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Perceptual processing demands influence voluntary task choice

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ABSTRACT

Previous studies have suggested that people are sensitive to anticipated cognitive processing demands when deciding which task to perform, but the influence of perceptual processing demands on voluntary task choice is still unclear. The present study tested whether voluntary task choice behavior may be influenced by unpredictable task-specific perceptual processing demands. Across four experiments using different voluntary task choice procedures, we randomly varied the perceptual discriminability of stimuli (easy vs. hard color discrimination) for one of the two tasks. We reasoned that people could only reactively adjust their task choice behavior to the unpredictable discriminability manipulation if they engaged in some perceptual processing before a task goal becomes sufficiently activated to select the task for further processing. The results confirmed this hypothesis: Task performance data demonstrated the presence of perceptual (discriminability effects) and cognitive (switch costs) processing demands. Participants' choice behavior was affected by both types of processing demands (as reflected in a task repetition bias and a bias to select the color task with easy compared to hard discriminations). Thus, the present findings indicate that both perceptual and cognitive processing demands influence voluntary task choice behavior. We propose that higher-level goal activations interact at least partially with early perceptual processes to influence task choice behavior, suggesting a locus of voluntary choices during or after the perceptual stage within the information-processing stream.

1. Introduction

Goal-directed adaptive behavior requires an interplay of multiple control mechanisms that help one to bias information processing towards a currently relevant task goal ("cognitive control", e.g., Braver, 2012; Shiffrin & Schneider, 1977; Verbruggen, McLaren, & Chambers, 2014). Whereas in the laboratory environment, the to-be-performed task is typically instructed, in real-world situations it is usually under people's control to choose a desired task goal in the face of dynamically interacting internal (perceptual, cognitive, motor) and environmental processing demands (e.g., Brüning, Mückstein, & Manzey, 2020; Gray, Sims, Fu, & Schoelles, 2006). For both theoretical and practical reasons, demystifying the mechanisms underpinning volitional control in such free choice situations–that is, understanding how people freely decide which of multiple tasks to perform and which information to attend at a given time–has been a continuing concern in the field of cognitive psychology (e.g., Arrington & Logan, 2004; Braem, 2017; Braun & Arrington, 2018; Chiu, Fröber, & Egner, 2020; Fröber & Dreisbach, 2017; Imburgio & Orr, 2021; Kool, McGuire, Rosen, & Botvinick, 2010; Shenhav, Straccia, Musslick, Cohen, & Botvinick, 2018). In many previous studies, the decision of which task goal to pursue preceded the act of processing external information (i.e., stimuli) associated with the task. Interestingly, some previous studies provide hints that people are apparently able to integrate external sensory (not-yet relevant) information into their voluntary actions (e.g., Arrington, 2008; Charles & Haggard, 2020; Mattler & Palmer, 2012; Mayr & Bell, 2006; Orr & Banich, 2014). Here, we directly evaluate the hypothesis that some perceptual processing occurs *before* a task goal is chosen. If so, as outlined below, this would allow people to flexibly adapt their voluntary task choices to changing perceptual processing demands and it would have implications for conceptualizing the locus of voluntary task choices within the information processing stream.

Voluntary task choice behavior is typically investigated in experiments in which participants are faced with two stimuli associated with two independent tasks in a given trial (e.g., Arrington & Logan, 2004; Fröber & Dreisbach, 2017; Kessler, Shencar, & Meiran, 2009). Each task is mapped to one hand and participants can decide which task they want to perform by pressing the corresponding task-specific response key. For

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example, they can choose to use the index and middle finger of the left (right) hand to categorize a number (letter) as odd vs. even (vowel vs. consonant). Critically, previous studies have shown that internal (i.e., cognitive) factors influence voluntary task choices as reflected in a strong bias to repeat the previously performed task (e.g., Arrington & Logan, 2004; Henare, Kadel, & Schubö, 2020; Masson & Carruthers, 2014; Mayr & Bell, 2006). Specifically, it is usually assumed that participants maintain two task goals in working memory and that they guide their task choice based on the most active task goal representation–which is typically the previously applied one–leading to both an avoidance of task switches in choice behavior and so-called switch costs in performance (i.e., worse task performance in switch compared to repetition trials; e.g., Arrington & Logan, 2005).

Interestingly, several studies suggest that participants can proactively counteract the imbalance in goal activations towards the potential repetition task based on contextual experimental factors (e.g., Braem, 2017; Dreisbach & Fröber, 2019). For example, the strong preference to select task repetitions decreases (a) when participants are instructed to randomly select tasks (e.g., Arrington & Logan, 2005; Liefooghe, Demanet, & Vandierendonck, 2010), (b) when a cue in advance of a trial indicates an increase in reward prospect (e.g., Fröber & Dreisbach, 2016), (c) when the proportion of forced choices increases in hybrid paradigms that combine voluntary and forced task choices (e.g., Fröber & Dreisbach, 2017), and (d) when repeating one task and/or switching to another task becomes gradually less vs. more attractive (e.g., in terms of expected task performance and/or mental effort) in dynamic "foraging" environments (e.g., Braun & Arrington, 2018; Gutzwiller, Wickens, & Clegg, 2019; Kool et al., 2010; Langhanns et al., 2021; Mittelstädt, Miller, & Kiesel, 2018, 2019; Mittelstädt, Schaffernak, Miller, & Kiesel, 2021). Clearly, the specific goals of these studies (and corresponding interpretations) differ in several important respects. However, the general point is that internal fluctuations in task goal activations can be proactively regulated to influence task choice behavior based on anticipated (*predictable*) changes in the task environment (for a similar suggestion in terms of the stability-flexibility framework, see Brosowsky & Egner, 2021; Dreisbach & Fröber, 2019).

Most relevant for the present purpose, several studies have also demonstrated that *unpredictable* external (i.e., exogenous) factors can bias voluntary task choices (e.g., Fintor, Poljac, Stephan, & Koch, 2020; Yeung, 2010). For example, (a) participants are biased to repeat the same task when the stimulus repeats (e.g., Demanet, Verbruggen, Liefooghe, & Vandierendonck, 2010; Mayr & Bell, 2006), (b) they are biased to choose the task for which the motor response is congruent to a task-irrelevant feature (e.g., Chen & Hsieh, 2013), and (c) they are biased to choose the task associated with the stimulus that appears first when two task stimuli are presented in random order with random interstimulus intervals (e.g., Arrington, 2008; Arrington & Weaver, 2015). Thus, these findings demonstrate an intriguing flexibility in adjusting task choice behavior, because they suggest that participants are able to reactively ("on-the-fly") adjust the on-going process of selecting a task and/or they can override an already chosen task during a trial (i.e., after stimulus onset).

One possibility to account for these findings is to assume that specific environmental characteristics (i.e., stimulus features) are directly linked to one of the two task goals (e.g., Arrington, Weaver, & Pauker, 2010; Waszak, Hommel, & Allport, 2003). For example, in the study by Arrington (2008), the univalent stimuli were uniquely linked to a task goal (i.e., letter and number stimuli to a letter and a number task, respectively). Hence, the first-presented stimulus may result in the instant retrieval of the corresponding task goal, making it more likely that participants select this task instead of the one associated with the second-present stimulus. In other words, these findings might be taken as evidence that task-specific features sometimes automatically–in so far as this process is unintentional and requires no time or mental resources–trigger the activation of one task goal over a threshold after which this task is selected and actual task processing begins (e.g., Arrington, 2008). However, a seemingly similar–yet crucially different–explanation of participants' reactive task choice behavior to external influences could be that some concurrent preliminary (time- and resource-consuming) task processing takes places before one of the two tasks is actually selected and the remaining task processing resumes. From this perspective, stimulus repetitions, stimulus-response congruency, and stimulus availability effects may demonstrate that some early processing has already taken place to influence voluntary task choices. For example, participants may be biased to select the task associated with first- over second-presented stimuli in the study by Arrington (2008) because they have already processed the former stimuli to a larger degree.

