

People are sensitive to environmental predictability when engaging cognitive control

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### **Abstract**

People flexibly engage either proactive or reactive control to achieve goals in dynamic environments. However, it remains unclear how specific environmental factors determine when proactive control is most effectively used. Across two experiments this study investigated how environmental predictability influences proactive control. We employed a self-paced task-switching paradigm in which adult participants triggered the target when they felt ready to respond to it and manipulated how reliably contextual cue information predicted the task rule. In Experiment 1, a fully predictable environment (100% cue reliability) led to longer preparation times, reflecting spontaneous proactive preparation, faster responses, and reduced switch costs compared to an unpredictable environment (50% reliability), indicating adaptive engagement of proactive control based on cue reliability. Experiment 2 further examined the relations between cue reliability and proactive control by comparing a more reliable condition (85% reliable cues) to a less reliable condition (65% reliable cues). Findings revealed that participants spent more time preparing under 85% reliability and showed larger performance differences between “matched” (cue accurately predicting the task) and “unmatched” trials. These results reinforce the view that adults can detect subtle differences in cue reliability and adjust their proactive control accordingly. Finally, an integration of the findings from Experiment 1 and 2 suggests that two thresholds of cue reliability govern both the decision to engage and the effectiveness of cognitive control when adults modulate their proactive control based on environmental predictability.

**Key words:** proactive control, self-preparation, cue reliability, task-switching

1                   **People are sensitive to environmental predictability**

2                                   **when engaging cognitive control**

3           Cognitive control processes are integral to our goal-directed behaviors, enabling  
4 individuals to adapt to dynamic and ever-changing environments. These processes are  
5 flexibly adjusted to meet moment-to-moment variations in task demands (Braem et al.,  
6 2019; Egner, 2023). Cognitive control can be temporally engaged through two distinct  
7 modes: proactive control and reactive control (Braver, 2012). Proactive control allows  
8 individuals to anticipate and prepare for upcoming events, thus engaging mental effort  
9 early to bias the cognitive system to prevent or minimize the effects of interference  
10 before it occurs; reactive control is instead mobilized later in response to unforeseen  
11 events to resolve interference after it occurs. Critically, the efficiency of these modes  
12 depends on the predictability of upcoming events or task demands (Braver, 2012;  
13 Chevalier et al., 2020; Munakata et al., 2023). Specifically, proactive control facilitates  
14 accurate and rapid responses to predictable events, while reactive control supports  
15 flexible responses to unpredictable ones. Moving beyond the traditional dichotomy of  
16 predictable versus unpredictable environments, the current study further examined how  
17 adults adaptively modulate their use of cognitive control modes in response to varying  
18 levels of environmental predictability.

19           A range of experimental paradigms has been employed to examine the use of  
20 proactive and reactive control, including the AX-CPT (e.g., Braver et al., 2007;  
21 Chatham et al., 2009), working memory tasks (e.g., Bhandari & Badre, 2018; Cowan et  
22 al., 2021), the Stroop task (e.g., Bugg & Smallwood, 2016), and the cued task-switching  
23 paradigm (e.g., Chevalier et al., 2015; Elke & Wiebe, 2017). In the cued task-switching

1 paradigm, participants are instructed to classify bivalent stimuli (e.g., blue bear, blue  
2 car, pink bear, pink car) according to one of two task rules (e.g., color or shape), as  
3 indicated by contextual cues presented before each trial. Proactive control involves  
4 activating task-relevant goals based on these contextual cues prior to the appearance of  
5 the target stimulus, while reactive control entails goal activation only after the target has  
6 been presented. Previous studies using the cued task-switching paradigm have shown  
7 that when contextual cues appear ahead of the target, adults spontaneously use the cue  
8 information to prepare for sorting the upcoming target according to one of task rules  
9 (e.g., Chevalier et al., 2015, 2020; Jin et al., 2020; Yanaoka et al., 2024) (see Figure 1).  
10 Such proactive preparation is associated with faster responses (e.g., Chevalier et al.,  
11 2015; Yanaoka et al., 2024), greater pupil dilation reflecting more mental effort (e.g.,  
12 Beauty, 1982, Chatham et al., 2009), and a more pronounced (pre)cue-locked posterior  
13 positivity in EEG measures reflecting proactive task selection (e.g., Karayanidis et al.,  
14 2009), compared to when contextual cues are not available in advance. These findings  
15 suggest that when they have access to informative cue information in advance, adults  
16 rely on proactive control to optimize performance.

