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Understanding the cognitive miser: Cue-utilization in effort-based decision making☆

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ABSTRACT

The notion that individuals adapt their behaviors in ways that are sensitive to the effortfulness of cognitive processing is pervasive in psychology. In the current set of experiments, we provide a test of a cue-utilization account of how individuals decide which course of action is more or less effortful. In particular, we contrast the influences of time costs and demands on executive control with the influence of an available effort cue. Using a variant of the demand selection task (DST) that specifically focused on making effort-based decisions, we provide evidence that effort-based decisions can be dissociated from both time costs and demands on executive control in a manner predicted by a cue-utilization account.

The idea that humans adapt their behavior in an attempt to avoid effort is pervasive in psychology (e.g., Fournier et al., 2019; Gray, Sims, Fu, & Schoelles, 2006; Kool, McGuire, Rosen, & Botvinick, 2010; Risko & Gilbert, 2016; Solomon, 1948; Zipf, 1949). For instance, according to Zipf (1949), "…the entire behavior of an individual is at all times motivated by the urge to minimize effort" (p. 3). While individuals are clearly motivated by factors other than avoiding effort, indeed in some cases individuals pursue effortful activities, it seems clear that effort represents an important variable in individuals' decision making (Inzlicht, Shenhav, & Olivola, 2018). As such, understanding how individuals decide the relative effortfulness of different courses of action is critical. To this end, the present investigation considers three theoretical proposals regarding the information on which effort-based decisions may be made: time costs, demands placed on the executive control system, and available effort cues.

Understanding what individuals are minimizing when they attempt to avoid effort has been arguably dominated by two influential ideas. The first is that individuals look to minimize time (e.g., Gray & Boehm-Davis, 2000; Gray & Fu, 2004; Gray et al., 2006; Maglio, Wenger, & Copeland, 2008; Morgan, Patrick, Waldron, King, & Patrick, 2009; Siegler & Lamaire, 1997), and the second is that individuals minimize the level of demand placed on the executive control system (e.g., Botvinick & Braver, 2015; Kool et al., 2010; Kurzban, Duckworth, Kable, & Myers, 2013; Westbrook & Braver, 2015; Yeung & Monsell, 2003).

According to accounts arguing that time acts as a key determinant in effort-based decisions, individuals minimize effort by selecting actions that will take the least amount of time (while maintaining an acceptable level of performance/reward). For example, according to the soft-constraints hypothesis (Gray et al., 2006) individuals select courses of action that tend to minimize performance costs in terms of time. On this account, the cognitive system assigns no privileged status amongst different types of effort, such as perceptual-motor effort (e.g., making eye movements) or memorial effort (e.g., retrieving an item from memory). Consistent with this idea, Gray and Fu (2004) demonstrated that individuals become increasingly likely to opt for a less accurate, memory-based strategy as the time costs associated with a more accurate, perceptual-motor strategy increase.

In addition to time playing a determining role in effort-based decisions, several accounts argue that individuals minimize their effort by selecting actions that will put the least demands on the executive control system (while maintaining an acceptable level of performance/reward). While definitions of executive control can vary in their details, there is a reasonable consensus on the situations that put increased

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demands on the executive control system (e.g., Miyake et al., 2000). Specifically, those tasks that engage the processes associated with control (i.e., the sets of superordinate functions that encode and maintain representations and feed to subordinate processes) are considered more demanding and closely tied to high cognitive effort (Botvinick & Braver, 2015). For example, one such situation consists of the maintenance and switching of task sets (Monsell, Yeung, & Azuma, 2000). Indeed, empirical work has demonstrated that tasks with relatively higher levels of switching are avoided in demand selection tasks (McGuire & Botvinick, 2010; Kool et al., 2010).

The contribution of time costs and executive control demands has largely been inferred by comparing conditions that differ on those metrics. To date, less effort has been spent attempting to understand how it is that individuals have access to this information, as seemingly required to use that information to make effort-based decisions. On these accounts, it seems reasonable to suggest that if individuals use this information, then they must have somewhat accurate access to it. For example, the Expected Value of Control (EVC) Theory (Shenhav, Botvinick, & Cohen, 2013) situates effort as a specific quantity tied to the intensity of a control signal that is used in an algorithmic fashion to discount the anticipated payoffs associated with acting. Such accounts mirror "direct access" views (e.g., King, Zechmesiter, & Shaughnessy, 1980; Schwartz, 1994) where higher-level decision-making systems have privileged access to veridical information when computing effort costs. This assumption is important in attempting to examine predictions based on such accounts.

While the influence of both time and executive control demands on effort avoidance have gained support from numerous domains, recent evidence has suggested the need for an alternative framework. Dunn, Lutes, and Risko (2016) demonstrated that effort-based choices can be dissociated from traditional indices of effort. The authors argued that this dissociation was inconsistent with the idea that time costs, or demands on the executive control system, are responsible for effort-based choices. Following from this, Dunn et al. (2016; see also Dunn & Risko, 2016; Dunn, Gaspar, & Risko, 2019) suggested a metacognitive account, wherein effort avoidance is driven by an inferential evaluation of effort based on available cues (see similarly, Desender, Buc Calderon, Van Opstal, & Van den Bussche, 2017; Desender, Van Opstal, & Van den Bussche, 2017; Payne, Bettman, & Johnson, 1993).

A metacognitive account of effort avoidance draws largely from cue-utilization models of metamemory that attribute judgments to inferential and heuristic processes based on a variety of cues (Koriat, 1997, 2007; Mueller, Dunlosky, & Tauber, 2016). On this view, when generating metacognitive judgments, individuals search for any cues in a qualitative fashion that are plausibly related to performance, directly contrasting accounts hypothesizing direct-access to object-level information (e.g., King et al., 1980; Schwartz, 1994). In the context of effort avoidance then, individuals would be expected to search for cues that are possibly related to effortfulness, rather than directly assessing veridical levels of demand (i.e., object-level information), given the latter is possible. While a cue-utilization account need not deny the influence of time costs or demands on executive control in effort-based decision-making, this shift in perspective moves to center stage the need to understand the inferences/heuristics made over effort related cues when making these decisions.

1. Present investigation

In the present investigation, we contrasted the influences of time costs and demands on the executive control system against the influence of a salient effort cue using variants of a demand selection task (DST; Botvinick & Rosen, 2009; Dunn et al., 2016; Gold et al., 2014; Kool et al., 2010; McGuire & Botvinick, 2010). This particular strategy was selected in order to provide a strong test of a cue-utilization account. That is, by contrasting two factors thought to heavily drive effort-based decision making against a salient effort cue not tied to either, we can determine the utility of considering the latter as a major determinant in decision-making contexts. It is important to note here that we are using veridical time costs and demands on executive control under the assumption discussed above that individuals have access in some manner to this information.

