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**On How to be Unpredictable:
Evidence from the Voluntary Task-Switching Paradigm**

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Abstract

The voluntary task-switching paradigm (Arrington & Logan, 2004) requires "random" selection between tasks and promises a window into executive task selection independently of exogenous influences present in standard task-switching situations. We show here that the degree to which subjects perserverate tasks across trials captures unique individual differences variance, but also that the switch rate is under strong stimulus-driven control: "Voluntary" switches are much more frequent when the stimulus changes than when it repeats. Most importantly, we show that individuals whose no-switch trials are selectively slowed exhibit less perseveration and stimulus-driven effects (and thus more "voluntary" selection). We suggest that selective slowing indicates a strategy of treating trials as discrete events--possibly through inhibition of the preceding task. These results not only demonstrate massive "non-voluntary" influences on voluntary selection that are largely independent of standard task-switching measures but also how such influences can be counteracted through strategic adaptations.

(144 words)

**On How to be Unpredictable:**
**Evidence from the Voluntary Task-Switching Paradigm**

Sometimes it pays to be unpredictable. A tennis player hitting the ball in the corner the opponent did not prepare for or a negotiator catching her counterpart off guard by making an unanticipated overture, will often profit from their unpredictable behavior (e.g., Glimcher, 2003). However, being unpredictable is hard. Not only are there known biases in people's conception of randomness (e.g., the gambler's fallacy). In most natural situations, being unpredictable is in essence an executive control problem because it requires insulating one's decision against "contextual" influences. One important source of influence is the recent history of one's own choices (Baddeley, 1966). For example, it should be easier to reuse a just-implemented plan of action than changing to a new plan (e.g., Rogers & Monsell, 1995), which in turn should lead to a perseveratory tendency in sequences of action choices. In fact, this is what Arrington and Logan (2004) recently showed for a situation that required "random" selection between two competing tasks on a trial-by-trial basis. Subjects switched only on around 35% of the trials, even though "true" random selection would have required a 50% switch rate. This is remarkable given that usually, when asked to produce a random binomial sequence, people tend to show an increased alternation rate (i.e., the gambler's fallacy). Thus, the voluntary task-switching paradigm allows to assess a bias towards perseveration and it seems tempting to interpret this bias in terms of the degree to which voluntary control can override the pull towards sticking with the currently most active task set.

A second obstacle in the way of randomness can come from environmental events that habitually trigger certain action tendencies (e.g., in tennis, an opponent player on the right side of the field may bias one to hit the ball into the left side of the field). In the present work, we will show that in a situation in which people are asked to make random selections between two tasks, an important source of influence is whether or not the stimulus situation changes across trials (see also Arrington & Logan, 2005). Stimulus changes prompt subjects to switch to the alternate task whereas stimulus repetitions induce task repetitions. Thus, the voluntary switching paradigm allows capturing two strong influences on random selection: the perseveration bias and the effect of stimulus repetitions/changes. Obviously, in competitive situations, an opponent could use either type of influence to predict one's own future actions (Glimcher, 2003; Rapoport & Budescu, 1992).

Both the perseveratory bias and the stimulus-repetition bias are interesting phenomena, but do they actually tell us something new that we cannot learn from the standard way of assessing executive task control? And if yes, what is the novel aspect that becomes apparent only when people try to make random task choices? These are the questions we will address in the remainder of this paper.

## Voluntary versus Standard Task Switching

Whereas in the voluntary switching paradigm introduced by Arrington and Logan (2003) subjects are free to choose between tasks on each trial, in the standard switching paradigm a task cue or a sequential rule ("switch every two trials") is necessary to inform subjects which task is currently required. The standard paradigm has become a widely-used tool for studying executive control. Specifically the switch cost, that is the response-time (RT) difference between trials after a switch in task compared to trials after a task repetition are supposed to reflect in some manner the demands of changing task-relevant cognitive configurations (e.g., Monsell, 2003; but see Logan & Bundesen, 2003). An additional phenomenon that will play a critical role in the current paper is the fact that not only switch RTs, but also no-switch RTs from a task-switching block show marked increases in response times when compared to RTs from single-task blocks. These, so called mixing costs or global costs, reflect the general demands of having to select between tasks on a trial-to-trial basis, even when no actual change in task is required (e.g., Mayr, 2001; Meiran, 2000).