With respect to this possibility, higher-level task goal activations influencing voluntary choice behavior might be at least partially biased by lower level (here: perceptual) processing when no task has yet been chosen. Specifically, consider that the task choice system is in principle set up to perform either of the two tasks. While the process of selecting one of the two tasks proceeds, information related to each of the two tasks might be at least partially accumulated in parallel, thereby gradually boosting activations of both not-yet-selected task goals until the task with the highest goal activation is selected and task-specific (presumably serial) processing resumes.

Unfortunately, however, those previous findings showing external influences on voluntary task choice behavior do not provide decisive evidence for this possibility, because a task-unique feature or stimulus is directly linked to one task goal (e.g., a color red to a red vs. blue color classification task; cf., Arrington, 2008; Mayr & Bell, 2006). Hence, it could be argued that a task goal is automatically retrieved (and a task selected) when encountering such task-related attributes before any actual processing takes place. What is needed for a more diagnostic test of whether any task-related perceptual processing occurs before task selection is an experimental design in which the perceptual processing characteristics of the same task attribute are selectively manipulated (e.g., a low vs. high saturated color red for a red vs. blue color classification task).

In the present study, we will address this concern. Specifically, we conducted four experiments using different voluntary task switching (VTS) procedures (Experiment 1: VTS with randomness instruction, cf. Arrington & Logan, 2004; Experiments 2 and 3: VTS with adaptive task delays, cf. Mittelstädt et al., 2018, Experiment 4: hybrid task switching paradigm with voluntary- and forced-choice trials; cf. Fröber & Dreisbach, 2017). In each experiment, participants could select which of two tasks to perform in a given trial (i.e., letter task vs. color task).[1] Critically, we manipulated the stimulus discriminability within the color task and easy vs. hard color task stimuli appeared randomly intermixed (see Fig. 1 for an overview of the experiment-specific manipulations). The use of a perceptual manipulation is especially attractive when considering that early perceptual processes and more central processes to retrieve task rules (i.e., task reconfiguration) presumably tap at least partially into different types of control systems (e.g., De Jong, 1993; Jentzsch, Leuthold, & Ulrich, 2007; Mackenzie & Leuthold, 2011; Miller & Durst, 2015; Rubinstein, Meyer, & Evans, 2001). Thus, we would expect to observe both switch costs for the color and letter task and better color task performance for easy vs. hard color stimuli (due to a shorter perceptual processing stage preceding switch-related cognitive processes). If the switch cost and perceptual difficulty effects rely on

[1] Note that additional instructions (e.g. Arrington & Logan, 2004) or global changes in the structure of the task environment (e.g., Fröber & Dreisbach, 2017; Mittelstädt et al., 2018) are usually needed to observe some task choice variability. Without any paradigm-specific instruction or manipulation, the strong avoidance of task switches may overshadow any potential external influences on choice behavior, because participants may primarily decide in advance of the experiment/blocks to choose the same tasks consecutively (e.g., Arrington et al., 2014; Arrington & Reiman, 2015).

independent mechanisms, there should be no evidence for an interaction of switch costs with current color discriminability.[2]

The focus of the present study, however, is whether and how participants integrate the perceptual (as operationalized by a color discriminability effect in task performance) and cognitive (as operationalized by switch costs in task performance) processing demands into their voluntary task choice behavior. In general, we expected that participants' task choice behavior in a current trial will be biased towards the task performed in the previous trial (i.e., task repetition bias). Critically, if people can flexibly adapt to unpredictably changing perceptual processing demands, participants should in general be more likely to select the color task with easy compared to hard discriminability color stimuli in a current trial, and this perceptual discriminability choice bias should occur following both color and letter task choices in the previous trial. This would indicate that easy (vs. hard) color stimuli reach a goal activation-selection threshold earlier, thereby localizing the process at which voluntary task choices occur within rather than before the information processing stream (i.e., locus during or after the perceptual stage). Alternatively, people may select tasks before they engage in any task processing, in which case participants' choice behavior should not be sensitive to the task-specific perceptual manipulation (i.e., locus before the perceptual stage).

2. Experiment 1

This experiment investigated whether voluntary task choice behavior is modulated by influences related to the perceptual difficulty of a color task (in addition to a letter task with equal perceptual difficulty) in a VTS paradigm with randomness instructions (Arrington & Logan, 2004).

2.1. Method

2.1.1. Participants

40[3] native German speakers were individually tested at the University of Freiburg, Germany, but data of seven participants were excluded due to fewer than 10 valid trials in at least one of the eight experimental conditions (letter−/color-task in the previous trial X letter−/color-task in the current trial X color stimulus discriminability in the current trial) after the data trimming procedure (cf. Mittelstädt et al., 2019, 2021 for a similar procedure[4]). The remaining 33 participants (21 female) ranged in age from 19 to 34 years ($M = 24.09$), and 30 were right-handed. In this and in the following experiments, all participants signed informed consent before testing. Furthermore, all experiments adhered to the standards set by the local ethics committee and were performed in accordance with the ethical standards described in the 1964 Declaration of Helsinki.

[2] Note that the present study was not designed to investigate the presence or absence of this interaction. Furthermore, the critical interpretation on choice behavior does not depend on (non-)existence of this interaction.

[3] The sample size was somewhat arbitrarily yet conservatively set in order to compensate for potential drop-outs. For example, a power analysis to detect a medium effect size ($\eta_p^2 = 0.06$) between "easy vs. hard" color task stimuli in color-task choices (one-sided) with a significance level of 5% indicated that we would have already over 80% power with 26 participants. Note that the actual effect in Experiment 1 was considerably larger ($\eta_p^2 = 0.40$), but we decided to stick to same sample size to allow for the possibility that the effect may be more difficult to detect in the less constrained (i.e., no randomness instruction) voluntary task choice environments used in Experiment 2 and Experiment 3.

[4] Furthermore, in this as well as the other three experiments, the results for task choice behavior were very similar when including all participants. Note that it was not possible to include all participants for task performance analyses because some participants had no or only very few trials in some conditions.

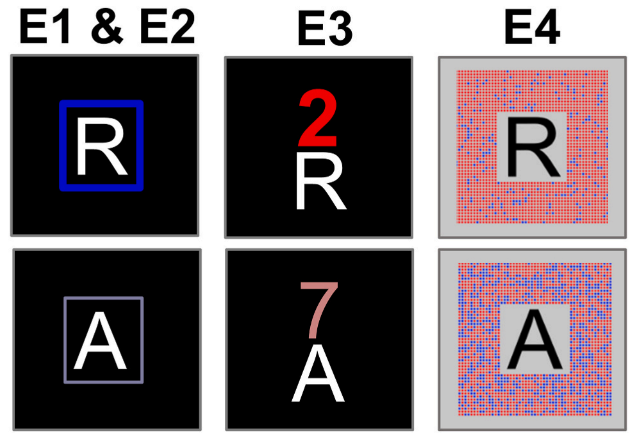

Fig. 1. Sketch of the stimulus display in voluntary task choice trials in Experiments (E) 1, 2, 3, and 4 with color presented in either a surrounding frame, a digit, or colored background dots (not to scale). On each trial, stimulus information related to two independent tasks (i.e., letter task and color task) was presented. The top row shows easy color task stimuli and the bottom row shows hard color task stimuli.

2.1.2. Apparatus and stimuli

Stimulus presentation and data collection were controlled by *E-Prime* software. All stimuli were presented on the black background of the computer monitor. In each trial, a white letter (height: ~ 6 mm, width: ~ 5 mm) was centrally presented and surrounded by a colored square (height: ~ 10 mm, width: ~ 10 mm). Participants were required to classify the color of the square (e.g., green vs. blue) or whether the letter was a vowel or consonant. Stimuli of the color classification tasks were two colors randomly selected out of three colors (red, blue, green) for each participant. Critically, the color was either easy or difficult to discriminate by varying thickness of the lines of the square (easy: ~ 1 mm; difficult: ~ 0.25 mm) and the RGB values (i.e., red easy: RGB [255,0,0]; red difficult: RGB[165,128,128], green easy: RGB[0,255,0]; green difficult: RGB[128,165,128], blue easy: RGB[0,0,255]; blue difficult: RGB[128,128,165]). Piloting testing was done to ensure that the specific experimental parameters of the color discriminability manipulation was appropriate. The stimuli for the letter classification task were the uppercase letters A, E, G, I, K, M, R, and U. The responses for each task were made with the index and middle finger of the same hand on a QWERTZ keyboard with the "y", "x", "," and "." keys. The task-to-hand mapping was counterbalanced across participants, and the specific finger-response mappings were randomly selected for each participant.