Across two experiments, individuals were presented with a pair of tasks consisting of a high- and a low-demand option, where one option took longer and placed more demands on the executive control system relative to the alternative option. Participants were first given experience with each option and were subsequently asked to generate a least-effortful preference (i.e., choices on the "free" trials constitute an effort-based choice). Unlike previous research using the demand selection paradigm, the addition of an initial experience stage with each option should provide individuals ample opportunity to differentiate between the two options. Moreover, utilizing explicit instructions with regard to generating a less effortful preference gives a strong indication of how each manipulation may affect individuals' evaluations of effort (Dunn et al., 2019; Gold et al., 2014). In addition, it differs from previous work (e.g., Kool et al., 2010) which was aimed more specifically at "preference." This affords a more direct test of the factors influencing effort-based decisions provided preferences could form based on factors unrelated to effort. Lastly, the use of an explicit effort frame also follows more recent work investigating the perception of effort/difficulty in general (Potts, Pastel, & Rosenbaum, 2018). That said, direct future comparisons of each of these methods (i.e., effort vs. preference frame) would be valuable.

The critical manipulation in the present experiments is the nature of the factors that differentiate the low- and high-demand option in each pair presented to participants. The first pair differed in whether a stimulus was rotated (i.e., the rotation pair; 0° vs 90°). The time costs of rotation on object identification are relatively small (Jolicoeur, 1990) and arguably place minimal demands on executive control. We are unaware of any definition of executive control that would associate the processes involved in identifying a single rotated digit as relying heavily on the executive control system. Critically, though, stimulus rotation represents a salient effort cue (i.e., it is both highly "available" and perceived as effortful; Dunn & Risko, 2016; Dunn et al., 2016). Here we define salience as the extent to which individuals are aware of either the rotation or switching cue (Dunn et al., 2019) and is indexed by a self-report questionnaire similar to that employed by Kool et al. (2010, Experiment 1).

The second pair of options differed in the probability of a task switch (i.e., the switching pair; 90% vs. 10%). Task-switching is associated with reliable time costs (Monsell, 2003), and as noted above, is a representative task that engages the putatively effortful processes associated with executive control (Botvinick & Braver, 2015; Botvinick & Rosen, 2009; Kool et al., 2010; McGuire & Botvinick, 2010; Yeung & Monsell, 2003). Nonetheless, recent research suggests that the probability of a task switch appears to be a relatively poor effort cue (i.e., it is "unavailable"; Dunn et al., 2019). Importantly, individuals often do not avoid options associated with more frequent switching even with large differences in the probability of a task switch (i.e., 90% vs. 10%; Gold et al., 2014). This occurs despite the costs of increased task switching and arguably reflects (amongst other possibilities) the fact that, (a) task-switching consists of a relation between consecutive trials, and (b) individuals are often unaware of even rather large differences in the proportion of a given trial type (e.g., Risko & Stolz, 2010; Schmidt, Crump, Cheesman & Besner, 2007). Thus, the switching pair features two options that will differ strongly in terms of time (i.e., hundreds of milliseconds) and demands on executive control (i.e., very little task-switching vs. task-switching nearly every trial). In the rotation pair the tasks should differ little in terms of time and arguably will not differ in terms of demands on executive control. Against this clear difference in relative time costs and executive control demands, the rotation pair features only the salient effort cue (i.e., stimulus rotation). Provided the strong evidence that time costs and demands on executive control can

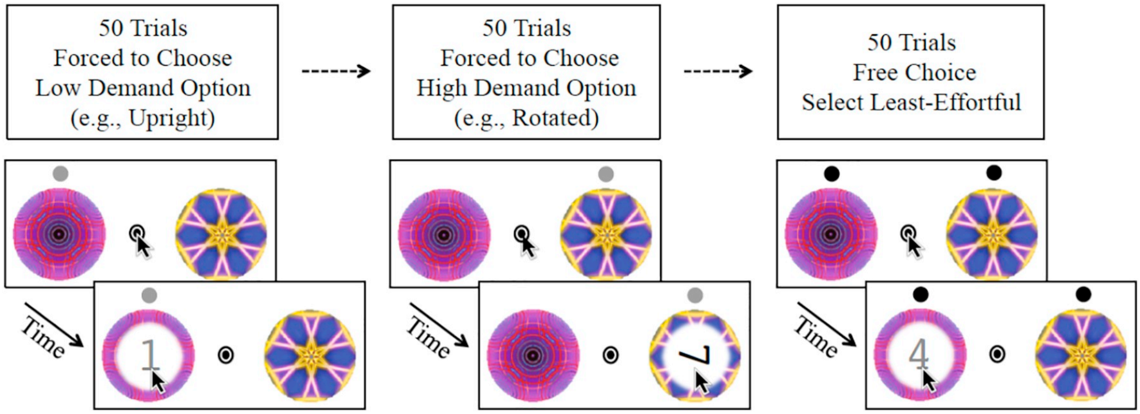

Fig. 1. Example DST in the rotation pair condition.
In the first block participants were cued to select one option by a small circle placed above the to-be-selected option. In the second block the cue moved to the opposing option where individuals completed an additional 50 trials. The order of the first two blocks was randomized. In the third block a circle was placed above both options indicating that the participant was to attempt to generate a least-effortful preference for one of the options and continue to select that option until the block was complete. Each of the options was either a low-demand or high-demand option. The rotation pair used in Experiments 1 and 2 is displayed in the figure where the low-demand option consisted of upright digits and the high-demand option consisted of rotated digits. In the switching pair (not shown) the low-demand option consisted of a lower probability of switching (i.e., 10% Experiment 1; 30% Experiment 2) and the high-demand option consisted of a higher probability of switching (i.e., 90% Experiment 1; 70% Experiment 2).

drive effort-based decisions, positive evidence for the cue-utilization account in this context (that is, if results demonstrate similar or greater effort avoidance in the rotation pair relative to the switching pair) would represent strong support for this approach to understanding effort-based decision making (Dunn et al., 2019).

2. Experiment 1

2.1. Method

2.1.1. Participants

Thirty-six University of Waterloo undergraduate students participated in the study in exchange for research credit. Sample size was estimated (Power = 0.8, $\alpha = 0.05$) from a pilot study suggesting a moderate effect in low-demand selections across the rotation and switching pairs ($d = 0.44$). In addition, completing counterbalancing was also taken into consideration. One participant was unable to satisfy the practice criterion outlined below and a program issue caused no switch trials to be delivered to another participant for the low-demand option, thus their data is not included in the following analyses ($N = 34$).

2.1.2. Design

A 2 (Pair of Alternatives: Rotation Pair, Switching Pair) × 2 (Demand Option: Low Demand, High Demand) within-subjects design was employed.