Arrington and Logan (2004) had argued that standard task-switching procedures may fail to elicit true, endogenous control, simply because subjects are not free to select tasks according to an internal process, but rather need to adhere to external prompts or instructed sequential rules. Thus, the voluntary paradigm may capture something about executive control that is not represented in the standard paradigm. This hypothesis, however, remains to be tested. For example, an individual may simply be less willing to switch if for him or her, switching is hard (i.e., takes a long time). In this case, the switch rate may represent no unique individual differences variance over and above what is already represented in standard switch costs. If the voluntary switching paradigm provides a unique way of assessing executive control then we expect to find measures that can be reliably established within the voluntary paradigm but that are relatively independent of traditional switching measures. As our results will show, the voluntary switch rate, and with some qualifications, also the effects of stimulus repetitions/changes capture a surprisingly large amount of both reliable and unique individual differences variance.

*Overcoming Non-randomness*

The finding that switch rate as well as the dependency of switch rate on stimulus repetitions/changes are fairly independent of standard task-switching measures leads to the final and most important question: What exactly is the unique aspect about voluntary task choice captured by these variables? And more specifically: Can we identify factors that allow overcoming the obstacles in the way of random task selection? Optimally, such random selection implies that each trial is processed in isolation, amnesic towards task choices or stimulus events on previous trials (Baddeley, 1966). Thus, one might speculate that those subjects who manage to approach each trial as a discrete event, rather than a continuous flow of interdependent selection instances, should be particularly successful in resisting perseveration or stimulus influences. On a mechanistic level, such a discrete-event strategy might be achieved by actively suppressing the most recent trial event, thereby clearing the slate for an unbiased decision on each new trial. Mayr and Keele (2000) have provided evidence for task-set inhibition in form of the so-called backward-inhibition effect (i.e., slower RTs when returning to a recently abandoned task). If subjects use inhibition during voluntary selection then we should expect that for those cases in which a previous-trial task is reselected, this task should be still suppressed and therefore take longer to reactivate. In other words, we predict that global costs assessed in the voluntary paradigm (i.e., voluntary no-switch RTs minus single-task RTs) but not voluntary switch costs are positively related to switch probability.

## The Present Study

In order to examine to what degree the voluntary switching measures capture reliable and unique individual differences variance, we assessed both voluntary and standard switching across two different sets of tasks. The first set of tasks (henceforth "Number tasks") was taken from Arrington and Logan (2004) and involved making either odd/even or larger/smaller than 5 judgments for numbers between 1 and 9 (omitting 5). The second set of tasks (henceforth "Spatial tasks") required making either spatially compatible or incompatible responses to the spatial location of a circle. In order to make the standard switching paradigm as comparable as possible to the voluntary switching paradigm, we used an alternate-runs paradigm (Rogers & Monsell, 1995) where subjects are asked to switch every two trials, but different from the usual procedure, we gave no external sequencing support. Thus, in terms of external stimulation, the voluntary and the standard paradigm were identical.

Stimulus repetitions are relatively rare in the Number tasks (i.e., p=.125) and therefore may not play a very prominent role. Therefore, our second set of tasks (the Spatial tasks) maximizes the potential role of stimulus repetitions/changes: With only two possible stimuli (a circle either near the top or the bottom of a vertically enlongated frame) repetitions versus changes are very prominent events, each occurring on about 50% of trials.

## Method

### *Participants*

Seventy-two undergraduate students from the University of Oregon participated in this study (44 female) in exchange for course credits.

### *Materials and Procedure*

On each trial of the Number tasks, a digit from 1 to 9 (excluding the digit “5”) was presented within a centrally located square, 4.7 cm x 4.7 cm, white frame. The digits were presented in red on a black background. Depending on task, subjects made a "lower versus higher than 5" judgment, or an odd/even judgment. For the high/low task, subjects used the "7" key if the digit displayed was greater than 5 and "4" key if the digit was less than 5. In the odd/even task, subjects pressed the “-” key for even digits, and the “+” key for odd digits

On each trial of the Spatial tasks, a large red dot on a black background appeared either at the top or the bottom within a 14.3 cm x 4.7 cm, vertically oriented rectangular frame. For the compatible task, participants pressed with their left index finger the keys “7” and “4" on the numerical keypad (which are vertically aligned) according to the dot position. In the incompatible task either the “-” key and “+” key (also vertically aligned on the numerical keyboard) had to be pressed, but now the top key had to be used for the bottom location and vice versa. The stimulus remained on the screen until a correct response was given.