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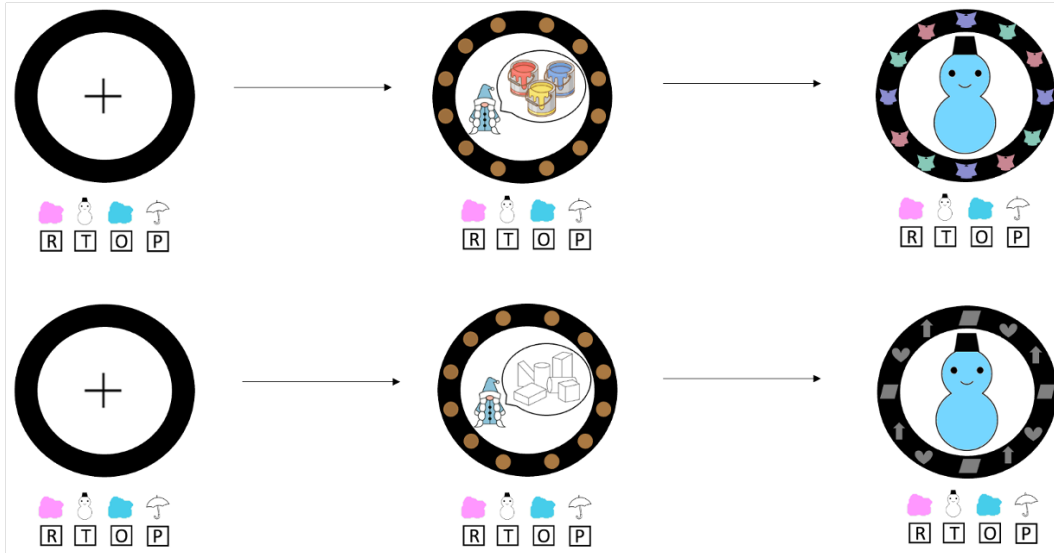
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1 **Figure 1.**

2 *Illustration of the cued task-switching paradigm.*



3 *Note.* After the presentation of a fixation point (left), contextual cues represented by an  
 4 elf (middle), indicating either color-matching (upper middle) or shape-matching (lower  
 5 middle), are presented before the onset of the cue and target (right). Contextual cues  
 6 make proactive preparation possible but not necessary.

7 Environmental reliability is a complex construct (Munakata et al., 2023), which is  
 8 determined by various components (i.e., timescales, locations, actions, people, and  
 9 outcomes) and their interactions. Chevalier et al. (2020), however, focused on one well-  
 10 controlled dimension of environmental reliability: the predictability of the upcoming  
 11 task based on a specific visual cue in the cued task-switching paradigm. This approach  
 12 allows one to isolate the effect of the reliability of a single environmental feature on  
 13 proactive preparation, while holding other, more complex contextual factors constant.  
 14 Specifically, they manipulated whether contextual cue information, which explicitly  
 15 signals one of two possible task rules (color or shape), reliably predicted a correct task  
 16 rule. In the reliable condition, task cues presented ahead of the target consistently  
 17 predicted the upcoming task on all trials, hence making proactive control a highly  
 18 effective strategy for improving performance. In contrast, in the unreliable condition,

1 task cues predicted the upcoming task correctly on only half of the trials. In this context,  
2 proactive preparation based on the cue would be inefficient and risky, as the effort is  
3 just as likely to lead to preparation for the wrong task as the correct one. In addition,  
4 Chevalier et al. also included an uninformative condition, where meaningless cue  
5 information was provided to make proactive preparation impossible. They found that  
6 adults engaged in greater proactive control—evidenced by behavioral, pupillometry,  
7 and EEG data—in the reliable condition compared to the unreliable and uninformative  
8 conditions. Chevalier et al. (2020) thereby provided evidence for adaptiveness in  
9 proactive control engagement as a function of contextual cue reliability.