2.1.3. Procedure

Each participant was tested in a single experimental session lasting approximately 45 min. Overall, each participant first performed two practice blocks with 80 trials per block with the task cued followed by 13 blocks with 100 trials per block with voluntary task selection.

In each voluntary task selection block, participants had to perform 50 trials in the color task and 50 trials in the letter task, but they were instructed that they could decide which task to perform in a given trial with the constraint to randomly select tasks. Specifically, participants received a German version of the following written instructions (cf. Arrington & Logan, 2004):

> *"You have to perform 50 color tasks (25 easy and 25 hard to discriminate colors) and 50 letter task in each block. You can decide which task you want to perform in a trial, but try to perform the tasks in a random order. For example, imagine that you have a coin that said "color-task" on one side and "letter-task" on the other. Try to perform the task as if flipping the coin decided which task to perform. So sometimes you will be repeating the same task and sometimes you will be switching tasks. We*

don't want you to count the number of times you've done each task or alternate strictly between tasks to be sure you do each one half the time. Just try to do them randomly. If a #-sign or a grey square appear instead of one task, you have to wait to perform the other task until the block is over."

The specific identities of the two task stimuli were randomly selected in each trial. After the necessary number of tasks of the same type was completed, placeholders were presented for the this task (i.e., "#"-sign for the letter task or grey square for the color task) and key presses for this task were not recognized anymore. Thus, participants were then required to perform the remaining number of trials of the other task until the block was completed. Note that even though color discriminability varied randomly from trial to trial we implemented the constraint that participants performed the color task equally often on easy and or hard color stimuli within a block (i.e., 25 easy color and 25 hard color tasks). After participants had performed the color task the required number of times for one discriminability, all further color stimuli were presented at the other discriminability.

Following correct responses, the stimulus display of the next trial was presented after a blank screen (response stimulus interval, RSI) of 300 ms. During RSIs, participants received auditory feedback via headphones (i.e., low-pitched sounds for correct and high-pitched sounds for incorrect responses). Note that random external influences on voluntary task choice behavior are usually smaller (or not present) with long compared to short intervals between trials (e.g., Arrington, 2008; Mittelstädt et al., 2019). This suggests that with long intervals a task has already been selected before the stimulus display appears. Because we are interested in whether parallel perceptual processing can *in principle* bias voluntary task choice behavior, we naturally also only used a short interval between trials to promote online (i.e., during a trial) task selection behavior in the present experiments.

Breaks between blocks were self-paced and participants received performance feedback after each block (i.e., mean response time in milliseconds, calculated from the onset of the first stimulus until a response was made, and number of errors). To ensure reasonably accurate performance, participants were presented with an additional error screen at the end of the block if they made >10 errors within a given block. This screen indicated the correct stimulus-response mappings and that there were too many errors in the block, and it was displayed for a fixed period of 30 s before participants could start the next block.

The two practice blocks with cued task order in the beginning of the experiment were identical to the voluntary task selection blocks except for the following changes: Participants had to perform 40 color (20 easy and 20 difficult color stimuli) and 40 letter tasks, but they were instructed which task to perform in a given trial. Specifically, a cue (written words "letter" or color") appeared above the stimuli. Participants were additionally presented with the correct stimulus-responses mapping after an erroneous trial for a self-paced time during this practice block.

2.2. Results

We first categorized the task performed on each trial based on the hand used to respond. Then, trials were classified as repetition or switch trials on the basis of the task performed on trials n and n – 1. The practice blocks with cued tasks, the first two voluntary task selection blocks and the first trial of each block were excluded from any analyses. Note that results were similar when only excluding the first free choice blocks for this and the other experiments. Since visual inspection of the switch rate pattern in Experiments 2 and 3 suggested that participants needed the first two blocks to learn the structure of the task environment, we decided to report the results when excluding the first two free choice blocks for all experiments. Following our standard data trimming procedure (cf. Mittelstädt et al., 2019, 2021), we then excluded any trials without the possibility of choosing between the two tasks for all analyses (7.7%).[5] Further, post-error trials (5.7%) were removed for all analyses. For RT and task selection analyses, 5.7% error trials were additionally excluded as well as trials with RTs <200 ms (0.02%) or >3000 ms (0.34%).

2.2.1. Task choice

Overall, the mean percentage of trials on which the color task was chosen over the letter task was 49.7%. Table 1 lists the mean percentage of color task choices in the current trial n as a function of the discriminability of the color-stimulus in trial n and the task performed in the previous trial n-1.

A 2x2 ANOVA with these two factors on the percentage of mean color-task choices revealed a significant main effect of current color discriminability, with more color-task choices when the color discrimination was easy (53.6%) compared to hard (45.9%) $F(1,32) = 21.50$, $p < .001$, $\eta_p^2 = 0.40$. The significant main effect of previous task reflected a strong task repetition bias, $F(1, 32) = 56.91$, $p < .001$, $\eta_p^2 = 0.64$. Specifically, there were more color-task choices when the color task was performed in the previous trial (65.6%) than when the letter task was (33.4%).

Note that it is also possible to analyze the potential effects of the color discriminability manipulation in terms of switch rates (instead of letter choice rates). Obviously, as can be seen in Appendix A, the results of this analysis mirror those of the letter choice rates analyses reported in the main text for all experiments.

2.2.2. Task performance (reaction times and percentage errors)

We also checked whether the color stimulus discriminability was effective in influencing task performance. Table 2 displays mean median reaction times[6] as a function of color-stimulus discriminability (easy vs. hard) and task (color vs. letter) in the current trial separately according to which task was performed in the previous trial (color vs. letter). A 2x2x2 ANOVA on these means revealed significant main effects of current color discriminability and previous task (all $ps < 0.001$, all $\eta_p^2s > 0.29$). As expected, however, each of these two effects was further modulated by the current task: The significant interaction between current color-stimulus discriminability and current task indicated that

Table 1
Mean percentage of color task choices in the current trial n as a function of discriminability of the color stimulus in the current trial (Easy Color n vs. Hard Color n) and the task performed in the previous trial (Color Task n-1, Letter Task n-1), separately for Experiments 1, 2, 3, and 4. Standard errors of the means calculated from within-condition standard deviations in parentheses.

	Color task *n-1*		Letter task *n-1*	
	Easy color *n*	Hard color *n*	Easy color *n*	Hard color *n*
Experiment 1	69.3 (2.4)	61.9 (2.2)	37.8 (2.4)	29.9 (2.3)
Experiment 2	69.5 (2.5)	66.1 (2.7)	35.6 (2.7)	29.5 (2.7)
Experiment 3	78.2 (1.8)	73.3 (2.3)	37.2 (2.6)	20.3 (1.7)
Experiment 4	71.2 (3.1)	54.8 (3.5)	22.0 (3.2)	13.8 (2.3)

[5] These excluded trials refer to trials in which there was no longer a choice between the color and the letter task. Note that in Experiments 1–3, the majority of these excluded trials were trials in which the color task had to be performed (i.e., 58%, 52%, and 56% in Experiment 1, 2 and 3, respectively).

[6] The use of median RTs (instead of mean RT) allows better comparisons of switch costs RT with switch SOA in Experiments 2 and 3 (cf. Mittelstädt et al., 2018, 2019, 2021). To be consistent, we decided to also use median RTs for Experiment 1 and 4. Note, however, very similar result patterns were obtained in all experiments when using mean instead of median RTs and the corresponding test statistics were also similar to the reported ones. Hence, the choice of median RTs did not influence the conclusions of the present study.