Across all tasks, the stimulus appeared 100 ms after the previous-trial response and remained on the screen until the response was entered. In case of an error, the stimulus simply stayed on the screen until the correct response was entered.

All subjects first worked through a total of twelve 48-trial blocks with the Spatial tasks and then through twelve 48-trial blocks with the Number tasks. For both task domains, the same basic sequence of blocks was used. The first two blocks tested single-task performance (Spatial: compatible for blocks 1 and 2, incompatible for blocks 3 and 4; Number: high/low for blocks 1 and 2, odd-even for blocks 3 and 4). Blocks 5-8 used the voluntary switching procedure and blocks 9-12 the standard switching procedure. For every change in block type, there was an on-screen instruction (with supporting instruction from the experimentor) and a 16-trial practice block that could be repeated on demand. For the voluntary switching block, subjects were asked to choose tasks as randomly as possible on a trial-by-trial basis, "much like a coin toss" (exact instructions were closely modeled after Arrington & Logan, 2004).

For the standard switching procedure subjects were asked to work through the block in an AABB schema (where compatible was A for spatial tasks and high/low was A for number tasks). In case of an error, the stimulus stayed on the screen and the AABB schema appeared with the current sequence position marked. Only after the correct response was entered, the next trial was initiated.

## Results and Discussion

Error trials and trials following errors, as well as RTs greater than 5000 ms were not considered for further analysis. Table 1 shows mean RT and error scores form all conditions. As error results confirmed RT results they will not be further considered here. Across both tasks there were substantial, and in all cases highly reliable ($p<.01$) differences between the single-task and the no-switch condition (global costs) as well as between the no-switch and the switch condition (switch costs). Replicating the results by Arrington and Logan (2004) we found a strong perseveratory tendency in the voluntary conditions. The switch rate was .30 for the Spatial tasks and .38 for the Number tasks. In both cases, the $p=.5$ value expected in case of random selection was far outside the confidence interval around these values.

### *Stimulus-controlled Volition?*

Are "voluntary" task choices truly endogenous, or are they affected by prominent stimulus events, such as stimulus repetitions versus changes? Figure 1 shows the proportion of total number of switches for stimulus repetitions versus changes. As apparent, the stimulus repetition/change factor has a dramatic effect on switch probability, with more than twice as many switches in case of stimulus changes than in case of repetitions for the Spatial tasks, $F(1,71)=120.01$, $p_{rep}>.99$, $eta^2= .63$, and with about 30% more switches in case of stimulus changes in the Number tasks, $F(1,71)=34.84$, $p_{rep}>.99$, $eta^2= .33$. The difference in repetition effects across tasks was also reliable, $F(1,71)=19.89$, $p_{rep}>.99$, $eta^2= .22$, and is probably due to the fact that stimulus changes are less prominent events in the Number tasks.

*Does the Voluntary Paradigm Capture Unique Individual Differences Variance?*

The correlation between switch rates for the Spatial and the Number tasks was surprisingly high, $r=.82$, $p_{rep}>.99$, (see Table 2). Thus, switch rate reflects an individual differences characteristic that generalizes across different tasks. As shown in the diagonal of Table 2, and broadly consistent with other psychometric studies of task switching (e.g., Kray & Lindenberger, 2000; Miyake, Friedman, Emerson, Witzki, & Howerter, 2000) also the remaining measures show substantial, albeit somewhat smaller, between-task correlations. We will report the following analyses on the level of across-task aggregates and we will mention task-specific results only where they deviate form the aggregate pattern.

In order to determine whether the switch rate captures not only reliable but also unique variance, we need to examine to what degree it is related to standard switch measures. As apparent from Table 2, the ability to switch fast translates into a somewhat higher switch rate in the voluntary paradigm. However, it is also obvious that with a correlation of -.24, $p_{rep}>.88$, switching speed captures only a small part of the variance contained in the switch rate. Also, as shown in Table 2, there was no correlation between the standard global score and switch probability. Thus, the switch rate actually does provide reliable information that is not available in the standard task-switching paradigm.