10 The current study extends this work in two key ways to further investigate the  
11 relationship between contextual cue reliability and proactive control adaptiveness. First,  
12 we aimed to build on the findings of proactive preparation. Chevalier et al. (2020)  
13 directly assessed proactive control engagement while task cues were presented using  
14 both event-related potentials (ERPs) and pupil dilation. Their findings indicated that  
15 adults showed more proactive control engagement in the reliable than unreliable  
16 condition, and greater ERP magnitude predicted faster responses in the reliable  
17 condition. To provide further converging evidence, we focused on a different direct  
18 measure of proactive preparation: the extent to which participants proactively prepare  
19 for upcoming targets and how long they do so based on task cues. Given this, the  
20 current study utilized a self-paced task switching paradigm (Chevalier & Blaye, 2016;  
21 Longman et al., 2017; Meiran et al., 2002), in which the participant triggers the onset of  
22 the target while task cues are presented. This allows participants to decide, without time  
23 pressure, when they feel ready to respond. This paradigm allows us to measure these

1 self-paced preparation times, defined as the intervals between cue onset and self-paced  
2 target onset, to directly examine whether or not individuals engage proactive  
3 preparation. Following Chevalier et al. (2020), Experiment 1 compared a reliable  
4 condition, where contextual cues are 100% reliable and perfectly predictable, to an  
5 unreliable condition, where contextual cues are 50% reliable and completely  
6 unpredictable. We predicted that participants would exhibit longer self-paced  
7 preparation times, indicative of greater proactive preparation, in the reliable condition  
8 compared to the unreliable condition.

9       Second, the current study aimed to examine whether the decision to use proactive  
10 control occurs under conditions of *partial* predictability. Chevalier et al. (2020)  
11 compared just two conditions: one in which information about the upcoming task was  
12 entirely predictable and another in which it was entirely unpredictable. They  
13 demonstrated that adults did not use proactive control adaptively in the totally  
14 unpredictable environment. However, few studies have addressed whether increasing  
15 environmental predictability encourages the use of proactive control. Bugg and  
16 Smallwood (2016) provided useful information relevant to this question. They  
17 employed a color-word Stroop task that manipulated the reliability of contextual cues  
18 that indicate whether the next trial would be congruent or incongruent. Their findings  
19 showed that when contextual cues consistently and accurately predicted the nature of  
20 the upcoming trial (i.e., 100% reliable), participants relied on these cues, resulting in a  
21 reduced cost of incongruency on reaction times compared to when the cues were  
22 meaningless. Importantly, the benefits of these cues diminished when they were only  
23 75% reliable. This finding suggests that an increase in reliability of 25 percentage points  
24 from a completely unpredictable condition is insufficient to induce participants to rely

1 on the cues proactively. This suggested that the previously undetermined threshold for  
2 adults to proactively engage with cues might lie somewhere between 75% and 100%.  
3 To test this possibility, we intentionally chose two conditions that were equidistant from  
4 a central, ambiguous point of 75% reliability. A more reliable condition (reliable task  
5 cues appear on 85% of trials) was designed to exceed the potential threshold for  
6 proactive engagement, whereas a less reliable condition (reliable task cues appear on  
7 65% of trials) was intended to fall below it. This specific design allowed us to examine  
8 whether a subtle increase in predictability is sufficient to trigger the adoption of a  
9 proactive control strategy. We expect that adults would be more likely to engage in  
10 spontaneous proactive preparation in the more reliable condition than in the less reliable  
11 condition.

12 Taken together, the two experiments used a self-paced task-switching paradigm to  
13 examine whether adults selectively decide to use proactive control based on the  
14 reliability of contextual cues. Specifically, we tested three preregistered predictions.  
15 First, we examined whether self-paced preparation times reflect changes in proactive  
16 control engagement dependent on contextual cue reliability. Our prediction was that  
17 adults would show longer preparation times in the reliable (or, in Exp 2, more reliable)  
18 condition than in the unreliable (or, in Exp 2, less reliable) condition. In a not  
19 preregistered analysis, we also explored whether preparation times were longer on  
20 switch trials than on no switch trials only in the reliable condition as proactive  
21 preparation is thought to be more demanding on switch trials. Second, we predicted that  
22 adults would show lower error rates, shorter response times, and smaller switch costs in  
23 the reliable (or more reliable) condition than in the unreliable (or less reliable)  
24 condition, suggesting that adults engage cognitive control more proactively when the