Table 2
Mean median reaction times (RTs) in Experiments 1, 2, and 3 as a function of the color stimulus discrimimability (easy color n vs. hard color n) and the task performed in the current trial (color task n, letter task n) when the previously performed task was the color (i.e., color task n-1) or letter task (i.e., letter task n-1). Switch costs are differences in trial n RTs depending on whether the same versus different task was performed in trial n-1. Discriminability costs are differences in trial n RT for hard versus color discrimination. Standard errors of the means in parentheses.

	Color task *n*			Letter task *n*		
	Easy color *n*	Hard color *n*	*Discriminability costs n*	Easy color *n*	Hard color *n*	*Discriminability costs n*
Experiment 1						
Color Task *n-1*	563 (12)	650 (17)	*87*	765 (30)	791 (30)	*26*
Letter Task *n-1*	783 (27)	849 (26)	*66*	639 (15)	639 (14)	*0*
Switch costs n	*220*	*199*		*126*	*152*	
Experiment 2						
Color Task *n-1*	474 (8)	550 (12)	*76*	677 (27)	695 (24)	*18*
Letter Task *n-1*	696 (32)	766 (31)	*70*	533 (10)	544 (11)	*10*
Switch costs n	*222*	*216*		*144*	151	
Experiment 3						
Color Task *n-1*	497 (7)	576 (11)	*79*	745 (20)	774 (22)	*29*
Letter Task *n-1*	843 (26)	914 (29)	*71*	548 (9)	545 (8)	*−3*
Switch costs n	*346*	*338*		*197*	*229*	

color task responses were substantially longer with hard compared to easy color stimuli (749–673 = 76 ms), whereas letter task responses were only slightly slower with hard compared to easy color stimuli (715–702 = 13 ms), $F(1, 32) = 30.14$, $p < .001$, $\eta_p^2 = 0.49$. In addition, the significant interaction between current task and previous task indicated substantial switch costs for both tasks, $F(1, 32) = 102.25$, $p < .001$, $\eta_p^2 = 0.76$. Specifically, participants were slower in performing the color task in the current trial when they performed the letter task than the color task in the previous trial (816–606 = 210 ms). Conversely, participants were slower in performing the letter task in the current trial when they performed the color task than the letter task in the previous trial (778–639 = 139 ms). Finally, there was also a significant two-way interaction between current color-stimulus discriminability and previous task reflecting a tendency for the RT advantage in the presence of easy color-stimuli over hard color-stimuli to be somewhat more pronounced when participants performed the color task in the previous trial (720–664 = 56 ms) than when they performed the letter task (744–711 = 33 ms), $F(1, 32) = 4.23$, $p = .048$, $\eta_p^2 = 0.12$. No other effects were significant (all $ps > 0.806$, all η_p^2s < 0.01).

The corresponding percentage error (PE) pattern displayed in Table 3 mirrored the RT pattern. The 2x2x2 ANOVA on these mean PEs revealed significant main effects of current task and previous task (all $ps < 0.003$, all η_p^2s > 0.25) as well as a significant interaction between these two factors indicating switch costs, $F(1, 32) = 14.28$, $p = .001$, $\eta_p^2 = 0.31$. There were costs when switching to the color task vs. repeating the color task in the current trial (8.0–5.1 = 2.9%) and there were costs when switching to the letter task vs. repeating the letter task in the current trial (5.2–4.8 = 0.4%). There was also a significant interaction between current task and current color-stimulus discriminability, $F(1, 32) = 14.72$, $p = .001$, $\eta_p^2 = 0.32$. Color task responses were 2.4% less error-prone with easy vs. hard color stimuli (5.3% vs. 7.7%), whereas letter task responses were 0.8% more error-prone in the presence of easy vs. hard color stimuli (5.4% vs. 4.6%). No other effects were significant (all $ps > 0.061$, all η_p^2s < 0.11).

2.3. Discussion

The results of this experiment were clear-cut. Performance data revealed a strong color stimulus discriminability effect in color task RTs. Furthermore, substantial switch costs were found and there was no evidence that these costs were modulated by stimulus discriminability. In line with previous findings, participants generally avoided task switching despite being instructed to select tasks randomly. Most importantly, however, participants adapted their task selection behavior to the

Table 3
Mean median percentage errors in experiment 1, 2, and 3 as a function of the color stimulus discrimimability (easy color n vs. hard color n) and the task performed in the current trial (color task n, letter task n) when the previously performed task was the color (i.e., color task n-1) or letter task (i.e., letter task n-1). Switch costs are differences in trial n RTs depending on whether the same versus different task was performed in trial n-1. Discriminability costs are differences in trial n RT for hard versus color discrimination. Standard errors of the means in parentheses.

	Color task *n*			Letter task *n*		
	Easy color *n*	Hard color *n*	*Discriminability costs n*	Easy color *n*	Hard color *n*	*Discriminability costs n*
Experiment 1						
Color Task *n-1*	3.4 (0.4)	6.7 (0.8)	*3.3*	5.5 (0.9)	4.8 (0.6)	*−0.7*
Letter Task *n-1*	7.2 (1.0)	8.8 (1.0)	*1.6*	5.2 (0.5)	4.3 (0.4)	*−0.9*
Switch costs n	*3.8*	*2.1*		*0.3*	*0.5*	
Experiment 2						
Color Task *n-1*	5.9 (0.5)	9.0 (0.7)	*3.1*	4.6 (0.7)	5.6 (0.8)	*1.0*
Letter Task *n-1*	6.8 (0.8)	9.8 (0.9)	*3.0*	7.3 (0.7)	8.3 (0.8)	*1.0*
Switch costs n	*0.9*	*0.8*		*−2.7*	*−2.7*	
Experiment 3						
Color Task *n-1*	3.6 (0.4)	9.9 (0.7)	*6.3*	3.3 (0.7)	4.0 (0.6)	*0.7*
Letter Task *n-1*	6.5 (0.9)	8.3 (1.0)	*1.8*	4.4 (0.4)	4.7 (0.5)	*0.3*
Switch costs n	*2.9*	*−1.6*		*−1.1*	*−0.7*	

processing difficulty of the color task stimuli as reflected in choosing the color task more often when the color discrimination was easy compared to hard, and there was no evidence that this discriminability effect on task preference depended on whether a color or letter task was performed in the previous trial.

Before elaborating further on these findings, however, we need to consider that participants were instructed to randomly select tasks. Although this additional instruction is needed to induce some variance in choice behavior (i.e., without any further instruction, participants usually primarily repeat tasks, cf. Arrington & Reiman, 2015; Kessler et al., 2009), this may impose additional demands that may distort participants' choice behavior in a way not normally seen without this instruction (e.g., Liefooghe et al., 2010; Lien & Ruthruff, 2008, see also Arrington, Reiman, & Weaver, 2014 for discussion of this issue). For example, in the present study one might argue that participants actually did not adapt their choice behavior to current perceptual processing demands to improve task performance, but they somehow used the random changes in color discriminability to better fulfil the instruction to select tasks randomly. Even if this is the case, however, it is noteworthy that people tended to choose the color task when the color stimulus was easy to discriminate. In principle, they could equally well have used discriminability to aid randomness by choosing the color task when its stimulus was hard to discriminate. In any case, in Experiment 2, we investigated whether the findings of Experiment 1 would generalize to a VTS task environment that avoids the randomness instruction.

3. Experiment 2

The previous results suggest that task-specific perceptual processing demands influenced task selection. Experiment 2 aimed to investigate whether this pattern would generalize to another VTS paradigm, the self-organized task switching paradigm introduced by Mittelstädt et al. (2018). Specifically, the onset of the task stimulus performed in trial n-1 was delayed in trial n by a certain SOA and this SOA increased with each additional repetition of the task. Thus, if participants wanted to repeat tasks, they had to wait longer for the repetition stimulus, whereas no waiting was required when they wanted to switch tasks. In this paradigm, reasonable variance in task choice behavior can be also achieved without the randomness instruction (i.e., mean switch rates ranged from 0.16 to 0.49 in the eight experiments reported by Mittelstädt et al., 2018, 2019, 2021). Thus, the random changes in color stimulus discriminability will now be implemented with the dynamic procedure of repeat-versus-switch stimulus availability. As in Experiment 1, we reasoned that an easy color discrimination makes the color task goal be available sooner and this makes it more likely to select the color task.