With regard to the core task-switching measure, the switch costs, the correlation across paradigms was .68, $p_{rep}$>.99. Thus, in this regard the voluntary and the standard paradigm seemed to capture highly overlapping information. This may be due to the fact that in our version of the standard paradigm subjects had to exert a great deal of top-down control and results may have been different with more bottom-up task-selection support in form of task cues (Meiran, 1996) or sequencing support (Rogers & Monsell, 1995).

To explore to what degree the susceptibility to stimulus influences forms a stable construct, we correlated the ratio between switch rate for stimulus changes versus repetitions. The relationship was reliable, albeit relatively small, r=.26, $p_{rep}$>.88, possibly reflecting the different roles this factor plays in the Spatial and the Number tasks. There were no reliable relationships with either standard global costs or switch costs.

To what degree are individuals with overall high switch rate also those who are more resistant to the stimulus influence? The relevant correlation was substantial when aggregating across both tasks, r=-.51, $p_{rep}$>.98 (spatial: r=-.61, p<. $p_{rep}$>.99, number: r=-.30, $p_{rep}$>.88) suggesting that individuals who switched frequently were also more independent of the stimulus repetition/change factor.

Summarizing this far, susceptibility to the perserveration bias and the stimulus repetition effect constitute reliable individual-differences measures (the switch rate more so than the stimulus repetition effect) and these two constructs share a considerable amount of variance. The next question is whether we can elucidate factors that account for the individual differences in the degree to which random, unbiased choices are made.

*Overcoming Non-Randomness*

In the introduction we had suggested that subjects might adopt a discrete-event strategy by inhibiting the most recent task in order to resist the tendency to perserverate the last-trial's task. Such a strategy should make it relatively speaking, harder to repeat a task (because it had just been inhibited), which in turn should translate into a positive relationship between global costs (i.e., the no-switch RTs assessed in the voluntary procedure minus the single-task RTs) and switch rate. The predicted correlation between global costs and switch probability was substantial ($r=.67$, $p_{rep}>.99$; see Table 2), and as shown in Figure 2, very orderly. The high correlation is the more striking as the correlation between the switch rate and the standard global cost was near zero (see Table 2). This pattern strongly suggests that voluntary, global costs reflect individual differences in strategic adaptations specific to the demand of making trial-to-trial decisions about the next task. It is possible that the tight relationship between the global cost and the switch probability simply suggests that if subjects generally slow down, then switch probability increases. If that was the case, the same relationship should also emerge when looking at switch RTs. However, the corresponding correlation was small and not reliable, $r=.07$, $p_{rep}>.6$. Figure 3 shows no-switch RTs and switch RTs for subjects split into three groups based on their voluntary switching frequency (left panel). As obvious, no-switch RTs were largest for subjects with high switch frequency and small stimulus change/repetition effects, whereas switch RTs showed no systematic effects.[1] The corresponding interaction between the switch factor and the frequency groups was reliable, $F(2,69)=6.69$, $p_{rep}>.98$, $eta^2=0.16$.

Stimulus repetitions/changes can only have an effect when the preceding-trial events are still present in memory. Thus, a discrete-event strategy as expressed in increased global costs might also help against the influence of stimulus repetitions. In fact, again we find a substantial negative correlation between voluntary global costs and the repetition effect, $r=-.43$, $p_{rep}>.99$ (Spatial: $r=-.63$, $p_{rep}>.99$; Number: $r=-.24$, $p_{rep}>.88$). Also, again, no corresponding effects were found for standard global costs (overall: $r=.05$, $p_{rep}>.6$; Spatial: $r=.13$, $p_{rep}>.77$; Number: $r=-.002$). The interaction between the switch factor and a three-way split of subjects in terms of frequency effects was reliable, $F(2,69)=6.69$, $eta^2=0.16$ (see Figure 3, right panel).

Finally, to what degree is the tendency to treat trials as discrete events, as indexed by the voluntary global cost, the driving force between the overlap in variance between the switch rate and the stimulus-repetition effect? Using partial correlation, we found that the first-order correlation between switch rate and the stimulus-repetition effect was reduced from .52 to .34 after controlling for voluntary global costs. This implies that 58% of the variance shared between the two measures was associated with voluntary global costs. Thus, the degree to which people adopt a discrete-event strategy explains a considerable amount of the variance shared between the two different ways in which subjects deviate from "true" random control.