1 upcoming task is more predictable. Third, we examined whether self-paced preparation  
2 times predicted task performance. We hypothesized that longer preparation times during  
3 the cue phase, reflecting greater proactive preparation, would be associated with  
4 beneficial performance outcomes that stem from engaging proactive control. This  
5 assumption is supported by previous studies demonstrating that longer preparation times  
6 are associated with greater accuracy and faster responses (Chevalier et al., 2020) and  
7 with a reduction in switch costs (Longman et al., 2017). Based on this, we predicted that  
8 longer preparation times would result in lower error rates, shorter response times, and  
9 smaller switch costs, and that this relation would be seen in the reliable (or more  
10 reliable) condition, not in the unreliable (or less reliable) condition. The preregistration  
11 documents associated with this study are available at <https://osf.io/z3h4f> (Exp 1) and  
12 <https://osf.io/xubzp> (Exp 2).

13

## 14 **Experiment 1**

### 15 **Method**

#### 16 **Participants**

17 The preregistered target sample was 52 adults, with an age range of 19 to 50  
18 years. As this was the first experiment to examine whether cue reliability affects  
19 preparation times in the self-paced task switching paradigm, we based our power  
20 analysis on a small-to-moderate effect size (Brysbeart, 2019; Cohen, 1988; Miles &  
21 Shevlin, 2001). Specifically, we assumed a target effect size of Cohen's  $d=0.40$ . Based  
22 on a power of 80% and an alpha of 0.05, G\*Power revealed that the minimum sample  
23 size required to detect the expected within-participant differences was 52 participants.  
24 To account for anticipated data exclusions from potential random responding, which

1 can occur in online experiments, we collected data from slightly more than the target  
2 sample (60 adults) using a research participant database managed by Lancers, Inc.  
3 (<https://www.lancers.jp>). All participants provided informed consent before the  
4 experiment and received 750 yen for completing all task procedures. Seven participants  
5 were excluded from the analysis because they either failed to complete all sessions or  
6 performed outside three standard deviations of the mean for overall accuracy. The final  
7 sample consisted of 53 adults, who were native Japanese speakers ( $M = 41.47$  years,  $SD$   
8  $= 6.62$  years, 31 females and 22 males). This study, along with subsequent experiments,  
9 was approved by the Institutional Review Board of Osaka Kyoiku University (24001:  
10 Environmental Predictability and Cognitive Control Modes).

### 11 **Procedure and experimental design**

12 The experiment was programmed in PsychoPy (Peirce et al., 2019) and run as an  
13 PsychoJS experiment on Pavlovia (<https://pavlovia.org/>). Participants accessed the  
14 experiment exclusively through Firefox or Chrome browsers. After providing informed  
15 consent and demographic information (age and sex), participants were introduced to the  
16 task, which was described as the "Santa Claus Game."

17 The procedure followed the cued task-switching paradigm described in Chevalier  
18 et al. (2020). Participants were instructed to assist Santa Claus by categorizing a series  
19 of gifts based on either a color rule or a shape rule. Each trial began with a fixation  
20 cross displayed within a colored circle at the center of the screen for 1000 to 1200 ms.  
21 Following this, a precue stimulus (either a red Santa elf or a blue Santa elf) appeared  
22 within the same colored circle before the target onset. Two key features characterized  
23 the precue phase. First, the precues predicted the upcoming relevant task (color- or  
24 shape-matching) with different reliability across conditions, influencing the extent to

1 which proactive control was adaptive. Second, participants were allowed to take as  
2 much time as they needed before triggering the target. They were explicitly instructed to  
3 initiate the target when confident about the upcoming task (color or shape) by pressing  
4 the space bar. After the target onset, the target stimulus remained until participants  
5 responded or for up to 4 seconds. The target was  $8 \times 8$  cm in size and varied on two  
6 dimensions (e.g., color: blue and pink; shape: bear and car). Along with the target, task  
7 cue stimuli were presented on the colored circle, which instructed participants to  
8 perform either a color identification task with 12 colorful patches or a shape  
9 identification task with 12 gray geometrical shapes. To aid responses, four  
10 unidimensional response pictures (e.g., a bear, a blue patch, a car, and a pink patch),  
11 along with response keys (i.e., “R”, “T”, “O”, and “P”), were constantly displayed in  
12 two horizontal rows at the bottom of the screen. Participants were asked to place the  
13 index and middle fingers of their left hand on the response keys (“R” and “T”), the  
14 index and middle fingers of their right hand on the response keys (“O” and “P”), and the  
15 thumb of their dominant hand on the space bar.

