The positions were located along the vertical and horizontal axes and the diagonals with the nearest edge an average of 1.25 cm from the fixation cross. A # symbol appeared in each of the possible target locations for a given condition: in all eight positions for the 8-position condition, in four positions either along the vertical and horizontal axes or along the diagonals for the 4-position condition, or in two positions along a single axis or diagonal in the 2-position condition (see Figure 1B). For the 2- and 4-position conditions, the positions were constant for a given subject, but the particular arrangement varied across subjects. The target stimuli were the numbers 2–9 and the letters A, B, C, E, I, L, U, and W presented in black 18-point Courier New font on a light grey background.

Procedure—The trial line is shown in Figure 1A. All trials began with a presentation of the cross and placeholders at possible target locations for the 1000-ms RSI. A number and letter replaced the placeholders in two possible target locations with either 0- or 100-ms SOAs. The identity, position, and order (for the 100-ms SOA) of the two stimuli were selected randomly. Both stimuli and any remaining placeholders were present on the screen until a key press response was made.

Subjects completed each position condition in separate 1-hour sessions completed on different days within one week of each other. The position condition was counterbalanced across subjects, though loss of some subjects' data, as noted above, resulted in imperfect counterbalancing of session order. Instructions for the individual task responses and the voluntary task switching procedure were provided on the computer and through supplemental verbal instructions. Each session began with 16 practice trials for each task. Subjects then received the voluntary task switching instructions. Subjects were informed that both a letter and number would appear on each trial and that they were to select one task to perform on each trial. They were further instructed to choose the tasks equally often in a random order. Subjects completed a 16-trial voluntary task switching practice block. Subjects received instructions to perform as quickly and accurately as possible, then completed 18 64-trial blocks.

Results

Task choice and performance measures were calculated as follows. Task choice was coded based on the hand used to respond. The data were initially trimmed to remove the first trial of each block, error trials, and the trials following errors. This data trimming procedure resulted in the removal of 10.8% of the trials. Error trials were not analyzed because of the difficulty in defining task choice on error trials (Arrington & Logan, 2004). For RT analysis, further trimming was performed on trials with RTs less than 150 ms or greater than 3000 ms, resulting in the further removal of 1.4% of the trials. Subjects showed a standard RT switch cost ($M = 106$ ms, $F(1, 15) = 38.8$, $p < .05$, $\eta^2_p = .721$).

The primary variable of interest is the probability of selecting the task associated with S1 or $p(S1)$. Figure 2A shows the mean $p(S1)$ as a function of SOA and position condition. In the 100-ms SOA condition, subjects selected the task associated with S1 more frequently than expected by chance. Critically this effect varied as a function of the position condition, with a smaller effect of stimulus availability in the 2-position condition. Analysis using a 3 position (two, four, and eight) by 2 SOA (0 and 100 ms) repeated-measures ANOVA showed a significant interaction of the two variables, $F(2, 30) = 3.9$, $p < .05$, $\eta^2_p = .207$, which was broken down to consider the simple effects of position. The 0-ms SOA in essence serves as a control condition since the designation of S1 for the 0 ms SOA was arbitrary. Unsurprisingly, there was no effect of position ($F < 1$) and no deviation of the $p(S1)$ value from chance. For the 100-ms SOA, the effect of position was significant, $F(2, 30) = 36.9$, $p < .05$, $\eta^2_p = .195$, with LSD contrasts indicating that the 2-position condition differed significantly from both the 4- and 8-position conditions, which did not differ from each other. In addition to showing differences across conditions, it is worth considering whether the effect of stimulus availability resulted in task selection above chance levels. The mean

estimate for the 2-position condition included 0.5 within its 95% confidence interval (CI), whereas the estimates for the 4- and 8-position conditions both excluded 0.5 from their 95% CIs. These results support the hypothesis that when subjects are able to use a stimulus set selection strategy (i.e. for the 2-position condition where a target appears in each location on every trial) they are less influenced by the bottom-up factor of stimulus availability. In situations where a stimulus set selection strategy is less effective (i.e. for the 4- and 8-position conditions where a target appears in a given position on only a half or a quarter of trials, respectively), subjects show a bias toward the S1 task resulting from the external influence of stimulus availability.