## Conclusion

Arrington and Logan (2004) had speculated that the voluntary switching paradigm might reveal aspects of executive control that cannot be captured within the more constrained, standard paradigm. Our results generally confirm this speculation, but also elucidate critical factors that determine to what degree random task choices are actually achieved. In addition to replicating Arrington and Logan's (2004) basic result of a strong perseveration bias in "random" task choices we show that this tendency is highly reliable across different tasks and relatively independent of traditionally assessed switch measures. Furthermore, we show that task choice is not only influenced through the nature of the preceding task, but also through bottom-up stimulus factors. Specifically, stimulus repetitions promote voluntary task repetitions whereas stimulus changes promote voluntary task switches. Thus, it seems that even when subjects have full control over task choice, it is difficult to escape prominent bottom-up influences.

During the time of the revision process, Arrington and Logan (2005) published a paper that as a less-central aspect reports small effects of stimulus repetitions/changes on switch rate. From the small size of these effects the authors concluded that task choice is largely endogenous. Empirically, the difference to the present results is probably more apparent than real: Arrington and Logan only used the Number tasks, which also in the present paper exhibited smaller repetition effects than the spatial tasks and their analyses focused on the average effect across a range of inter-task intervals, whereas we had focused on a short inter-task interval. Theoretically, the present finding of massive stimulus-induced effects at least for certain conditions (e.g., prominent stimulus events and a short inter-task interval) demonstrates that in principle, the cognitive system is highly susceptible to exogenous influences during voluntary choice, even if these may not always become fully apparent.

With regard to the virtues of the voluntary switching paradigm the finding of strong exogenous influences contains both bad and good news. On the one hand it somewhat qualifies the claim that this paradigm is particularly suited to study endogenous control (Arrington & Logan, 2004, 2005). On the other hand, it shows that this paradigm is well suited to examine exactly those aspects that stand in the way of voluntary control.

Taking together the strong effects of prior task and stimulus changes/repetitions on task choice it may seem that there is little that is actually voluntary in the voluntary switching paradigm. However, we also identified an important individual-differences characteristic that modulates the degree to which subjects can operate independently of the recent past and/or prominent stimulus events. Empirically, this characteristic expresses itself in the fact that a selective slowing of no-switch response times (but not switch response times) in the context of the voluntary paradigm goes along with an increased rate of switching and a lower dependency on stimulus changes/repetitions. We suggest that selective slowing of no-switch RTs indicates a "discrete-event" approach to individual trials. One possible mechanism behind such an approach is the inhibition of the most recent task (Mayr & Keele, 2000; Mayr, Diedrichsen, Ivry, & Keele, in press). Inhibition of the most recent task should make it harder to re-access the same task in case of a no-switch decision, but should not interfere with selecting the alternate task. This is fully consistent with our finding that switch rate increased and stimulus-repetition effects decreased as a function of voluntary no-switch RT (global cost), but not as a function voluntary switch costs.

The conclusion that task-set inhibition is critical for a discrete-event strategy is indirect and based on correlational data. An alternative possibility is that longer no-switch RTs provide more opportunity for passive decay of the preceding task. However, in a follow-up experiment in which the inter-trial interval was varied between 100 and 1000 ms, we found only a small increase of switch rate for the longer interval and a reliable correlation between global costs and switch rate for both the short and the long interval. Finally, there is recent evidence from Philip and Koch (in press) suggesting that in a standard switching situation, task-set inhibition is larger when subjects switch between tasks frequently. This result is consistent with our proposal that task-set inhibition is under some strategic control and functionally linked to the frequency of switching.

In this work, the voluntary switching paradigm has proven useful for exploring both automatic memory- and stimulus-driven influences on voluntary selection, as well as what strategies individuals use to escape these influences. Thus, this paradigm seems well suited to capture the so far little understood processes involved when people try to be unpredictable in the face of executive-control constraints.