16 Critically, the reliability of the precues was manipulated across conditions (see  
17 Figure 2). In the reliable condition, the red Santa elf always preceded the relevant task  
18 cue, ensuring precue-based proactive preparation was both possible and adaptive. For  
19 example, the red Santa elf always appeared with colorful paint cans when the upcoming  
20 task was color matching and with gray shapes when the upcoming task was shape  
21 matching. In contrast, in the unreliable condition, the precue correctly predicted the task  
22 cue in only half of the trials and mismatched in the remaining trials. For instance, the  
23 blue Santa elf appeared with colorful paint cans for color matching in half of the trials,  
24 while in the other half, it preceded the shape matching task. In other words, the task cue

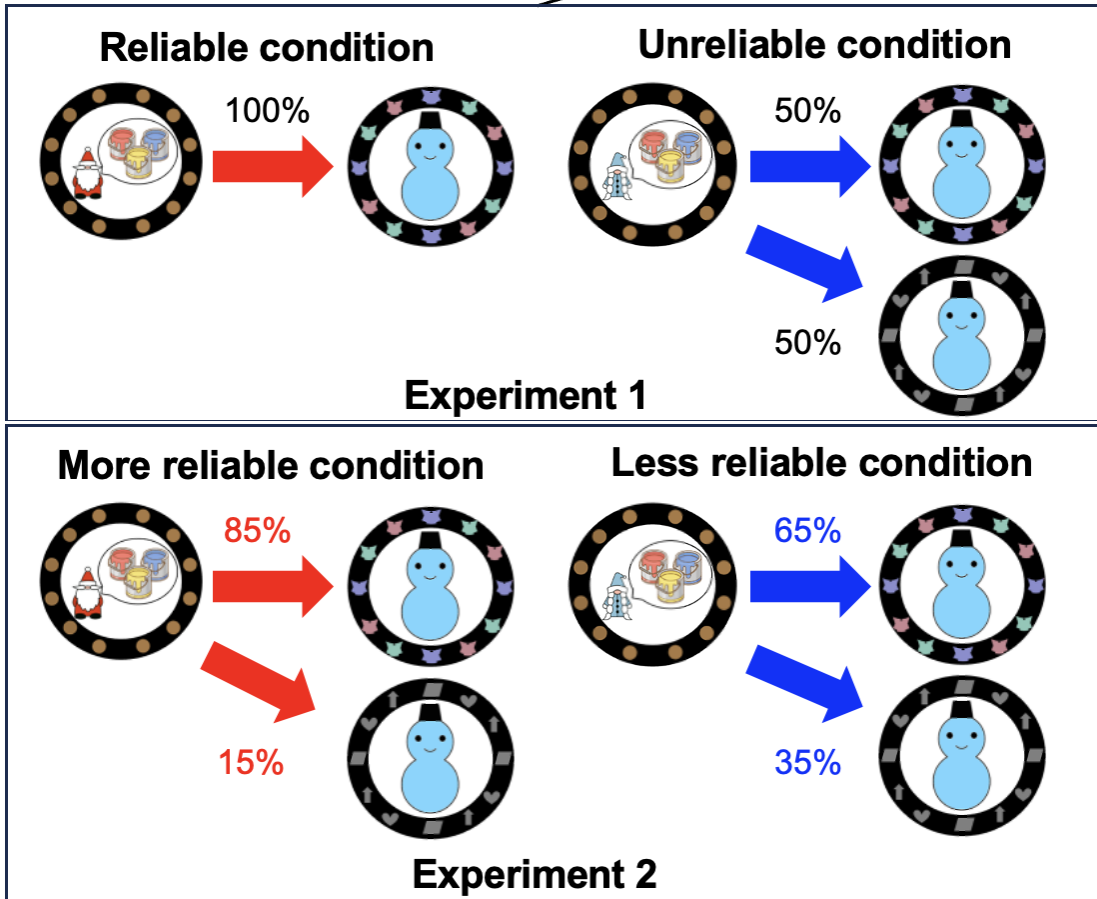
1 information provided by the precue was completely random. Participants experienced  
2 both the reliable and unreliable conditions. The order of the two conditions was  
3 counterbalanced across participants. At the beginning of each condition, participants  
4 were explicitly informed about contextual cue reliability. Specifically, in the reliable  
5 condition it was made clear that a red Santa elf always helped participants by showing  
6 the upcoming task, whereas the blue Santa elf in the unreliable condition tries to help  
7 but sometimes fails due to being somewhat absent-minded. This reliability manipulation  
8 was introduced during both the demonstration and practice trials.