2.1.3. Apparatus

The DST was programmed in MATLAB using the Psychophysics Toolbox extensions (Brainard, 1997; Pelli, 1997). Stimuli were presented on a 24″ LCD monitor approximately 70 cm away from the participant. Participants used a standard optical mouse to provide responses.

2.1.4. Stimuli

The stimuli employed followed Kool et al. (2010; Experiment 3) and Gold et al. (2014; see Fig. 1).[1] Individuals were presented with two options, a low-demand and a high-demand option (the relative demand was not communicated to participants), to the left and right of the center of the screen. Once the mouse was placed over a target centered between the two options, both pairs were activated for selection. Individuals were then free to move the mouse over an option to reveal a colored digit, either blue or yellow. When digits (1, 4, 7, & 8)[2] were colored blue, individuals were tasked with making a magnitude judgment (i.e., greater than or less than) with five as the reference number. When digits were colored yellow, individuals were tasked with making a parity judgment (i.e., odd or even). The left mouse button served as a "less than five" or an "odd" response, while the right mouse button served as a "greater than five" or "even" response. For the rotation pair, the low-demand option consisted of all upright digits (0°), whereas the high-demand option consisted of all digits rotated ± 90°, with both options associated with a 50% probability of a task-switch. For the switching pair, the low-demand option consisted of a 10% probability of a task switch, whereas the high-demand option consisted of a 90% probability of a task-switch, with digits always presented upright.

Individuals entered the testing room and provided informed consent. A practice session consisting of three blocks with feedback was first completed in order for individuals to gain sufficient experience with task response mappings. Individuals were required to reach a minimum accuracy of 90% in the last practice session prior to moving on to the main experiment. Instructions for the DST stated that individuals were to complete three blocks in the experiment for each pair of alternatives. To provide experience with the demand associated with each pair, the first two blocks involved forced-choice instructions. In this phase, a small cue was displayed above one of the two options signaling that choices were only to be made from that cued option. The starting option that was sampled from was randomized and counterbalanced. Once the first cued option was sampled for 50 trials, the cue would then move to the other option where individuals would sample for 50 trials. Critically, the third block (also 50 trials) constituted the free-choice portion of the experiment. It was brought to the attention of

[1] We would like to thank Wouter Kool for providing the base MATLAB code for the experiment.

[2] In both Kool et al. (2010) and Gold et al. (2014) the digit set included 1, 2, 3, 4, 6, 7, 8, and 9. However, during debriefing sessions of the pilot study individuals often stated that the 6 and 9 digits were indistinguishable in the rotated conditions, therefore they were removed from the digit set for the current experiments. Removal of these digits also caused a need to remove an odd and even digit below 5 to keep the digit set balanced across both the parity and magnitude tasks.

Table 1
Demand selection task and mean performance results for Experiments 1 and 2.

	Rotation pair		Switching pair	
	Low demand option	High demand option	Low demand option	High demand option
Experiment 1				
Low demand selections	67% (37%)	–	61% (39%)	–
Block RT (ms)	1121 (251)	1192 (266)	931 (202)	1216 (277)
Switch cost (ms)	110 (184)	152 (174)	255 (319)	47 (297)
Repeat trials	1070 (244)	1115 (249)	923 (225)	1175 (327)
Switch trials	1180 (290)	1267 (307)	1178 (339)	1222 (291)
Accuracy	97% (4%)	98% (2%)	98% (2%)	98% (2%)
Experiment 2				
Low demand selections	72% (35%)	–	47% (37%)	–
Block RT (ms)	1041 (251)	1097 (250)	1120 (286)	1212 (285)
Switch Cost (ms)	141 (181)	181 (200)	154 (217)	80 (185)
Repeat Trials	1002 (252)	1046 (248)	1074 (290)	1160 (320)
Switch Trials	1143 (281)	1227 (289)	1228 (338)	1240 (296)
Accuracy	98% (4%)	98% (2%)	98% (2%)	98% (3%)

Note: Standard deviations are presented in parentheses.

individuals that after the first two blocks they may have noticed differences between the options, and may begin to feel that one option is more effortful than the other. For the free-choice block, individuals were explicitly told to attempt to develop a preference about which option they felt was the *least effortful* of the two and continue to choose that option until the block was complete (see Gold et al., 2014 for similar directed instructions). Individuals were randomly assigned to an order (i.e., rotation pair first, switching pair first) and order was counterbalanced across participants.

At the end of the DST individuals completed a self-report questionnaire similar to that reported in Kool et al. (2010 pp. 668) which included questions regarding whether individuals felt they constructed a less-effortful preference, on what that preference was based, if a noticeable difference across options was apparent, and whether individuals were explicitly aware of a difference in the probabilities of a task-switch. In addition, a question was added assessing how confident (from 0% to 100%) individuals were in their belief that there was some difference across options (see Appendix A). The entire experiment took approximately 45 min to complete.

2.2. Results

Results are reported first for the RTs for task responses, switch costs, and accuracy, followed by choices in the DST (see Table 1) and self-report data. All effect sizes associated with within-subject comparisons are Cohen's d using SD_{avg} as the standardizer term (see Cumming, 2012, p. 291). All reported 95% confidence intervals (CI) are bootstrap bias-corrected and accelerated (BCa) intervals (DiCiccio & Efron, 1996). To supplement inferential statistics, Bayesian estimation analyses were conducted on selections in the DST and RTs using the BEST package (Kruschke, 2013) in R (R Core Team, 2014) using 100,000 estimates of the effect size across groups using Markov Chain Monte Carlo (MCMC) sampling. Ninety-five percent Highest Density Intervals (HDI), as well as the simulated mode effect size (i.e., the maximum a posteriori estimate; MAP) are presented. In addition, Bayes Factors (BF) computed using the BayesFactor package (Morey & Rouder, 2015) in R are presented. Interpretations of Bayes Factors follow the general criteria outlined by Kass and Raftery (1995). In addition, response times faster than 200 ms were removed for all RT analyses.

2.2.1. Performance

No RTs were faster than 200 ms. Grand mean outlier and by-subject within-condition outlier analyses were conducted on raw RTs using a 2.5 standard deviation cut-off and resulted in the removal of approximately 6% of all trials.