3.1. Method

3.1.1. Participants

We tested again 40 native German speakers at the University of Freiburg, Germany, but data of six participants were excluded due to fewer than 10 valid trials in at least one condition after the data trimming procedure. The remaining 34 participants (27 female) ranged in age from 19 to 34 years ($M = 23.97$), and 28 were right-handed.

3.1.2. Apparatus, stimuli and procedure

The apparatus, stimuli, and procedure were the same as in Experiment 1 except for the following changes. Following the adaptive delay procedure by Mittelstädt et al. (2019), stimuli for the two tasks (letter surrounded by colored square) were only presented simultaneously in the first trial of a block, whereas in the remaining trials only the stimulus needed for a task switch was presented immediately. The other (potential repetition) stimulus was presented with an SOA that depended on the number of consecutive task repetitions. Specifically, the SOA linearly increased by an additional 50 ms with each task repetition until it was reset by a task switch (i.e., SOA step size = 50 ms). Participants were instructed that the stimulus for one of the tasks appeared later than the other task and that they should select the tasks to minimize the time in each trial (i.e., no randomness instruction). Specifically, participants received a German version of the following instructions

> *"You have to respond to 50 colors (25 easy and 25 hard to discriminate colors) and 50 letters in each block. Try to perform all of these 100 tasks as quickly and accurately as possible: Reaction time measurement starts with the onset of the first task stimulus (i.e., letter or colored square), and responses can be given after this onset. You can freely decide which task you want to perform in one trial, but try to respond as quickly and accurately as possible. If a #-sign or a grey square appear instead of one task, you have to wait to perform the other task."*

3.2. Results

We followed the same data preparation procedure as in Experiment 1: The practice blocks with cued task order, the first two free choice blocks, and the first trial of each block were excluded from any analyses. We then excluded any trials without the possibility of choosing between the two tasks (9.1%). Further, trials in which a response was given prior to stimulus onset (<0.1%) and post-error trials (7.9%) were removed for all analyses. For RT and task selection analyses, 8.0% error trials were additionally excluded as well as trials with RTs <200 ms (0.2%) or >3000 ms (0.2%). Note that the reported RTs always indicate the time from the onset of the stimulus related to the task that the participant performed until the key press.

3.2.1. Task choice

Overall, the mean percentage of trials on which the color task was performed was 50.2%. Table 1 shows mean color task rates as a function of discriminability of the color-stimulus in the current trial and the task performed in the previous trial. As in Experiment 1, a 2x2 ANOVA on these means revealed that both main effects were significant: The significant main effect of current color discriminability reflected more color task-choices when the color discrimination was easy (52.5%) compared to hard (47.8%), $F(1,33) = 5.94$, $p = .020$, $\eta_p^2 = 0.15$. The significant main effect of previous task reflected more color-task choices when in the previous trial the color task (67.8%) instead of the letter task (32.6%) was performed, $F(1, 33) = 54.78$, $p < .001$, $\eta_p^2 = 0.62$. However, in contrast to Experiment 1, the interaction was also significant, indicating that the preference to select the color task with easy over hard color task stimuli was somewhat larger when the previous trial was the letter than the color task., $F(1, 33) = 5.5$, $p = .025$, $\eta_p^2 = 0.14$.

3.2.2. Task performance (RTs and PEs)

Table 2 displays mean median reaction times as a function of the three conditions (i.e., previous task, current task and current color-stimulus discriminability). A 2x2x2 ANOVA on these means revealed significant main effects of current color discriminability and previous task (all $ps < 0.001$, all η_p^2s > 0.30). As in Experiment 1, each of these two main effects was modulated by the current task condition. The significant interaction between current color discriminability and current task indicated that color task responses were more affected by color discriminability (585 vs. 658 ms) than letter task responses (605 vs. 619 ms), $F(1, 33) = 32.66$, $p < .001$, $\eta_p^2 = 0.50$. The significant interaction between current task and previous task indicated switch costs: Responses were slower when switching than repeating the color task (731–512 = 219 ms) as well as when switching instead of repeating the letter task (686–539 = 147 ms), $F(1, 33) = 65.53$, $p < .001$, $\eta_p^2 = 0.67$. No other effects were significant (all $ps > 0.342$, all η_p^2s < 0.03).

The 2x2x2 ANOVA on mean PEs (Table 3) revealed that all main effects were significant (all $ps < 0.003$, all η_p^2s > 0.24). Furthermore, there was a significant interaction between current task and current color discriminability indicating a larger increase in errors for hard compared to easy color stimuli when participants performed the color task (9.4–6.4 = 3.0%) than the letter task (6.9–6.0 = 0.9%), $F(1, 33) = 9.79$, $p = .004$, $\eta_p^2 = 0.23$. No other effects were significant (all $ps > 0.106$, all η_p^2s < 0.08).

3.3. Discussion

The results of Experiment 2 replicated all major findings of Experiment 1. The color discriminability effects on RT and PE were primarily reflected when performing the color task, and substantial switch costs were found for the two tasks. More importantly, the choice pattern indicated again that the perceptual difficulty biased participants' task selection behavior towards selecting the color task more often when the color stimulus was easy vs hard to discriminate. Considering that we did not instruct participants to select tasks randomly as in Experiment 1, this suggests that participants' perceptual choice bias was not simply a by-product of the randomness instruction.

4. Experiment 3

This experiment aimed to provide another conceptual replication of the results found in the previous experiment by using different stimuli. Specifically, we again used the self-organized task switching paradigm and participants had to perform the same tasks, but we presented a colored number rather than a colored square in addition to the letter stimulus in each trial. This change was implemented in order to make sure that the stimulus display always changed from trial to trial. In the previous experiment, full stimulus repetitions were possible (e.g., red easy colored square in trial n-1, red easy colored square in trial n). Feature-based control settings are known to affect behavior in task switching settings (e.g., Arrington et al., 2010; Schmidt & Liefooghe, 2016), and as mentioned in the introduction these settings may also artificially cause the discriminability-based effects on choice behavior in the previous experiments. To exclude this possibility, in this experiment, both the letter and also the number containing the color feature always changed from trial to trial.

4.1. Method

4.1.1. Participants

40 native German speakers were individually tested at the University of Freiburg, Germany, but data of three participants was excluded due to <10 valid trials in at least one condition after the data trimming procedure. The remaining 37 participants (24 female) ranged in age from 18 to 35 years (M = 24.1), and 33 were right-handed.

4.1.2. Apparatus, stimuli and procedure

The apparatus and stimuli were the same as in Experiment 2 except for the following changes. In each trial, a colored number (numbers 2–9) instead of a colored square was presented for the color task (e.g., green/blue) in addition to a letter for the letter task (i.e., consonant/vowel). The stimuli of the two tasks appeared one above the other at the center of the screen (distance: ~ 2 mm) with letter/digit stimulus location constant across the experiment but counterbalanced across participants. The color was again easy or difficult to discriminate by varying the line thickness of numbers (i.e., bold vs. not bold font) and the RGB values. Note that in each trial both a number and a letter were randomly selected with the constraint that no stimulus was presented twice consecutively.

4.1.3. Procedure

Participants first performed two practice blocks with 80 trials per block with cued task order similar to Experiment 1 (i.e., 40 color and 40 letter task) followed by 15 (instead of 13) blocks with 100 trials per block with the free choice procedure used for the experimental blocks in Experiment 1 (i.e., 50 color [25 easy and 25 hard] and 50 letter tasks). The RSI was set to 50 ms in this experiment.

4.2. Results

The practice blocks with forced choice, the first free choice block, and the first trial of each block were excluded from any analyses. We then excluded any trials without the possibility of choosing between the two tasks (7.1%). Further, trials in which a response was given prior to stimulus onset (< 0.1%) and post-error trials (6.0%) were removed for all analyses. For RT and task selection analyses, 6.0% error trials were additionally excluded as well as trials with RTs <200 ms (0.1%) and >3000 ms (0.1%).