If subjects adopt a stimulus set selection strategy, subjects may maintain attention to the selected location across subsequent trials resulting in an increased likelihood of performing the task associated with a stimulus appearing in the same position as the stimulus responded to on trial $n-1$. To test this prediction, we considered a subset of trials when either the S1 or S2 appeared in the same location as the target responded to on trial $n-1$. Figure 3A shows the mean probability of performing the task associated with a location repetition as a function of stimulus order and position condition. A 2 stimulus order (S1 and S2) by 3 position (two, four, and eight) by 2 SOA (0 and 100 ms) repeated-measures ANOVA revealed significant main effects of stimulus order, $F(1, 15) = 5.2, p < .05, \eta^2_p = .259$, and position, $F(2, 30) = 9.5, p < .05, \eta^2_p = .387$. Breaking down the significant effect of position using LSD contrasts, subjects were more likely to perform the task associated with a stimulus appearing in the same location as the target stimulus on the previous trial for the 2-position condition ($M = 0.612$) than either the 4- or 8-position conditions ($M = 0.518$ and $M = 0.504$, respectively), which did not differ from each other. Furthermore, only the 2-position condition excluded 0.5 from its 95% CI suggesting that the location repetition resulted in a significant bias only in the 2-position condition, consistent with the results from the first analysis.

Discussion

The results support the idea that participants do engage a top-down stimulus set selection strategy involving possible target locations when choosing a task to perform during voluntary task switching. First, the effect of stimulus availability varied as a function of the position condition such that the impact of the external environment was reduced in the 2-position condition. Following the predictions based on ECTVA (Logan & Gordon, 2001), a stimulus set selection strategy, represented as a π value set high for one possible target location, should reduce the advantage in a race for categorization associated with the first stimulus to appear. As further evidence that such a strategy was implemented, targets appearing in the location of the target responded to on trial $n-1$ had an increased probability of being the task selected on trial n for the 2-position condition consistent with an account where the filtering of target stimuli based on a particular location is continued across some proportion of trials. While repetition priming can result from both top-down and bottom-up factors (Lamb, Pond, & Zahir, 2000), the current pattern likely does not represent bottom-up repetition priming given that it was not seen across all position conditions.

Examining the pattern of effects across the position condition more closely, both the stimulus availability and location repetition effects showed a binary pattern across the three different levels of the position variable. In the 2-position condition, there was both no effect of stimulus availability and also a large effect of location repetition. The pattern was reversed in both the 4- and 8-position conditions with a significant effect of stimulus availability and no effect of location repetition. Importantly in neither measure did the 4- and 8-position conditions differ significantly from each other, and for the $p(S1)$ measure the pattern of means was in the opposite direction of that predicted if subjects were attempting to employ the stimulus set selection strategy. This pattern suggests that subjects were selective in their use of a stimulus set selection strategy, limiting the strategy to only the 2-position condition, when this strategy would always allow for task selection based on responding to the target appearing in the selected location. The pattern of results is not consistent with a general use of the stimulus set selection strategy across conditions with a decreasing effectiveness of the strategy with increasing numbers of positions.

Experiment 2

The displays in Experiment 1 were sparse: two stimuli appearing to replace identical placeholders. The sudden onset of the target stimuli may have been sufficient to rapidly guide attention to a target location (Yantis & Jonides, 1990), thus diminishing the need for a top-down strategy for selecting target positions. In Experiment 2, the two targets appeared embedded within six distractor stimuli. The targets and distractors appeared sequentially, one every 34 ms, resulting in a dynamic and visually cluttered display where sudden onsets do not serve as an indicator of target location. In such an environment, top-down control of visual attention, such as that proposed in the stimulus set selection strategy, may be more likely to appear when bottom-up cues are absent. The presence of distracting stimuli in the environment can substantially alter the deployment of selective attention (Lavie, 1995) and may alter the use of a stimulus set selection strategy.

Method

Participants—Nineteen undergraduates completed the experiment in exchange for partial course credit. All subjects reported normal or corrected-to-normal vision. Data from three participants were excluded due to accuracy levels below 80%.

Tasks and design—The basic task structure and experimental design was the same as Experiment 1. The position variable included two, four, or eight positions. The two SOAs were 34 and 102 ms resulting from the ordering of the two target stimuli within the sequential onset of target and distractor stimuli in the display array.