2.2.1.1. Performance. Accuracy did not vary as a function of pairs or demand option (all Fs < 1.33). With respect to task RTs at the block level, a 2 (Pair of Alternatives) × 2 (Demand Option) repeated measures ANOVA demonstrated a significant main effect of pair of alternatives, $F(1, 33) = 7.77$, $MSE = 29{,}979.34$, $\eta_p^2 = 0.19$, $p < .001$, and demand option, $F(1, 33) = 73.98$, $MSE = 14{,}453.64$, $\eta_p^2 = 0.69$, $p < .001$, as well as a pair × demand option interaction, $F(1, 33) = 20.96$, $MSE = 18{,}496.28$, $\eta_p^2 = 0.39$, $p < .001$. The difference in response time between the low- and high-demand option (i.e., what we term the "demand effect") for the rotation pair ($M = 71$ ms, $SD = 155$) was significantly smaller than for the switching pair, ($M = 284$ ms, $SD = 204$), $M_{Diff} = 213$ ms, $t(33) = 4.56$, $SE = 45.36$, $d = 1.19$, 95% BCa CI [121 ms, 304 ms], $p < .001$. Aligned with the reported inferential statistics, Bayesian analyses demonstrated strong evidence for the alternative (i.e., that there is a difference between means), MAP = 0.79, 95% HDI [0.38, 1.19], $BF_{ALT} = 380.87$.

Next for switch costs, a 2 (Pair of Alternatives) × 2 (Demand Option) × 2 (Switch vs. Repeat Trials) repeated measures ANOVA demonstrated a significant main effect of demand option $F(1, 33) = 24.91$, $MSE = 31{,}387.63$, $\eta_p^2 = 0.43$, $p < .001$, a significant main effect of switch trial, $F(1, 33) = 26.41$, $MSE = 51{,}295.65$, $\eta_p^2 = 0.45$, $p < .001$, a significant demand option × switch trial interaction, $F(1, 33) = 6.46$, $MSE = 17{,}906.98$, $\eta_p^2 = 0.16$, $p = .02$, and a significant pair of alternatives × demand option × switch trial interaction, $F(1, 33) = 9.57$, $MSE = 27{,}693.48$, $\eta_p^2 = 0.23$, $p < .01$. To further examine this three-way interaction, switch costs (i.e., switch trials – repeat trials) were computed for each demand option within the rotation and switching pairs. Comparisons demonstrated that switch costs within the rotation pair did not differ across the low demand ($M = 110$ ms, $SD = 184$) and high demand options ($M = 152$ ms, $SD = 174$), $M_{Diff} = 42$ ms, $t(33) = 1.09$, $SE = 39.74$, $d = 0.24$, 95% BCa CI [−37 ms, 122 ms], $p > .1$, MAP = 0.24, 95% HDI [−0.13, 0.69], $BF_{NULL} = 3.17$. In contrast, higher switch costs for the low demand ($M = 255$ ms, $SD = 319$) relative to the high demand options ($M = 48$ ms, $SD = 174$), were demonstrated within the switching pair, $M_{Diff} = 207$ ms, $t(33) = 3.35$, $SE = 61.49$, $d = 0.67$, 95% BCa CI [82 ms, 333 ms], $p < .01$, MAP = 0.58, 95% HDI [0.20, 0.96], $BF_{ALT} = 16.96$.

The difference in RTs between the low- and high-demand options in the switching pair was significantly larger (about three times) than in the rotation pair. In contrast, the average switch costs for the high-demand option for the rotation pair was similar to the average switch costs for the low-demand option, whereas the low-demand option produced higher average switch costs relative to the high-demand option for the switching pair. The latter interaction likely reflects a type of preparation effect (Monsell, 2003).

Following from these results, if individuals are utilizing the effort cue associated with stimulus rotation, then we should observe higher rates of low-demand choices for the rotation pair relative to the switching pair. Alternatively, if time costs and demands on executive control are driving effort-based decisions in the DST, there should be more choices for the low-demand option in the switching pair than in the rotation pair. Last, if relative switch costs are driving selections in the DST, then we should observe similar frequencies of selections across options for the rotation pair, and higher frequencies of selections of the *high-demand* option for the switching pair (i.e., individuals should avoid the low-demand option associated with higher average switch costs).

2.2.2. Demand selection task

Individuals chose the low-demand option in the rotation pair 67% of the time ($SD = 37\%$). This value significantly differed from chance and demonstrated positive evidence for the alternative (i.e., low-demand selections were greater than chance), $t(33) = 2.62$, $SE = 0.06$, $d = 0.45$, 95% BCa CI [53%, 70%], $p = .013$, MAP = 0.47, 95% HDI [0.09, 0.90], $BF_{ALT} = 3.44$. Individuals chose the low-demand option for the switching pair 61% of the time (SD = 39%). This value did not significantly differ from chance and did not demonstrate evidence for the null or alternative, $t(33) = 1.71$, $SE = 0.10$, $d = 0.29$, 95% BCa CI [49%, 74%], $p = .1$, MAP = 0.30, 95% HDI [−0.05, 0.70], $BF_{ALT} = 0.68$. Low-demand choices across pairs did not significantly differ, $M_{Diff} = 5\%$, $t(33) = 0.64$, $SE = 0.08$, $d = 0.14$, 95% BCa CI [−9%, 2%], $p > .1$, and provided evidence for the null, MAP $d = 0.07$, 95% HDI [−0.30, 0.44], $BF_{NULL} = 4.51$.[3]

Least effort selections were similar across the rotation and switching pairs, despite the fact that the difference in terms of time and overall demand on executive control was much greater in the switching pair than in the rotation pair[4] (see Fig. 2). Furthermore, if we consider demands on executive control as the magnitude of the switch costs across options, this does not change the conclusion. The differences in switch costs between options was much greater in the switching pair (i.e., larger switch costs in the low-demand option with infrequent switching) than the rotation pair and least effort selections went in the direction opposite than that predicted by the pattern in the former. Last, there was no difference in the magnitude of the switch cost in the rotation pair, but there was a marked difference in low-effort selections.

2.2.3. Self-report

One individual did not complete the self-report portion of the experiment ($N = 33$ for the following analyses). Considering all remaining individuals, 79% (26) reported noticing some difference across options for the rotation pair and 70% (23) reported noticing some difference for the switching pair, Sign Test $p > .1$. Self-reported confidence in reporting noticing a difference across options was similar for the rotation pair ($M = 82\%$, SD = 20%) and the switching pair ($M = 76\%$, SD = 21%), $M_{Diff} = 6\%$, $t(31) = 1.52$, $SE = 0.04$, $d = 0.28$, 95% BCa CI [−1%, 13%], $p > .1$. Sixty-one percent of individuals (20) reported they became explicitly aware of a difference in switching across the options in the switching pair, Binomial Test, $p > .1$ (participants were not explicitly asked about stimulus rotation). Sixty-four percent of individuals (21) explicitly reported stimulus rotation as the determinant of their preference for the rotation pair relative to only 33% (11) of individuals explicitly reporting differences in the probability of switching as the determinant of their preference for the switching pair, Sign Test $p = .031$.

Consistent with least effort selections being similar in Experiment 1 individuals reported noticing "some" difference (and confidence in that difference) in effort across the low- and high-demand options at about the same rate across the rotation and switching pairs. Interestingly, in the rotation pair individuals were more likely to say that stimulus rotation was the basis of their preference than individuals in the switching pair were to say that the task switching was the basis of their preference (see Table 2).