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# Author Note

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Footnotes

[1] There were also substantial correlations between voluntary switch costs and both switch probability (-.45) and the repetition effect (.35). However, global and local switch costs are mathematically non-independent because no-switch RTs enter the computations of each of the two scores. We used hierarchical regression to assess unique contributions of local switch costs after entering global costs as a first predictor. Voluntary switch costs as second predictor explained 14% variance of the switch rate and 10% of the repetition effect. These variance estimates dropped to 6% for both switch rate and the repetition effect if standard switch costs were entered as an additional predictor before entering the voluntary switch costs. Thus, while voluntary and standard RT switch costs alike represent efficiency of switching and are moderately related to both switch probability and repetition effect, there is a small, additional predictive component that is unique to voluntary switch costs.

Table 1. Mean RTs (SD) and error percentages (SD) for all relevant task conditions.

| | Spatial Tasks | | Number Tasks | |
|---|---|---|---|---|
| | RT | Errors | Mean | Errors |
| single task | 379 (70) | 2.5 (2.6) | 568 (80) | 4.1 (3.4) |
| standard noswitch | 607 (177) | 3.6 (2.8) | 647 (127) | 2.8 (2.3) |
| standard switch | 1018 (287) | 9.4 (7.0) | 1040 (265) | 6.0 (4.5) |
| voluntary noswitch | 499 (151) | 5.7 (6.2) | 762 (169) | 4.3 (4.0) |
| voluntary switch | 845 (248) | 14.1 (11.1) | 997 (237) | 6.5 (6.4) |

Table 2. Correlations between core variables, each averaged across Spatial and Number tasks. First-order correlations are shown above the diagonal; correlations after partialling out averaged, single-task baseline RTs are shown below the diagonal. The diagonal contains each variable's correlation between the number and the spatial tasks.

| | SGlobal | SSwitch | VGlobal | VSwitch | Rate | Rep. |
|---|---|---|---|---|---|---|
| SGlobal | .57** | .19 | .43** | .28* | .02 | .05 |
| SSwitch | .09 | .46** | .08 | .68** | -.24* | .16 |
| VGlobal | .40** | -.01 | .43** | -.11 | .67** | -.43** |
| VSwitch | -.06 | .54** | -.28* | .34** | -.45** | .36** |
| Rate | .14 | -.17 | .73** | -.43** | .82** | .51* |
| Rep. | .03 | .16 | -.45** | .42** | -.51** | 26* |

Note. SGlobal = standard global cost, SSwitch = standard switch cost, VGlobal = voluntary global cost, VSwitch = voluntary switch cost, Rate = voluntary switch rate, Rep. = relative stimulus-repetition effect on switch rate. Both types of global costs are computed by subtracting single-task baseline RTs from either standard or voluntary no-switch RTs. Both types of switch costs are computed by subtracting standard or voluntary switch RTs from standard or voluntary no-switch RTs. * = $p_{rep}$>.88, ** = $p_{rep}$ >.95.

Figure Captions

Figure 1. Mean switch rate as a function of stimulus repetitions versus changes for both the Spatial and Number tasks. Error bars reflect the 95% within-subject confidence interval associated with the repetition effect for each of the two tasks.

Figure 2. Scatterplots showing individual switch-rates as a function of voluntary global costs (left panel) and the relative stimulus repetition/change effect on switch rate as a function of voluntary global costs (right panel).

Figure 3. Voluntary global costs (no-switch RTs minus baseline RTs) and voluntary switch RTs (minus baseline RT) for three groups of subjects (n=24) varying in switch rate (left panel) and relative stimulus repetition/change effect (right panel). Error bars reflect the 95% within-subject confidence interval associated with the interaction between switch/no-switch and the group variable.