Stimuli and apparatus—The apparatus for stimulus presentation and response recording remained the same as Experiment 1, as did the basic stimuli for each task. In addition to the letter and number stimuli, a set of symbol distractors, !, @, \$, {, >, and ?, in the same font, size and color as the target stimuli appeared on every trial occupying the locations not devoted to the potential target stimuli (see Figure 1B). The spatial layout of the 2-, 4-, and 8-position conditions was the same as Experiment 1, except that placeholders appeared in all

eight positions even when only two or four positions served as potential target locations. Otherwise, all stimulus characteristics were the same as Experiment 1.

Procedure—Trials began with a fixation screen containing a cross and eight # symbol placeholders presented for a 1000-ms RSI. The target and distractor stimuli then appeared, replacing the placeholders, at a rate of one every 34 ms until all eight positions contained a letter, number, or distractor stimulus. Stimuli appeared in the eight positions in a pseudorandom fashion. The two target stimuli appeared either sequentially or separated by two distractor stimuli, to generate the 34- and 102-ms SOAs. The target stimuli never appeared first or last in the sequence of stimuli. For the 34-ms SOA condition, S1 appeared second, fourth, or sixth in the sequence. For the 102-ms SOA condition, S1 appeared second, third, or fourth in the sequence.

As in Experiment 1, subjects completed individual task practice followed by voluntary task switching instructions and practice with the full procedure. Subjects then completed 18 60-trial blocks. Subjects completed three sessions on separate days, one for each position condition. The session order was counterbalanced across subjects, though with the loss of subjects as described above this counterbalancing was imperfect.

Results

Task choice and performance measures were calculated as in Experiment 1. Trimming of the first trial of each block, error trials, and the trials following errors removed 11.0% trials. RT trimming further removed 2.5% of the trials. Again subjects showed a standard RT switch cost ($M = 100$ ms, $F(1, 15) = 28.3$, $p < .05$, $\eta^2_p = .654$). Additionally, performance slowed as the number of possible target positions increased ($M_s = 797, 879$, and 950 ms, for the 2-, 4-, and 8-position conditions, respectively, $F(2, 30) = 9.5$, $p < .05$, $\eta^2_p = .387$), suggesting that the visual clutter induced by the distractor stimuli did disrupt task performance more as the location uncertainty increased.

Figure 2B displays the $p(S1)$ values as a function of position and SOA. As can be seen in the graphs, the pattern largely replicates Experiment 1. A 3 position (two, four, and eight) by 2 SOA (34 and 102 ms) repeated-measures ANOVA showed a significant interaction of the two factors, $F(2, 30) = 5.7$, $p < .05$, $\eta^2_p = .277$, which was broken down to consider the simple effects of position at each SOA. For the 34-ms SOA, where any effect of stimulus availability is expected to be small, the effect of position was marginally significant, $F(2, 30) = 2.7$, $p < .1$, $\eta^2_p = .154$, with LSD contrasts indicating a significant difference between the 2- and 4-position conditions. Further, only the 4-position condition had a mean estimate that excluded 0.5 from the 95% CI. For the 102-ms SOA where the effect of stimulus availability is expected to be robust, the effect of position was significant, $F(2, 30) = 6.1$, $p < .05$, $\eta^2_p = .290$, with LSD contrasts indicating that the 2-position condition differed significantly from both the 4- and 8-position conditions, which did not differ from each other. Finally, all three position conditions had mean estimates that excluded 0.5 from their 95% CIs.

The effect of location repetition is shown in Figure 3B. Again, the pattern of data largely replicated that seen in Experiment 1, with a numerically larger effect of location repetition in

the 2-position condition than in the 4- and 8-position conditions. A 2 stimulus order (S1 and S2) by 3 position (two, four, and eight) by 2 SOA (34 and 102 ms) repeated-measures ANOVA revealed a significant main effect of stimulus order, $F(1, 15) = 33.4, p < .05, \eta^2_p = .690$, but only a marginally significant effect of position, $F(2, 30) = 2.7, p < .1, \eta^2_p = .153$. While numerically the largest effect, the 2-position condition ($M = 0.587$) did not differ significantly from either the 4- or 8-position conditions ($M = 0.516$ and $M = 0.539$, respectively). Finally, only the 8-position condition excluded 0.5 from its 95% CI. One caveat to these analyses should be considered: the 2-position condition had a large variability that drove the unclear results of this statistical test. However further examination of that variability is informative when considering whether subjects adapted a stimulus set selection strategy in that condition. While on average there was a larger location repetition effect in the 2-position condition, two subjects actually showed a dramatic (~15–18%) shift toward *fewer* task repetitions when the position repeated in the 2-position condition compared to the 4- and 8-position conditions. This pattern is suggestive of the implementation of a stimulus set selection strategy in the 2-position condition that involved actively shifting the attention weights between the two target positions from trial to trial.