2.3. Discussion

In Experiment 1 the low- and high-demand options in the switching pair were associated with a greater difference in task RTs within block and theoretically a greater difference in demand on executive control than in the rotation pair. Nevertheless, individuals avoided the high-demand option in the rotation pair (i.e., the 90° rotated stimulus) at a rate similar to the high-demand option in the switching pair (i.e., a 90% chance of a task switch; see Fig. 2). From a cue-utilization perspective, this result can be seen to reflect the influence of the salient stimulus rotation cue. That is, the presence of this effort cue led to rates of least effort selections equivalent to that produced by a large difference in time and demands on executive control associated with switching and the cue therein. Provided the central role the latter two contributions have played in theoretical discussions of effort-based decision making, this result provides support for a cue-based contribution. It is also important to note that while switch costs were similar across options for the rotation pair, the low-demand option produced larger switch costs relative to the high-demand option for the switching pair. Yet, in neither case did it appear that less effortful selections followed the option associated with switch costs.

Self-report data demonstrated that a 90° rotated stimulus and a high probability of a task switch (i.e., 90% vs. 10%) evoked a similar level of awareness, consistent with the DST results. Again, this is despite the large differences in time costs and demands on executive control across the options. While individuals were equally likely to report "some" difference in effort between the pairs, more individuals reported stimulus rotation than task switching as the determinants of their choice. It may be the case that, although becoming aware of the switching cue, individuals did not endorse task switching as a source of effort (e.g., Michaelian, 2012). Alternatively, individuals may have experienced differences in effort across the options (e.g., Kurzban et al., 2013), but were unable to explicitly identify switching as the source of the difference.

One objection to these interpretations could take the following form. The differences in time between the low- and high-demand options in the rotation pair and switching pair are clear. Thus, a salient cue can arguably counteract such differences. While the idea of time costs being the sole determinant of effort-based choices has been challenged before (Dunn et al., 2016; Kool et al., 2010; McGuire & Botvinick, 2010; Westbrook, Kester, & Braver, 2013), this is the first such evidence wherein a salient effort cue was explicitly contrasted against time costs. While the latter contribution might be clear, the claim regarding the differences in demand on executive control between the rotation and switching pairs is less clear. One simply cannot rely on performance to infer differences in demand on executive control. We have been clear to note that the claim that the rotation pair and switching pair differ in terms of their relative demand on executive control is not based on the relative differences in time. Rather, it is based on the a priori theoretical claim that the difference in demand on executive control between an upright and rotated digit is smaller than the difference in demand on executive control between switching 10% of the time and switching 90% of the time. Experiment 1 provides evidence that a salient effort cue can overcome differences in demands on executive control to the extent that one accepts that the difference in demands on executive control between an upright and rotated digit is smaller than the difference in demands on executive control between switching 10% of the time and switching 90% of the time. While critically assessing this claim is important, simply taking the outcome of Experiment 1 as prima facie evidence that the claim is incorrect risks rendering the executive control hypothesis unfalsifiable.

[3] In addition to these analyses, non-parametric tests were conducted on rates of low-demand selections. Wilcoxon Signed-rank tests confirmed the parametric and Bayesian analyses in that low-demand selections for the rotation decks differed from chance, $p = .02$, whereas low-demand selections for the switching decks did not, $p > .1$. Furthermore, treating individuals dichotomously as "avoiders" within each deck type (i.e., > 50% low-demand selections) demonstrated that 68% of individuals fell into the "avoider" category for the rotation decks, binomial test against chance, $p = .058$, whereas 66% of individuals fell into the category for the switching decks, $p = .12$. Importantly, however, dichotomizing individuals into these categories can be argued to be too conservative given individuals with selections near chance are treated the same as individuals with high frequencies of low-demand selections.

[4] Wilcoxon Signed-rank tests confirmed the parametric and Bayesian analyses in that low-demand selections for the rotation decks differed from chance, $p = .01$, whereas low-demand selections for the switching did not, $p > .1$. Furthermore, 75% of individuals fell into the "avoider" category for the rotation decks, $p < .01$, whereas only 50% of individuals fell into the category for the switching decks, $p > .1$.

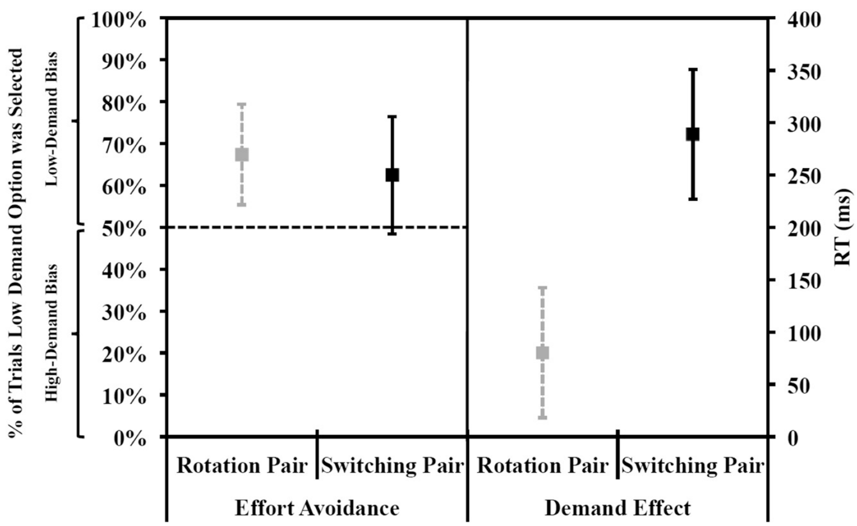

Fig. 2. The left panel consists of the percentage of selections of the low-demand options for each pair. The right panel consists of the demand effect in RT (i.e., high-demand option minus low-demand option) for each pair. Error bars in the left panel represent 95% Bias-corrected and accelerated (BCa) confidence intervals. Error bars in the right panel represent 95% within-subject confidence intervals (Masson & Loftus, 2003).

Table 2
Self-report data for Experiment 1.

	Rotation pair	Switching pair
Reported that there was a difference between the two options (i.e., low- and high-demand).	79%	70%
Confidence that there was a difference between the options.	82%	76%
Generated a less-effortful preference for one of the options in the final (free choice) block.	85%	76%
Explicitly reported preference was based on stimulus rotation (rotation pair)/% of switching (switching pair).	64%	33%
Explicitly aware of a difference in % of switching for the switching pair.		61%

3. Experiment 2

Experiment 2 looked to extend the results of Experiment 1 by reducing the difference in the probabilities of a task switch in the switching pair to 70% and 30% (from 90% vs. 10%) for the high- and low-demand options, respectively. This should reduce the difference in time and demands on executive control. In the previous experiment, rates of effort avoidance for the switching pair were statistically similar to rates for the rotation pair. If we assume that the low-demand selections will remain similar in the rotation pair, then this raises the interesting possibility that individuals will avoid the high-demand option in the rotation pair more than they avoid the high-demand option in the switching pair. Lastly, in Experiment 2 we looked to further gauge individuals' awareness of each of the effort cues. To do so we added a self-report question allowing individuals to express what they believed the specific difference was (if any) across the options for both of the pairs (this was only done for the switching pair in Experiment 1).