9 Each condition started with two demonstration trials providing guidance on how  
10 to sort based on the cued dimension (e.g., color), followed by four practice trials with  
11 the same dimension. Demonstration and practice trials were then repeated for the other  
12 sorting task (e.g., shape). Participants then completed ten practice trials in which both  
13 tasks were mixed. Finally, participants completed three blocks of 41 test trials for each  
14 condition (123 test trials/condition), including 60 switch trials and 60 no-switch trials  
15 (plus 3 start trials). Switch and no-switch trials occurred unpredictably. In total,  
16 participants completed 246 test trials. Participants were instructed to answer as quickly  
17 and accurately as possible and received not only immediate feedback (i.e., current or  
18 incorrect) at the end of each trial but also a performance score (mean RT in ms/10) +  
19 (errors\*5) at the end of each block.

20

21 **Figure 2.**

22 *Illustration of the self-paced task-switching paradigm used in Experiments 1 and 2.*



Note. In Experiment 1, the precue was perfectly reliable in the “reliable condition,” consistently predicting the upcoming task with 100% accuracy. In contrast, in the “unreliable condition,” the precue correctly predicted the task on only 50% of the trials. In Experiment 2, the precue’s reliability was adjusted to intermediate levels. Specifically, in the “more reliable condition,” the precue correctly predicted the task on 85% of trials, while in the “less reliable condition,” it was accurate on 65% of trials. Participants determined the duration of the precue phase themselves, advancing to the next phase via a key press when they felt ready to respond.

### Data processing

The dependent measures extracted from the cued task-switching paradigm were error rates (ranging from 0 to 1), preparation times (the interval between cue onset and self-paced target onset), and response times (the interval between target onset and the

1 participants' response). Only correct trials were included in the analyses of preparation  
2 and response times. As outlined in our preregistration (<https://osf.io/z3h4f>), trials with  
3 response times faster than 200 ms, or exceeding  $M + 3 \text{ MAD}$  (Median Absolute  
4 Deviation; Leys et al., 2013), or falling below  $M - 3 \text{ MAD}$ , were excluded. No lower  
5 limit was applied to preparation times, as this allowed us to account for participants'  
6 decisions not to prepare.

### 7 **Data analysis.**

8       The study design, hypotheses, and analytic plan were preregistered and the  
9 datasets and analysis code are available on the Open Science Framework  
10 (<https://osf.io/z3h4f>). Using the lme4 package (Bates et al., 2015) in the R system (R  
11 Core Team, 2023), we conducted regression analyses with linear mixed-models for  
12 preparation times and response times. We also conducted generalized mixed-models  
13 logistic regression analyses for error responses. We applied the maximal random-effects  
14 structure justified by our experimental design (Barr et al., 2013). The significance of  
15 each predictor was represented by the coefficient, chi-square, and  $p$ -value resulting  
16 from the likelihood ratio test.

17       First, to test whether preparation times were longer in the reliable condition than  
18 in the unreliable condition, we ran linear mixed-models (LMMs) with the predictors of  
19 preparation times, that is, cue reliability (reliable and unreliable conditions), trial type  
20 (switch and no-switch trials), and their two-way interaction. The model included  
21 random intercepts for participants and random slopes for cue reliability. A significant  
22 coefficient for a main effect of cue reliability in the appropriate direction was  
23 considered evidence supporting the first prediction.