4.2.1. Task choice

Overall, the mean percentage of trials on which the color task was performed was 49.8%. Table 1 shows again mean color-task choice rates as a function of previous task and current color discriminability. As in the previous two experiments, a 2x2 ANOVA revealed that both main effects were significant (with $p = .089$, $\eta_p^2 = 0.08$ for the interaction): The significant main effect of current color discriminability reflected more color task choices when the color discrimination was easy (52.7%) compared to hard (46.8%), $F(1, 36) = 15.90$, $p < .001$, $\eta_p^2 = 0.31$. The significant main effect of previous task showed again a strong repetition bias as reflected in less color-task choices when in the previous trial the letter task (23.8%) instead of the color task (75.7%) was performed, $F(1, 36) = 182.78$, $p < .001$, $\eta_p^2 = 0.84$.

4.2.2. Task performance (RTs and PEs)

Table 2 displays mean median RTs as a function of color-stimulus discriminability and task in the current trial separately as a function of which task was performed in the previous trial. A 2x2x2 ANOVA on RTs revealed significant main effects of current color discriminability, current task, and previous task (all $ps < 0.001$, all η_p^2s > 0.41). As in Experiment 2, however, there was a significant 2-way interaction between current task and current color discriminability indicating that color task responses were more strongly affected by color discriminability (670 ms vs. 745 ms) than letter task responses (647 ms vs. 660 ms), $F(1, 36) = 17.76$, $p < .001$, $\eta_p^2 = 0.33$. Furthermore, there was also a significant interaction between previous task and current task reflecting costs when switching to rather than repeating the color task (878–537 = 341 ms) and when switching to rather than repeating the letter task (760–547 = 213 ms), $F(1, 36) = 227.35$, $p < .001$, $\eta_p^2 = 0.86$. No other effects were significant (all $ps > 0.117$, all η_p^2s < 0.07).

The 2x2x2 ANOVA on mean PEs (Table 3) also revealed that all main effects were significant (all $ps < 0.034$, all η_p^2s > 0.11). A significant two-way interaction between current task and current color discriminability revealed a stronger color discriminability effect for the color task (9.1–5.0 = 4.1%) than the letter task (4.4–3.8 = 0.6%), $F(1, 36) = 17.85$, $p < .001$, $\eta_p^2 = 0.33$. There was also a significant two-way interaction between previous task and current color discriminability reflecting that the average PE difference between easy vs. hard discriminable color was larger when the previous task was a color (6.9–3.4 = 3.5%) than a letter task (6.5–5.4 = 1.1%), $F(1, 36) = 12.82$, $p = .001$, $\eta_p^2 = 0.26$. Finally, there was also a significant three-way interaction between all factors, $F(1, 36) = 11.48$, $p = .002$, $\eta_p^2 = 0.24$. As can be seen in Table 2, the stronger color discriminability effect for color compared to letter task responses was more pronounced for repetition compared to switch trials. Separate 2x2 ANOVAs for each previous task condition revealed that the two-way interaction between current task and current color discriminability was significant when the previous task was the color task, $F(1, 36) = 37.60$, $p < .001$, $\eta_p^2 = 0.51$, but not when the previous task was the letter task, $F(1, 36) = 1.59$, $p = .216$, $\eta_p^2 = 0.04$. In other words, the color discriminability effect is especially large for the second of two consecutives color tasks.

4.3. Discussion

The results of Experiment 3 replicate all major findings observed in the previous two experiments in a design without any full feature repetitions. Thus, these findings reinforce the idea that task goals are not automatically activated by specific environmental features and that instead some perceptual processing has taken place before a task goal is selected for further processing.

5. Experiment 4

In the first three experiments, we established perceptual difficulty as a novel factor driving voluntary task choice behavior–that is, people are biased to choose the task associated with an easy- compared to hard-to-discriminate stimulus. As mentioned in the introduction, we propose that participants can adapt to the unpredictable perceptual processing demands by at least partially processing target-related information before actually choosing a task goal. This idea receives further support from dual-task research using the psychological refractory period (PRP) paradigm (for a review, see Pashler, 1994) demonstrating parallel perceptual processing of two tasks' stimuli with the same or similar discriminability manipulation that we have used in the first three experiments (e.g., De Jong, 1993; Jentzsch et al., 2007; Miller & Durst, 2015). However, one may also argue that varying the saturation of color task stimuli only produced the effect in choice behavior due to a bias in early exogenous attentional processes prior to perceptual processing. For example, task choice might simply be influenced by whichever stimulus is allocated visual attention, and a more highly saturated color signal might more strongly attract visual attention to the color task stimulus.

In Experiment 4, we addressed this concern by investigating whether the pattern of the first three experiments would replicate when using a different perceptual type of manipulation. Specifically, as can be seen in Fig. 1, for the color task, participants had to decide whether there were more blue or red dots surrounding the letter task stimulus and we varied only the ratio of the differently colored dots across conditions (i.e., color ratio easy: 90% vs. 10%; color ratio hard: 62.5% vs. 37.5%). Since the size and overall number of dots as well as the colors of individual dots were equal across conditions, it seems difficult to argue that there was a salience difference between the easy and hard conditions. Moreover, we decided to use another voluntary task switching procedure, the hybrid free-forced choice task-switching paradigm in which voluntary ("free") and non-voluntary ("forced") trials are combined (e.g., Fröber & Dreisbach, 2017; Jurczyk, Fröber, & Dreisbach, 2019). This allowed us to get a "pure" measure of the color task difficulty effect in task performance of forced choice trials because task performance in these trials is not confounded by task choice behavior. Finally, in contrast to the previous experiments, we omitted any reference to the color task manipulation in our instructions, and participants were also not explicitly instructed to select and perform the tasks as quickly and accurately as possible.

5.1. Method

5.1.1. Participants

60 participants were tested online. All participants provided informed consent and received monetary compensation for participation. Following our preregistration, data from 16 participants were excluded[7] (see also Results section). The remaining 44 participants (23 female, 39 right-handed) ranged in age from 18 to 65 years (M = 27.66 years).

5.1.2. Apparatus and stimuli

The experiment was conducted online using the JavaScript library jsPsych (De Leeuw, 2015). All visual stimuli were presented on a grey background. A centrally positioned plus sign served as fixation point. The letter task and its stimuli were identical to the previous three experiments. For the color task, participants had to classify whether the dots surrounding the letter (cf. Fig. 1) were primarily red or blue by pressing a left vs. right key. Critically, the classification was either easy or difficult because of the proportions of the two colored dots (i.e., color ratio easy: 90% vs. 10%, color ratio hard: 62.5% vs. 37.5%). As in the previous experiments, responses for each task were made with the index and middle finger of the same hand and the task-to-hand mapping was counterbalanced across participants whereas the specific response-finger mappings were randomly selected for each participant.

5.1.3. Procedure

Participants were tested in 8 blocks of 104 trials per block (i.e., 832 trials in total). Each experimental block consisted of 50% free choice and 50% forced choice trials. The color task was easy in half of the free choice trials and difficult in the other half. Furthermore, half of the forced choice trials required a response to the letter task whereas the other half required a response to the color task (with equal frequencies of hard and easy color forced task stimuli in each block).

At the beginning of each trial, the fixation cross appeared on the screen for 500 ms. In free choice trials both color and letter task stimuli were displayed at the offset of the fixation cross. In forced choice trials, only one stimulus (i.e., letter or color) was presented. Following correct responses, a blank screen with an intertrial interval (ITI) of 750 ms was presented before the next trial started. In case of an error, an additional error screen was presented for 3 s.

Participants were instructed that in free choice trials, they were free to perform whichever task they wanted. However, in forced choice trials they had to perform the task related to the presented stimulus. The stimulus (stimuli) remained on the screen until the participant responded.

5.2. Results

We first categorized the task performed on each trial based on the hand used to respond. The first block and the first trial of each block were excluded from all analyses. Furthermore, we excluded trials with RTs $<$200 ms or $>$3000 ms from all analyses (1.6%). For RT and task choice analyses, we additionally excluded any erroneous trial.