Discussion

In a more cluttered stimulus environment designed to encourage the top-down selection of position, the pattern of results again indicated the use of a stimulus set selection strategy. Considering just the long SOA condition comparable to Experiment 1, Experiment 2 replicated the basic effect of number of target positions on $p(S1)$ showing a reduction in the bias toward the first stimulus to appear in the 2-position condition as compared to the 4- and 8-position conditions. These results support the hypothesis that top-down stimulus set selection may drive task selection resulting in decreased stimulus-driven influences on task selection. Further, there is some limited evidence that in the more demanding visual environment, where abrupt stimulus onset is not a useful exogenous cue for a target stimulus, subjects may be attempting to use a top-down stimulus set selection strategy more broadly. The location repetition effect was significantly different from .5 for the 8-position condition, suggesting that subjects may be using such a strategy even when the top-down selection of a position prior to target onset does not guarantee that a target will appear at the selected location. However, the lack of a significant location repetition effect in the 2- and 4-position conditions makes drawing strong conclusions from these data unwarranted.

General Discussion

Voluntary task switching requires subjects to perform in a multitask environment where they must select which task to perform on each trial (Arrington & Logan, 2004). While the task was designed to encourage the engagement of top-down cognitive control over task selection processes, the factors that influence task selection in this environment have been shown to involve both top-down and bottom-up processes (Arrington, 2008; Demanet, et al. 2010; Mayr & Bell, 2006; Yeung, 2010). While the top-down selection of a task is generally thought of in terms of the intention to perform a specific task and the subsequent task preparation (Arrington, Reiman, & Weaver, 2014), the current experiments demonstrate that this choice may sometimes be accomplished through the selection of a task-irrelevant

stimulus characteristic that is independent of task identity. Evidence for this conclusion comes from the findings that 1) the influence of bottom-up effects of stimulus availability decrease as position uncertainty decreases allowing for effective use of a location-based stimulus set selection strategy; and 2) the effect of repeating a target location on task selection decreases as the position uncertainty increases making such location-based selection less adaptive. Together these findings suggest that subjects may sometimes be guiding task selection in a top-down fashion in the absence of forming the intention to perform a particular task.

Evidence for the use of a stimulus set selection strategy raises some interesting theoretical questions about the process of task selection in voluntary multitask environments. Accounts of the task selection effects in voluntary task switching studies have generally assumed that subjects select a particular task to perform on each trial (e.g. subjects decide to perform the *number* task; Arrington & Logan, 2005; Mayr & Bell, 2006; Vandamme, Szmalec, Liefvooghe, & Vandierendonck, 2010; Vandierendonck, et al., 2012; Yeung, 2010). Similar to proposals in standard task switching studies (Kiesel, et al., 2010; Vandierendonck, et al., 2010), once a task goal has been established based on the interpretation of a task cue, for example as a task goal in declarative working memory (Rubinstein, Meyer, & Evans, 2001) or the task-level representation of the task set in ECTVA (Logan & Gordon, 2001), then task preparation or task set reconfiguration (Rogers & Monsell, 2005) can occur. Such task preparation is generally thought to involve retrieving aspects of the appropriate task set from long term memory (Mayr & Kliegl, 2000), resolving interference from competing task sets (Yeung, Nystrom, Aronson, & Cohen, 2006), and establishing task-specific attentional weights (Meiran, 2000). Recently such task selection and task preparation processes have been shown to be at least partially dissociable in voluntary task switching (Poljac & Yeung, 2014). Here focusing specifically on the task selection processes, the current results suggest that task selection may not require the instantiation in working memory of a goal to perform a particular task. Subjects may instead determine the task to be performed on the basis of establishing a top-down stimulus set that is independent of the specifications of a particular task. In terms of ECTVA, this process would equate to setting a high π value for a particular target location, which in the current experimental environment is task irrelevant.