3.1. Method

3.1.1. Participants

Thirty-six University of Waterloo undergraduate students participated in the study in exchange for research credit.

3.1.2. Design

A 2 (Pair of Alternatives: Rotation Pair, Switching Pair) × 2 (Demand Option: Low-Demand, High-Demand) within-subjects design was employed.

3.1.3. Apparatus

All apparatus were the same as in Experiment 1.

3.1.4. Stimuli

For the rotation pair, the low-demand option consisted of all upright digits, whereas the high-demand option consisted of all digits rotated ± 90°, and the probability of a task switch was reduced to 30% for both options. For the switching pair, the low-demand option consisted of a 30% probability of a task switch, whereas the high-demand option consisted of a 70% probability of a task switch, with digits always presented at 0° for both options.

3.1.5. Procedure

The procedure was the same as that for Experiment 1. However, the self-report questionnaire completed by individuals at the end of the DST was changed to include a free-response question asking individuals to identify the attribute of the task they felt was the difference across options for each pair (see Appendix B).

3.2. Results

All reporting procedures follow Experiment 1 (see Table 1).

3.2.1. Performance

One participant's trial had a response faster than 200 ms and was removed. Grand mean outlier and by-subject within-condition outlier analyses conducted on raw RTs using a 2.5 standard deviation cut-off resulted in the removal of approximately 6% of all trials.

3.2.1.1. Performance. Again, accuracy did not vary as a function of pairs or demand options (all *F*'s < 1.15). With respect to block response time, a 2 × 2 repeated measures ANOVA demonstrated a significant main effect of pairs of alternatives, $F(1, 35) = 10.39$, $MSE = 32{,}520.3$, $\eta_p^2 = 0.23$, $p < .01$, and demand option, $F(1, 35) = 9.04$, $MSE = 21{,}922.92$, $\eta_p^2 = 0.21$, $p < .01$, but not a significant pair × demand option interaction, $F(1, 35) = 1.25$, $MSE = 9896.01$, $\eta_p^2 = 0.04$, $p > .1$. The difference between the low- and high-demand option for the rotation pair ($M = 56$ ms, SD = 158) was statistically similar to the difference for the switching pair, ($M = 92$ ms, SD = 196), $M_{Diff} = 37$ ms, $t(35) = 1.12$, $SE = 32.05$, $d = 0.19$, 95% BCa CI [−30 ms, 102 ms], $p > .1$. Similarly, Bayesian analyses demonstrated positive evidence for the null (i.e., the two demand effects were equivalent), MAP = 0.21, 95% HDI [−0.15, 0.54], BF_{NULL} = 3.13.

Next, for switch costs, a 2 (Pair of Alternatives) × 2 (Demand Option) × 2 (Switch Trial) repeated measures ANOVA demonstrated a significant main effect of pair $F(1, 35) = 5.30$, $MSE = 68{,}533.83$, $\eta_p^2 = 0.13$, $p = .027$, a significant main effect of demand option $F(1, 35) = 4.59$, $MSE = 49{,}135.36$, $\eta_p^2 = 0.12$, $p = .039$, and a significant main effect of switch trial, $F(1, 35) = 51.62$, $MSE = 27{,}007.58$, $\eta_p^2 = 0.59$, $p < .001$. Furthermore, a non-significant pair × demand option × switch trial interaction was demonstrated, $F(1, 35) = 4.06$, $MSE = 14{,}357.99$, $\eta_p^2 = 0.10$, $p = .052$. Following Experiment 1, we further examined this three-way interaction by computing the switch costs for each demand option within the rotation and switching pairs. Comparisons demonstrated that switch costs within the rotation pair were similar across the low-demand (M = 141 ms, SD = 181) and high-demand options (M = 181 ms, SD = 200), M_{Diff} = 40 ms, $t(33) = 0.97$, $SE = 39.35$, $d = 0.21$, 95% BCa CI [−37 ms, 105 ms], $p > .1$, MAP = 0.24, 95% HDI [−0.15, 0.60], BF_{NULL} = 3.63. Similar switch costs for the low-demand (M = 154 ms, SD = 217) relative to the high-demand options (M = 80 ms, SD = 185) were demonstrated within the switching pair as well, M_{Diff} = 74 ms, $t(33) = 1.64$, $SE = 44.25$, $d = 0.37$, 95% BCa CI [−3 ms, 159 ms], $p > .1$, MAP = 0.27, 95% HDI [0.08, 0.63], BF_{NULL} = 1.67.

In contrast to Experiment 1, both the rotation and switching pairs demonstrated similar differences between the low- and high-demand options in terms of performance. In addition, switch costs were statistically similar across options for both the rotation pair and switching pair. If individuals are utilizing the effort cue associated with stimulus rotation, then we should observe higher rates of low-demand options for the rotation pair relative to the switching pair. Alternatively, if time and overall demands on executive control are driving choices in the DST, then there should be no difference in participants' selections of the low-demand option across the two pairs.

3.2.2. Demand selection task

Individuals chose the low-demand option in the rotation pair 72% of the time (SD = 35%), and this value significantly differed from chance and demonstrated strong evidence for the alternative hypothesis (i.e., selections are greater than chance), $t(35) = 3.85$, $SE = 0.06$, $d = 0.64$, 95% BCa CI [61%, 84%], $p < .001$, MAP = 0.57, 95% HDI [0.36, 1], BF_{ALT} = 61.11. Individuals chose the low-demand option for the switching pair only 47% of the time (SD = 37%). This value did not significantly differ from chance and demonstrated positive evidence for the null (i.e., selections are equivalent to chance; see also Dunn et al., 2019), $t(35) = -0.55$, $SE = 0.06$, $d = -0.09$, 95% BCa CI [35%, 58%], $p > .1$, MAP = −0.1, 95% HDI [−0.43, 0.25], BF_{NULL} = 4.86. In addition, low-demand choices across pairs differed significantly, M_{Diff} = 25%, $t(35) = 3.14$, $SE = 0.08$, $d = 0.72$, 95% BCa CI [8%, 41%], $p > .01$, and provided positive evidence for the alternative, MAP = 0.51, 95% HDI [0.17, 0.92], BF_{ALT} = 10.73[4].