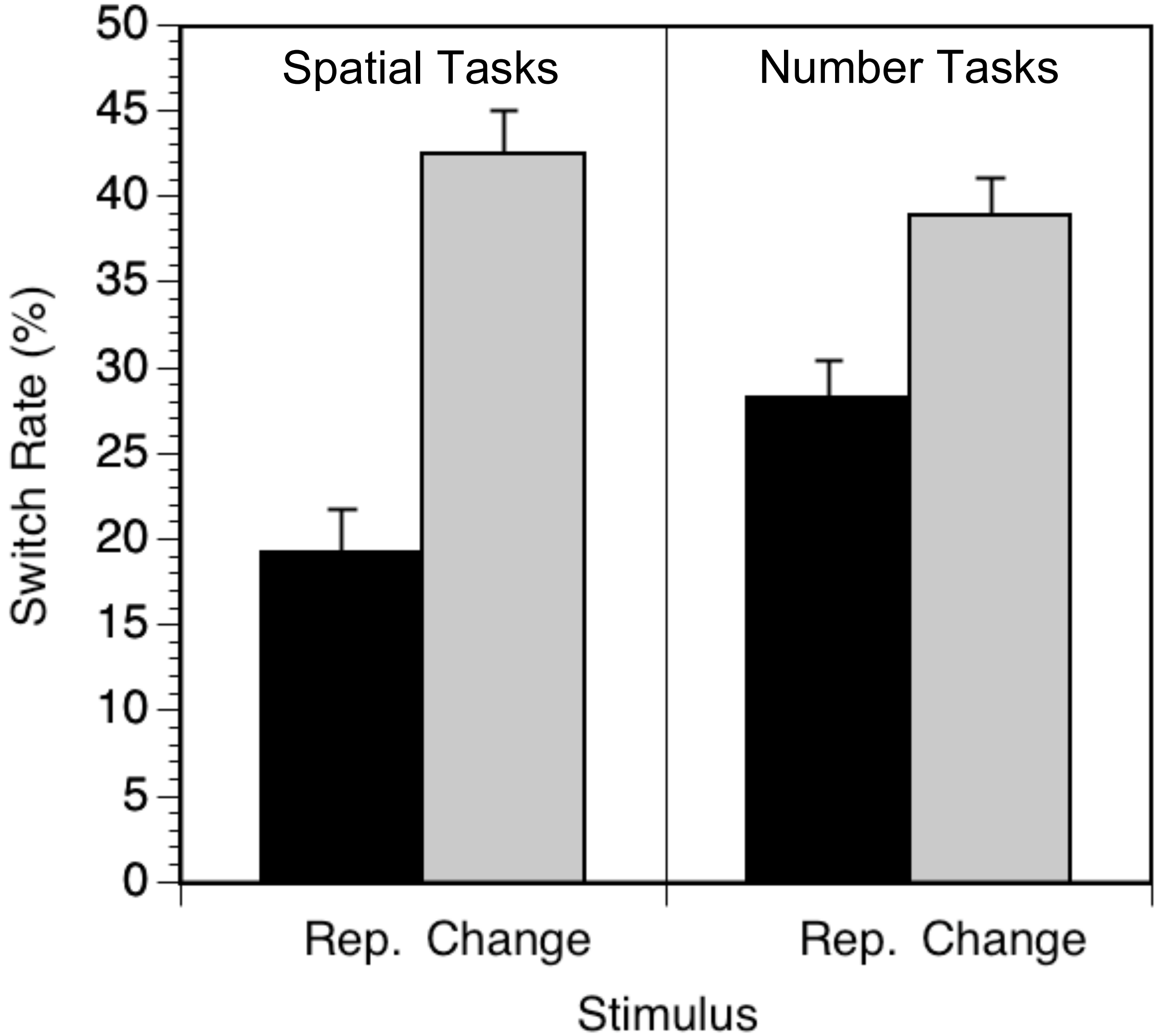
Spatial Tasks
Number Tasks
Switch Rate (%)
50
45
40
35
30
25
20
15
10
5
0
Rep. Change
Rep. Change
Stimulus