It is worth noting that the idea of task selection via a particular stimulus set differs from the notion of a stimulus-set component of the task set as described by Meiran (2000). In that case, the stimulus set is specific to the stimulus characteristics that are relevant for a particular task set (e.g. attention to color vs attention to shape as in Arrington, Altmann, & Carr, 2003) and is established following the interpretation of a task cue indicating what stimulus characteristic will be relevant to performance of the intended task. In the current situation, the notion of using a stimulus set selection strategy refers to setting attention weights for particular target locations, which in the current pair of tasks is a stimulus characteristic that is task irrelevant. Such a location-based attentional control setting will enhance processing of whatever stimulus appears at the attended location regardless of the task with which it is associated (Posner, 1980; c.f. Klein, 1994). This distinction between task relevant and task irrelevant uses of the stimulus set does not imply that the processes of establishing the stimulus set are any different, but that they occur for different reasons. As

Meiran and others have developed the idea, the stimulus set is established because it is relevant to the current task goal. As we are using the idea of a stimulus set in the current argument, the relationship is flipped such that a task is selected because the relevant stimulus for that task is associated with a pre-established stimulus set.

While it appears that some sort of stimulus set selection strategy is likely to be occurring in the current multitask environment, the evidence for how that strategy is implemented is less clear. In Experiment 1 both the $p(S1)$ and location repetition analyses across the position conditions showed the binary pattern of position, with the 2-position condition resulting in a different pattern of responding than the 4- and 8-position conditions, which did not differ significantly from each other. This pattern favors an interpretation that the stimulus set selection strategy was used only in circumstances where the strategy would always lead to a target appearing at the attended location. In terms of ECTVA (Logan & Gordon, 2001), the executive only sets π values for a particular location when that location will always contain a target, thus diminishing of the advantage for categorizing S1 found at the long SOA only in the 2-position condition. In Experiment 2 where the stimulus environment was more cluttered, the pattern was less clear. While statistically the $p(S1)$ data showed the same binary pattern as Experiment 1, there appears to be a slight graded effect of position on the stimulus availability effect with the 8-position condition showing a greater bias than the 4-position condition. Additionally the location repetition data suggested that even with high position uncertainty in the 8-position condition, subjects appeared to use the stimulus set selection strategy at least to some extent. These results may suggest that the strategy was applied across all conditions (i.e. π values were set by the executive on at least some of the trials across all position conditions), but the systematic change in relative attention weights resulting from increases in the number of positions diminished the effect monotonically. These differences between the patterns of results in Experiments 1 and 2 suggest that factors in the multitask environment, such as visual complexity, likely influence when subjects will use the stimulus set selection strategy.

The current results have important theoretical implications for models of task selection in voluntary task switching. In order to gain some control over the experimental environment and ensure that subjects switch tasks, most voluntary task switching experiments instruct subjects to perform tasks in a random order. Explanations of choice behavior under these instructions suggest that subjects attempt to select task sequences that match an internal representation of randomness either by maintaining the sequence of recent tasks in working memory (Arrington & Logan, 2005) or retrieving task sequences from long term memory (Vandierendonck, et al., 2012). In these accounts, the top-down strategies for maintaining a random task order are occasionally overcome by bottom-up intrusions of tasks through availability of a recently performed task or stimulus-based priming (Arrington, Weaver, & Pauker, 2010; Demanet, et al., 2010; Mayr & Bell, 2006). The current results suggest that rather than performing such active selections of a task sequence, subjects may be “outsourcing” the control needed to maintain a random sequence of tasks to the environment by selecting a target location and responding to the target appearing at that location. With the positions for the letter and number targets determined randomly, this strategy should result in random task selection. Given the cognitive load placed on subjects by the demand

to produce random sequences (Baddeley, Chincotta, & Adlam, 2001), strategies that limit this load through outsourcing the task sequencing to the environment are in line with the tendency for subjects to make choices to decrease cognitive load (Kools, McGuire, Rosen, & Botvinick, 2010). However, outsourcing of control is likely not limited to situations when subjects are trying to maintain a particular pattern of selecting random sequences. Indeed, such outsourcing of control to the stimulus environment has been suggested in other task switching paradigms (Mayr & Bryck, 2007). Further research will need to consider whether changes to the task demands, such as in less constrained multitask environments where random instructions are not provided, show evidence of systematic changes in the use of stimulus set selection strategies. Considering the broader spectrum of multitask environments confronted in everyday life, while rarely accompanied with instructions to perform tasks at random, many other demands in the environment may lead to increased cognitive load and thus the need to outsource task choice during volitional behavior. A mother straightening the playroom at the end of the day may allow the order in which she perceives each object as she moves through the room to determine the task sequence of placing books on the shelf or tossing toys in the chest rather than actively selecting a task (e.g. place books on shelf) in advance, preparing to perform it, then searching for the objects that support that task.