Interestingly, despite similar performance across the rotation and switching pairs, avoidance rates for the rotation decks were demonstrably higher than avoidance rates for the switching decks (see Fig. 3). Furthermore, selections did not follow the pattern hypothesized by switch costs alone driving selections.

3.2.3. Self-report

Considering all individuals, 92% (33) reported noticing some difference across options for the rotation pair whereas only 47% (17) reported noticing some difference for the switching pair, Sign Test $p < .001$. Fifty-six (20) percent of individuals explicitly reported that the difference across options for the rotation pair was stimulus rotation, whereas only 22% (8) explicitly reported switching as the difference across options for the switching pair, Sign Test $p < .05$. Last, 64% of individuals (23) explicitly reported stimulus rotation as the determinant of their preference for the rotation pair relative to only 22% (8) of individuals explicitly reporting differences in the probability of switching as the determinant of their preference for the switching pair, Sign Test $p = .001$. Thus, more individuals reported being aware of and utilizing the stimulus rotation cue relative to switching (see Table 3).

3.3. Discussion

In Experiment 2 we reduced the difference in the proportion of switching across the options in the switching pair. This reduction led to the difference in the low- and high-demand options in terms of time being statistically similar to that in the rotation pair. Despite this similarity, effort avoidance rates for the rotation pair were much higher than in the switching pair (see Fig. 3). This dissociation was predicted based on the cue-utilization perspective. Furthermore, individuals more frequently reported being aware of, and making use of, the rotation cue for their less-effortful choices than the probability of switching. Overall, the results of Experiment 2 provide further support for cue-utilization being a critical determinant in effort-based decision making in situations where these types of information (i.e., cues, time costs, demands on executive control) are presumably available.

4. General discussion

The present investigation examined how individuals decide which course of action is the least effortful. To achieve this, we contrasted the influence of time costs and demands on the executive control system against the influence of a more salient effort cue not associated with much in the way of either time or executive demands. Both DST experiments demonstrated evidence for a strong influence of a cue-utilization process in effort-based decision making. In Experiment 1 individuals avoided the high-demand option associated with stimulus rotation at a similar rate as the high-demand option associated with a high probability of a task switch, even though the performance costs and demands on executive control in the switching pair were greater than in the rotation pair. In Experiment 2 individuals avoided the high-demand option associated with stimulus rotation at a higher rate than the high-demand option associated with a higher probability of a task switch, even though the performance costs across the pairs were similar and the demands on executive control were arguably greater in the switching pair. The present results provide strong evidence that this cue based theoretical approach to effort-based decision making is viable.

4.1. Cue-utilization in effort avoidance

According to a cue-utilization account, effort-based decisions are driven by the availability of cues and the inferences/heuristics applied to those cues when generating an evaluation of effort. While the present experiments have focused on contrasting cue-utilization with time costs and demands on executive control, it is important to note that the current proposal does not make the claim that the latter two factors do not contribute to effort-based decisions. Indeed, a productive way forward might be to conceptualize time and demands on executive control as potential cues within a cue-utilization framework. An important consideration on this front will be a need to consider, for example, how individuals might use time. For example, Potts et al. (2018) demonstrated that subjective duration was a better predictor of task choice than objective task durations (see also Dunn & Risko, 2016). Nevertheless, the purpose of the present experiments was to assess the extent to which a positive case could be made for the notion that effort-based choices can be conceptualized as a kind of cue-based inference. The evidence on this front seems clear.

While the theoretical proposal here might appear counterintuitive in that individuals could often end up making "non-optimal" effort-based decisions, it is important to note that effort avoidance is itself a potentially effortful task (Boureau, Sokol-Hessner, & Daw, 2015; Payne

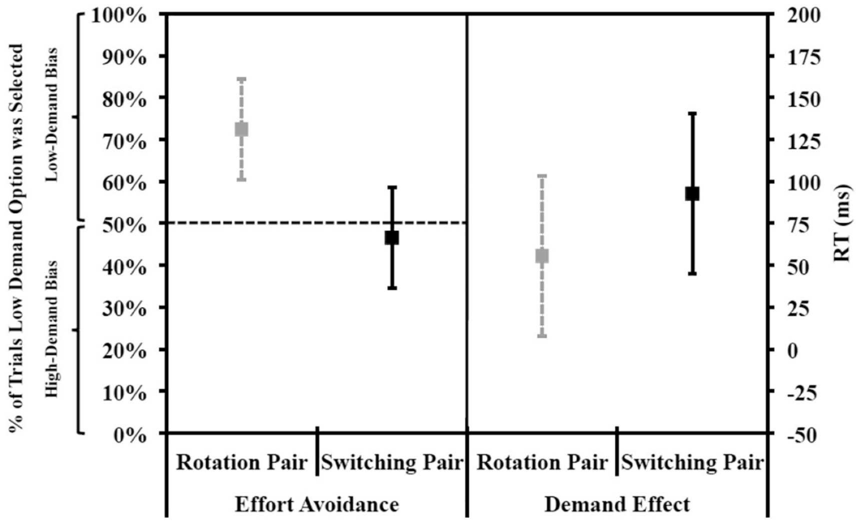

Fig. 3. The left panel consists of the percentage of selections of the low-demand options for each pair. The right panel consists of the demand effect in RT (i.e., high-demand option minus low-demand option) for each pair. Error bars in the left panel represent 95% Bias-corrected and accelerated (BCa) confidence intervals. Error bars in the right panel represent 95% within-subject confidence intervals (Masson & Loftus, 2003).

Table 3
Self-report data for Experiment 2.

	Rotation pair	Switching pair
Reported that there was a difference between the two options (i.e., low- and high-demand).	92%	47%
Confidence that there was a difference between the options.	89%	77%
Difference between options was stimulus rotation (rotation pair)/% of switching (switching pair).	56%	22%
Generated a less-effortful preference for one of the options in the final (free choice) block.	81%	72%
Preference was based on stimulus rotation (rotation pair)/% of switching (switching pair).	64%	22%

et al., 1993). That is, monitoring some veridical demand cost (assuming one can do so) with the goal of optimally minimizing effort may place additional demands on the system beyond that of the task at hand. Both the time- and executive control-based accounts imply what could be argued to be such a demanding monitoring process (e.g., Shenhav, Botvinick, & Cohen, 2013). Exploiting a salient effort cue on the other hand arguably involves little in terms of additional demand (Gigerenzer & Goldstein, 1996; Payne et al., 1993; Shah & Oppenheimer, 2008). Reliance on effort cues can thus be conceptualized as a least effort solution to the problem of selecting a least effort solution.[5]

While the present investigation was not directly designed to assess the relation between the explicit awareness of effort cues and effort avoidance, a number of notable patterns emerged across experiments through self-report measures. For example, in Experiment 1 rates of effort avoidance across pairs were similar, as well as the frequencies of individuals self-reporting some difference across options in each of the pairs. Thus, it appears that explicit awareness of effort cues and effort avoidance might be tightly coupled (Desender, Buc Calderon, et al., 2017; Desender, Van Opstal, & Van den Bussche, 2017; Dunn et al., 2016; Dunn et al., 2019). Consistent with this idea, Dunn et al. (2019) demonstrated, in a comparison between 70% vs. 30% switch probabilities, that the only sub-group of participants that avoided the "more effortful" 70% switching option were those who could correctly, and more confidently, identify which option featured more switching.