Figure 1

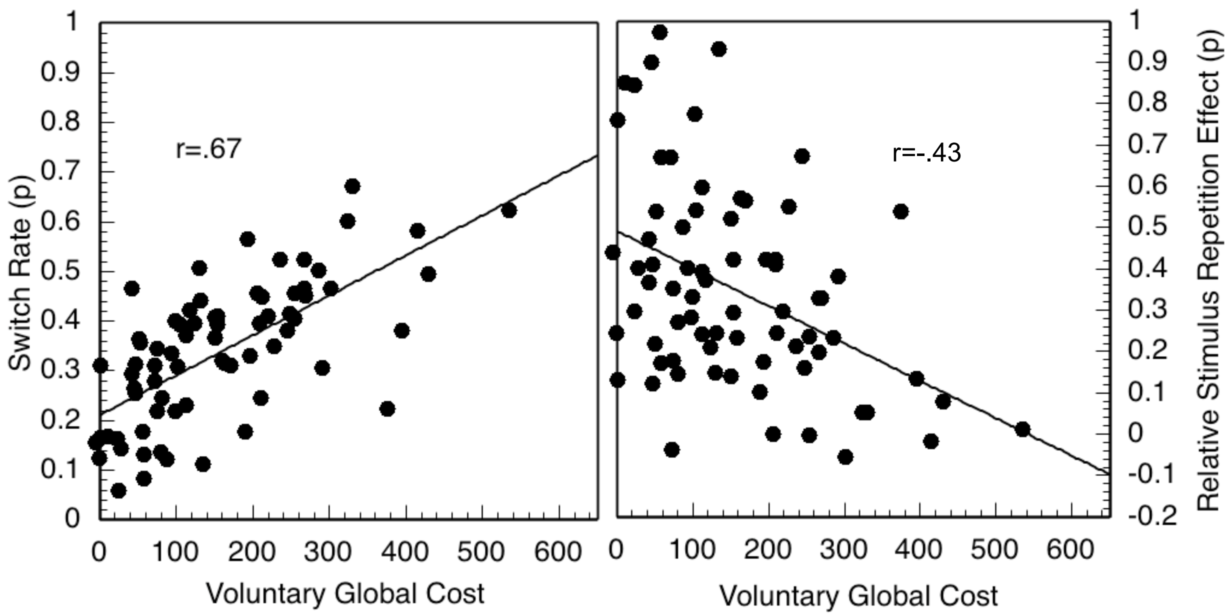
r=.67
Switch Rate (p)
Voluntary Global Cost
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
100
200
300
400
500
600
r=-.43
Relative Stimulus Repetition Effect (p)
-0.2
-0.1
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Voluntary Global Cost

Figure 2

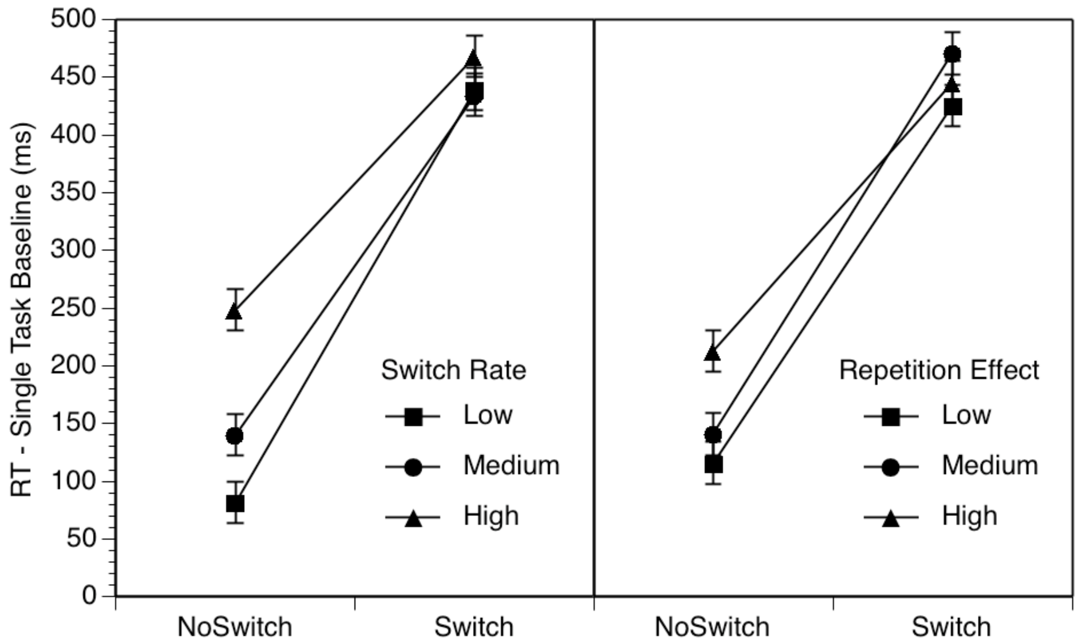
RT - Single Task Baseline (ms)
500
450
400
350
300
250
200
150
100
50
0
NoSwitch
Switch
NoSwitch
Switch
Switch Rate
Low
Medium
High
Repetition Effect
Low
Medium
High

Figure 3