Given the benefit in terms of reduced cognitive demands to perform a random sequence when using the stimulus set selection strategy during voluntary task switching, it is noteworthy that even in the 2-position condition, where the strategy always results in attending to a target location, it appears that the strategy was only used on a minority of trials. This pattern might arise because only a small number of subjects use the strategy but implement it consistently, or because a larger number of subjects use the strategy but implement it inconsistently. Further consideration of the location repetition effect for individual subjects suggests that the pattern might arise from both mechanisms. In both Experiments 1 and 2 there were three subjects who appear to have used the stimulus set selection strategy on at least 50% of trials, seven subjects who appear to have used the strategy on between 10% and 50% of trials, and the remainder who show no evidence of having used the strategy. Thus, while the majority of subjects seem to adopt the strategy for some proportion of trials, the results suggest that the strategy is largely implemented inconsistently across the session¹. Examination of the first and second half of the session suggests that this is not a global shift across the course of the experiment as there were no systematic changes in performance from the first to second half of the experimental sessions. Shorter-term fluctuations in cognitive control over time may well play a role in the shifting of strategy use during volitional behavior (Leber, Turk-Browne, & Chun, 2008).

In addition to the theoretical implications, the current studies make a clear methodological point. Researchers interested in studying the explicit formation of an intention or a goal to perform a particular task should be aware that performance in voluntary task switching may not always reflect such a process. The voluntary task switching paradigm is generally run with a single response to the target stimulus used to assess task selection as well as measure

¹We thank André Vandierendonck for suggesting this consideration of individual differences in the application of the stimulus set selection strategy.

task performance. A good alternative would be to use a double registration variant of voluntary task switching, which requires a response to a prompt indicating which task has been selected (Arrington & Logan, 2005) before the target display appears. When subjects indicate the task to be performed prior to the onset of the target display, the influence of top-down processes such as the stimulus set selection strategy, as well as bottom-up stimulus-based processes (Arrington, 2008; Arrington, et al., 2010; Demanet, et al, 2010; Mayr & Bell, 2006), are likely greatly diminished (c.f. Millington, Poljac, & Yeung, 2013).

Finally, it is worth noting that both the basic stimulus availability effect and the stimulus set selection strategy point toward a role for visual attention mechanisms in task selection in multitask environments. Exogenous orienting to a sudden onset stimulus, such as the appearance of S1, may mediate the effect of the stimulus environment on task choice (Yantis & Jonides, 1990). Further investigations employing direct manipulations designed to elicit attentional capture or measuring eye movements may provide an avenue for consideration of this relationship. Endogenous deployment of visual attention such as that involved in the stimulus set selection strategy put forth in the current work may serve as a way in which top-down control over task selection is implemented. The varied roles of exogenous and endogenous orienting of visual attention (Posner, 1980; Yantis, 2000) in the processes engaged in volitional behavior in multitask environments should be addressed more specifically in future research.

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Figure 1.

A) Example trial line depicting displays in a sample trial for the 4-position condition. Displays not shown to scale. B) Examples of the final target displays for the 2-, 4-, and 8-position conditions from Experiment 1 and for Experiment 2.

Figure 2.

Probability of performing the task associated with stimulus 1, $p(S1)$, as a function of position condition and SOA for Experiment 1 (panel A) and Experiment 2 (panel B). Error bars represent 95% confidence intervals calculated based on the standard error of the mean for each cell in the design.

Figure 3.

Probability of performing the task associated with the stimulus in the location repeated from trial $n-1$, $p(\text{Location Repetition})$, as a function of position condition and stimulus order (S1 or S2) for Experiment 1 (panel A) and Experiment 2 (panel B). Error bars represent 95% confidence intervals calculated based on the standard error of the mean for each cell in the design.