4.2. The probability of a switch-by-switch cost interaction

With respect to the notion that individuals avoid demands on executive control, the demonstration of an interaction between the probability of switch trials and switch costs provides an important observation. Specifically, the interaction can be interpreted in the context of Braver's (2012) dual mechanism framework that distinguishes between proactive and reactive control. Proactive control consists of a form of sustained, preparatory control, while reactive control consists as a type of "as-needed" control recruited when an event demanding control is detected. The reduction of the switch cost in a context with a high switch probability (relative to a low switch probability) can be interpreted as the engagement of a more proactive mode of control relative to a more reactive mode of control. Proactive control in this context could, for example, consist of maintaining both task sets in a partially activated state. Consistent with such a mechanism is the observation that the probability of switching by switch cost interaction seems largely due to differences in repeat trial response times (see Table 1).

Against this background, two points are worth noting. First, in Experiment 1 where the probability of switching by switch cost interaction was particularly large, effort-based choices demonstrated an avoidance of the high-probability switch option, which can be taken as being associated with more of a proactive mode of control. This suggests that avoidance of demands on executive control might be more strongly tuned to avoiding proactive rather than reactive control. The second observation is that the presence of this interaction suggests, at least on some level, a response to the probability of a switch manipulation. While not the aim of the present research, further examination of the probability of switching by switch cost interaction might promise a more nuanced understanding of the relation between different types of control and effort-based decisions.

4.3. Conceptual hurdles

Cognitive effort is an inherently difficult construct to define and operationalize. As such, as noted at various points above, the conclusions we have drawn rely on certain assumptions that we consider reasonable based on the current literature. Nevertheless, hurdles exist that should be made explicit. The results appear straightforward with respect to the contrast between a salient effort cue and time costs. In Experiment 1, the difference in time between the low-and high-demand

[5] We would like to thank Gordon Pennycook for useful discussions on this point.

options was greater for the switching pair than the rotation pair, but there was no difference in effort-based selections. In Experiment 2 the difference in time between the low- and high-demand options was statistically equivalent for the switching and rotation pairs, but the difference in effort-based selections was greater in the rotation pair. With these dissociations in hand it is clear that the salient effort cue in the rotation pair was making an important contribution beyond time costs to effort-based selections. This is an important theoretical contribution, and on its own provides support for the utility of considering a cue-utilization framework for effort-based decisions.

One rather thorny conceptual issue arises in our contrast of cue-based influence against demands on executive control. This is a product of the fact that demands on executive control cannot be directly indexed. Rather, we have to rely on existing knowledge about what should be more or less demanding on the executive control system. This is due to the executive control hypothesis and not a shortcoming of the present experiments. An unwillingness to make a priori assumptions about what tasks require more or less from the executive control system would remove the executive control hypothesis from the proverbial table (i.e., it would be untestable). We do not think one needs to take this position. Our theoretical understanding of executive control appears advanced enough that we can, a priori, classify tasks as more or less demanding on the executive control system. This does not mean that our conclusions will be correct. Rather, they will be correct only as far as our current understanding of executive control permits. Therefore, it is important to make clear the assumptions one is making. We have assumed here that the difference in the demands on executive control between processing an upright versus rotated digit is less than the difference between less versus more frequent task switching. To the extent that one can take issue with these assumptions a priori would undermine the strength of our conclusions with respect to executive control. The trap to avoid, of course, is taking issue with this assumption *post-hoc*. That is, assuming that differential effort avoidance in and of itself provides evidence for differential demands on executive control (e.g., the difference in demands on executive control between a rotated and upright stimulus is equivalent to the difference between switching 10% and 90% of the time given they do not differ in effort-based choices). Future work using converging operations, for example, physiological measures, to measure demands on executive control would be valuable in helping to adjudicate these different conceptual issues.

In summary, investigations into the psychology of cognitive effort are beset by challenging conceptual issues. Provided the central role the construct of effort plays in psychological theorizing, meeting this challenge is important. Part of this work requires acknowledging these challenges, which we feel we have done. A second part requires engaging those challenges thoughtfully by articulating when they raise interpretational problems and when they do not, as opposed to simply dismissing all results given the existence of the conceptual issues. The latter approach represents too blunt a tool if we want an understanding of effort that matches the theoretical weight it bears in explaining behavior.

5. Conclusion

One of the fundamental principles of human psychology is that humans tend to use effort as a critical determinant in their choices between different courses of action. The experiments reported here contribute to our understanding of how it is we make such decisions. Future work examining the theoretical account provided here promises further insights into the inner workings of the cognitive miser.

Appendix A. Self-report questionnaire deployed in Experiment 1

Q1. What was it like performing the task in part 1 (1–2 sentences)?

Q2. How did you choose between the decks in the last (3rd) block (1–2 sentences)?

Q3. Did you develop a least-effortful preference for one of the decks in the last (3rd) block (circle one)?

YES NO

Q4. Was there any difference between the decks in part 1 (circle one)?

YES NO

Q5. How confident did you feel that there was/was not a difference between the decks (from 0%–100%)?

Q6. For some participants, one of the two decks had the tendency to switch between colors more often while the other deck tended to repeat the same color. Did it seem like this was the case for you (circle one)?

YES NO

Note: Individuals completed all seven questions upon completion of both the rotation pair and switching pair (i.e., part 1 and part 2).

Appendix B. Self-report questionnaire deployed in Experiments 2 and 3

Q1. What was it like performing the task in part 1 (1–2 sentences)?

Q2. Was there any difference between the decks in part 1 (circle one)?

YES NO

Q3. How confident did you feel that there was/was not a difference between the decks (from 0%–100%)?

Q4. If you answered YES to question 2 above, what do you believe the difference(s) was between the decks (1 sentence)?

Q5. How did you choose between the decks in the last (3rd) block in part 1 (1 sentence)?

Q6. Did you develop a least-effortful preference for one of the decks in the last (3rd) block (circle one)?

YES NO

Q7. If you answered YES to question 6 above, what was the attribute (s) that you used to decide that one deck as less effortful than the other?

Note: Individuals completed all seven questions upon completion of both the rotation pair and switching pair (i.e., part 1 and part 2) in Experiment 2.

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