After our data trimming procedure, we examined whether participants followed any consistent global task choice strategies in free choice trials (i.e., always selecting the same task or always selecting the same or the alternative task as was performed in the previous trial) which may overshadow any potential effects of the central color task manipulation. Specifically, we excluded 10 participants who selected the letter task in $>$95% of free choice trials and 4 participants who selected the color task in $>$95%. Furthermore, we excluded data from two additional participants due to exceptionally high RTs (mean RTs of $>$1800 ms). No data of other participants had to be excluded due to the preregistered criteria. Further, all of the results below were very similar when including the data of all participants.

5.2.1. Task choice

Table 1 shows the mean percentage of color task choices as a function of the discriminability of the color-stimulus in the current trial and of the task performed in the previous trial (averaged over previous free and forced choice trials). A 2x2 ANOVA on these means revealed significant main effects of current color discriminability, $F(1, 43) = 26.95, p < .001$, $\eta_p^2 = 0.39$, and previous task, $F(1, 43) = 279.56$, $p < .001$, $\eta_p^2 = 0.87$. There were more color task-choices when the color discrimination was easy (46.6%) compared to hard (34.3%), and there were also more color task-choices when the color task was performed in the previous trial (62.9%) than when the letter task was performed previously (17.9%). The interaction was also significant, $F(1, 43) = 15.30$, $p < .001$, $\eta_p^2 = 0.26$. As can be seen from Table 1, the preference to select the color task with easy over hard stimuli was present for both previous task responses

[7] https://osf.io/vce2s.

Table 4
Mean median reaction times (RT) and mean percentage errors (PE) in the color task in forced choice trials in experiment 4 as a function of the color stimulus discrimimability (easy color n vs. hard color n) and the previously performed task (i.e., color task n-1 or letter task n-1). Switch costs are RT differences in color task rt in trial n for letter task n-1 versus color task n-1. Discriminability costs represents differences in hard color n minus easy color n conditions. Standard error of the means in parentheses.

	Color task RT and PE in trial *n*		
	Easy color *n*	Hard color *n*	*Discriminability costs n*
RT in ms			
Color Task *n-1*	654 (17)	821 (26)	*167*
Letter Task *n-1*	890 (23)	1072 (33)	*182*
Switch costs n	*236*	*251*	
PE in %			
Color Task *n-1*	3.2 (0.7)	4.7 (0.8)	*1.5*
Letter Task *n-1*	8.1 (1.3)	8.0 (1.2)	*−0.1*
Switch costs n	*4.9*	*3.3*	

($ps < 0.002$) with a larger difference in choice percentage when the previous trial was the color than letter task.

5.2.2. Task performance (RTs and PEs in forced choice trials)

Table 4 displays mean median RTs for the color task as a function of previous task and current color-stimulus discriminability. A 2x2 ANOVA[8] on these color task RT means revealed significant main effects of color discriminability and previous task (both $ps < 0.001$, both η_p^2s > 0.73), but no significant interaction ($p = .386$, $\eta_p^2 = 0.02$). Responses were slower when the color discriminability was hard (946 ms) vs. easy (772 ms) and when switching to (981 ms) instead of repeating (737 ms) the color task. A parallel ANOVA on color task PEs revealed only a significant main effect of previous task ($p < .001$ and $\eta_p^2 = 0.44$; all other $ps > 0.151$, η_p^2s < 0.05), reflecting more errors when switching (8.0%) than repeating (4.0%) the color task.

For completeness, we also analysed letter task performance in forced choice trials as a function of the previous task. Responses were slower and more error prone when switching (805 ms and 4.3%) instead of repeating (651 ms and 3.0%) the letter task, but the difference was only significant in RTs ($p < .001$, $\eta_p^2 = 0.71$) and not PEs ($p = .107$, $\eta_p^2 = 0.06$).

5.3. Discussion

In line with the previous three experiments, participants were biased to repeat tasks and they were also biased to select the color task more often when the color stimulus was easy versus hard to discriminate. Moreover, the task performance data in forced choice trials revealed the presence of both perceptual (discriminability effects) and cognitive (switch costs) processing demands. Thus, this experiment provides further support for a task choice model according to which some perceptual processing takes place before a task goal is actually selected.

6. General discussion

In the present study, we wanted to know whether people incorporate unpredictable task-specific perceptual processing demands into their task choice behavior when they freely decide which of two tasks to perform. Specifically, we hypothesized that they may do so because some perceptual task processing can take place before a task goal becomes sufficiently activated in order to determine the choice. We tested this possibility by varying the perceptual difficulty of stimuli related to one of the two tasks (i.e., the color task) across four experiments.

In all experiments, performance data revealed a strong stimulus discriminability effect in color task RTs indicating that our discriminability manipulation was effective. Furthermore, substantial switch costs were found. Together, these findings suggest the presence of both perceptual (i.e., color discriminability effect) and cognitive (i.e., switch costs) processing demands. More importantly, in all experiments participants adapted their task choice behavior to both cognitive processing demands (as reflected in a task repetition bias) and perceptual processing demands (as reflected in a bias to select the color task with easy compared to hard stimuli). Because the perceptual difficulty of the color task stimuli changed unpredictably on a trial-by-trial basis, participants could only adapt to perceptual processing demands by reactively adjusting during a trial. Thus, these findings suggest that participants engage in some perceptual processing before they finally select and deliberately continue processing one of the two tasks.

As reviewed in the introduction, it is usually assumed that people guide their voluntary task choice behavior based on the most active task goal, and several studies have demonstrated that people are able to proactively adjust task goal activations based on predictable changes of the task environment (e.g., Dreisbach & Fröber, 2019; Szumowska & Kruglanski, 2022). For example, Szumowska and Kruglanski (2022) have shown that the degree of engaging in sequential multi-tasking (task switching) depends on the relative activation of different task goals (e.g., multitasking increases when people maintain more active goals). A theoretical implication of the current findings is that perceptual processes can bias task goal activation on the fly. For example, it seems likely that perceptual processing of the separate stimuli for two tasks proceeds in parallel, thereby increasing goal activations of the two tasks goals in parallel. Once a goal is sufficiently activated, a task is chosen and more central cognitive processes take place. In the present experiments, because the goal activation threshold to choose a task was reached earlier with easy compared to hard color stimuli, participants were biased to choose the color task with lower perceptual processing demands. Interestingly, the specific temporal perceptual processing demands in RTs were twice as large as the temporal delays (switch SOA) incorporated in choice behavior in Experiment 2 and 3 (see Appendix A). Thus, the decision about which task to perform is not based entirely on the time at which the color discrimination is made. It appears that the goal activation threshold is reached before perceptually identifying the color, which may suggest a locus of task choice during perceptual processing. In any case, a practical implication of these findings is that not only offloading task goals from working memory but also eliminating external information related to task goals could prevent potential negative impacts (e.g., distraction, task confusion) of engaging in multitasking.

On a more functional level, the current findings strengthen the idea that the avoidance of mental effort is an important factor in driving voluntary behavior (e.g., Brosowsky & Egner, 2021; Gutzwiller et al., 2019; Irons & Leber, 2018; Kool et al., 2010; Shenhav et al., 2017). Because participants' choice behavior was sensitive to both perceptual and cognitive processing demands, the present study also suggests that effort avoidance may relate to partially distinct mental processes. It should be noted that effort avoidance may not necessarily reflect irrational behavior and instead could at least partially also indicate rational attempts to optimize task performance (e.g., Dreisbach & Jurczyk, 2021; Frömer, Lin, Wolf, Inzlicht, & Shenhav, 2021; Gray et al., 2006; Leonhard, Fernández, Ulrich, & Miller, 2011; Mittelstädt et al., 2019). Some additional support for the idea that task choice may be linked to the expected (objective) task performance costs in the present study comes when considering the time (i.e., as measured by SOA) when participants decided to switch tasks in Experiment 2 and 3. As elaborated in

[8] As can be seen in our preregistration, we had actually stated that we would conduct a 2x2x2 ANOVA with the factors of color discriminability, previous task, and current task on forced choice mean RTs and PEs as in the previous three experiments. However, we then realized that this analysis is not possible because there is no color task stimulus—and hence no color discriminability manipulation—in forced choice letter task trials, so we had to analyze the two tasks separately.

Appendix A, we reanalysed all results in terms of voluntary task switching behavior in order to explore how the condition-specific costs of task switching were traded off against the temporal costs of waiting for the repetition stimulus. In essence, these analyses indicate that participants tended to switch task when the switch costs matched or were larger than SOA waiting times–that is, task choice behavior that helps to optimize local (i.e., switch cost = switch SOA) or global (i.e., switch cost > switch SOA) task performance (cf. Mittelstädt et al., 2021). Thus, it seems worthwhile to consider performance optimization and different mental processes when further illuminating the role of mental effort in driving voluntary task choice behavior.

Compliance with ethical standards

All authors declare that they have no conflict of interest. All procedures were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards as well as with the EU and national data security regulations (GDPR and DSGVO). Informed consent was obtained from all participants.

Open practice statement

Raw data of all experiments are available via the Open Science Framework (OSF) at https://osf.io/bfky8/. Preregistration of Experiment 4 is also available via the OSF at https://osf.io/vce2s.

CRediT authorship contribution statement

Victor Mittelstädt: Conceptualization, Methodology, Software, Formal analysis, Writing – original draft. **Jeff Miller:** Conceptualization, Methodology, Writing – review & editing. **Andrea Kiesel:** Conceptualization, Methodology, Writing – review & editing, Supervision, Funding acquisition.

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Appendix A

In this appendix, we report task selection behavior in terms of task *switching* (i.e., switch rates in Experiment 1–4, switch SOA in Experiments 2 & 3) as well as a comparison of switch costs with switch SOA in Experiments 2 and 3 (cf. Mittelstädt et al., 2019).

A.1. Switch rates (experiments 1–4)

As can be seen in Table A1, the decision to switch tasks was strongly influenced by the interactive effect of previous task and current color task discriminability in all experiments. If participants performed the color task in the previous trial, they switched less (i.e., stayed with the color task more) when the current color stimulus was easy compared to hard to discriminate, whereas they switched more (i.e., selected the color task more) when they performed the letter task in the previous trial. Thus, the 2x2 ANOVAs with the factors of previous task and current color discriminability revealed significant interactions in all experiments. In other words, this interaction reflected a stronger preference for the color task when the color stimuli was easy compared to hard (as reflected in repeating or switching to the color task depending on previous task choice). Thus, the corresponding test-statistics of these interaction are similar to the test statistics related to the main effects of current color discriminability observed in the ANOVA on color task choices reported in the main text.

A.2. Switch SOA (experiments 2 and 3)

We also explored whether the effect of color discriminability on task selection would appear when measuring switching behavior in terms of switch SOA (i.e., how much SOA is needed to promote a task switch in the corresponding conditions). To calculate switch SOAs, we followed the procedure described in the Appendix of Mittelstädt et al. (2019). Specifically, we computed the proportion of switches at each SOA separately for each participant and separately for each of the four conditions (i.e., Color-Task n/Letter-Task n X Color-Easy n/Color-Hard n) and accumulated the probabilities across SOAs. We then computed the corresponding individual interpolated median switch SOAs for each condition based on the corresponding cumulative probability distribution functions. Table A1 shows the corresponding median switch SOA for each condition. The descriptive pattern indicates that in both Experiments 2 and 3 the switch SOA mirrored the switch rate pattern. Specifically, switch SOA (i.e., when switching to the letter task) was smaller for hard compared to easy color stimuli when the previous task was a color task, whereas switch SOA (i.e., when switching to the color task) was larger for hard compared to easy color stimuli when the previous task was a letter task. For each of the two experiments, a 2x2 ANOVA with the factors of current color discriminability and previous task was conducted on these switch SOAs.

Experiment 2. The 2x2 ANOVA revealed no significant main effects (both $ps > 0.634$ and η_p^2s < 0.01) and no significant interaction, $F(1, 33) = 2.0$, $p = .166$, $\eta_p^2 = 0.06$.

Experiment 3. In contrast to Experiment 2, this ANOVA revealed in addition to a significant main effect of discriminability, $F(1, 36) = 7.45$, $p = .010$, $\eta_p^2 = 0.17$, a significant interaction, $F(1, 36) = 16.54$, $p < .001$, $\eta_p^2 = 0.32$.

A.3. Comparison of switch costs with switch SOA (experiments 2 and 3)

Table A1 also displays the mean median switch costs for the corresponding conditions. In order to compare the sizes of switch SOAs to the sizes of switch costs, we first directly compared these measures via paired *t*-test separately for each condition. For completeness, in order to see whether the chosen trade-offs differ across conditions, we also conducted 2x2 ANOVAs with the factors of current color discriminability and previous task on the difference scores (i.e., switch cost minus SOA, see Table A1).

Experiment 2. When the previous task was the letter task, there were no significant differences between switch costs and switch SOAs for current color easy, $t(1, 33) = 0.05$, $p = .962$, $\eta_p^2 < 0.01$, or for current color hard, $t(1, 33) = 0.55$, $p = .587$, $\eta_p^2 < 0.01$. When the previous task was the color task, switch costs were (marginal) significantly slightly larger than switch SOA for current color easy, $t(1, 33) = 2.03$, $p = .050$, $\eta_p^2 = 0.11$, and current color hard, $t(1, 33) = 2.48$, $p = .019$, $\eta_p^2 = 0.16$. The 2x2 ANOVA on the mean difference scores only yielded a significant main effect of previous task, $F(1, 33) = 11.85$, $p = .002$, $\eta_p^2 = 0.26$. Thus, these analyses suggest that participants seemed to equally trade off switch costs against switch SOA when the previous task was the letter task, although they switched at SOAs somewhat smaller than their costs when they previously performed the color task.

Experiment 3. When the previous task was the letter task, there were no significant differences between switch costs and switch SOA for current color easy, $t(1, 36) = 0.14$, $p = .893$, $\eta_p^2 < 0.01$ and for current color hard, $t(1, 36) = 0.30$, $p = .770$, $\eta_p^2 < 0.01$. When the previous task was the color task, switch costs were significantly larger than switch SOA for current color easy, $t(1, 36) = 4.17$, $p < .001$, $\eta_p^2 = 0.33$, and for current color hard, $t(1, 36) = 4.69$, $p < .001$, $\eta_p^2 = 0.38$. The 2x2 ANOVA on the mean differences scores revealed a significant main effect of previous task, $F(1, 36) = 37.95$, $p < .001$, $\eta_p^2 = 0.51$. Thus, these analyses suggest that participants were quite good at trading off the condition-specific costs when deciding to switch away from the letter task but not when deciding to switch away from the color task. We have no explanation for this task asymmetry

Table A1
Mean percentage of switch choices in the current trial n as a function of discrimimability of the color stimulus in the current (easy color n vs. hard color n) and the task performed in the previous trial (color task n-1, letter task n-1) separately for experiment 1, 2, 3 and 4. For experiment 2 and 3, the corresponding condition-specific mean median switch costs, switch SOA and switch (cost minus SOA) are additionally displayed. Standard error of the means in parentheses.

	Color task *n-1*		Letter task *n-1*	
	Easy color *n*	Hard color *n*	Easy color *n*	Hard color *n*
Experiment 1				
Switch choice in %	30.7 (2.4)	38.1 (2.2)	37.8 (2.4)	29.9 (2.3)
Experiment 2				
Switch choice in %	30.5 (2.5)	33.9 (2.7)	35.6 (2.7)	29.5 (2.7)
Switch cost RT in ms	222 (24)	216 (25)	144 (24)	150 (23)
Switch SOA in ms	162 (19)	148 (18)	143 (20)	160 (17)
Switch (Cost Minus SOA)	*60*	*68*	*1*	*−10*
Experiment 3				
Switch choice in %	21.8 (1.8)	26.7 (2.3)	27.3 (2.6)	20.3 (1.7)
Switch cost RT in ms	346 (28)	337 (27)	197 (18)	229 (19)
Switch SOA in ms	226 (20)	210 (20)	199 (19)	234 (19)
Switch (Cost Minus SOA)	*120*	*127*	*−2*	*−5*
Experiment 4				
Switch choice in %	28.8 (3.1)	54.8 (3.5)	78.0 (3.2)	86.2 (2.3)

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