1 To evaluate the second prediction, the same regression model used for testing the  
2 first prediction was used but with response times as the dependent variable. For error  
3 rates we also carried out generalized mixed-models logistic regression analysis with the  
4 same variables. In these models, random intercepts for participants and random slopes  
5 for cue reliability were included. A significant coefficient for the main effect of cue  
6 reliability in the appropriate direction and a significant two-way interaction would  
7 constitute support for the second prediction that adults showed lower error rates, shorter  
8 response times, and smaller switch costs in the reliable condition than in the unreliable  
9 condition.

10 Finally, to examine the relation between preparation times and task performance,  
11 with response times as a dependent variable, the linear mixed-model included factors of  
12 cue reliability (reliable and unreliable conditions), trial type (switch and no-switch  
13 trials), preparation times, the two-way interactions (cue reliability  $\times$  trial type, cue  
14 reliability  $\times$  preparation time, and trial type  $\times$  preparation time), and the three-way  
15 interaction. The model included random intercepts for participants and random slopes  
16 for cue reliability. Evidence supporting the third prediction that longer preparation times  
17 would predict shorter response times and/or smaller switch costs specifically in the  
18 reliable condition would be indicated by significant coefficients for the cue reliability  $\times$   
19 preparation time interaction and the three-way interaction.

20

## 21 **Results**

### 22 **Preparation times and cue reliability (prediction 1)**

23 Figure 3 (left) depicts mean preparation times for each condition. To aid  
24 interpretation of within-participant effects, condition-difference plots are also provided

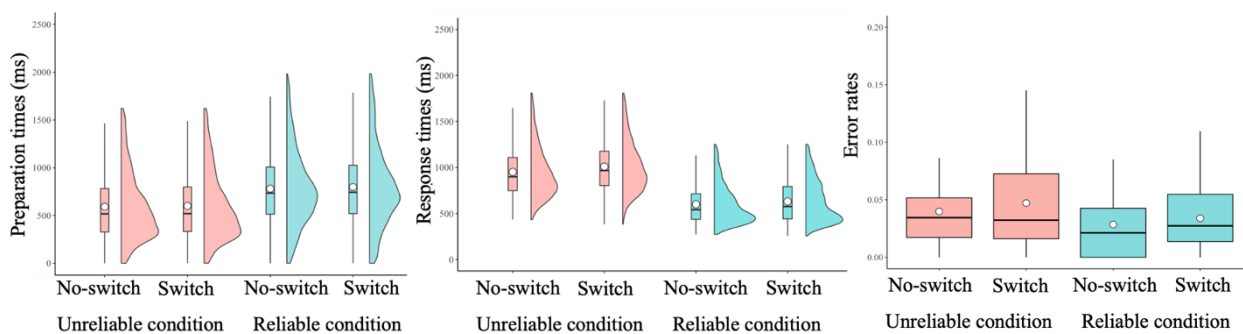
1 in supplementary Figure S1 (left). Our focal comparison revealed a significant main  
 2 effect of cue reliability ( $b = 0.09$ ,  $t = 6.85$ ,  $\chi^2(1) = 47.50$ ,  $p < .001$ ), reflecting longer  
 3 preparation times in the reliable condition ( $M = 791$  msec,  $SD = 411$  msec) than in the  
 4 unreliable condition ( $M = 596$  msec,  $SD = 350$  msec).

5 There was indeed a significant interaction between trial type and cue reliability ( $b$   
 6  $= 0.01$ ,  $t = 2.42$ ,  $\chi^2(1) = 5.86$ ,  $p = .016$ ). A pairwise test revealed that longer preparation  
 7 times were seen on switch trials ( $M = 799$  msec,  $SD = 422$  msec) than on no-switch  
 8 trials ( $M = 782$  msec,  $SD = 394$  msec) in the reliable condition ( $b = 0.01$ ,  $t = 4.90$ ,  $p$   
 9  $< .001$ ), whereas this difference was not statistically significant in the unreliable  
 10 condition ( $b = 0.004$ ,  $t = 1.48$ ,  $p = .139$ ) (switch:  $M = 600$  msec,  $SD = 353$  msec, no-  
 11 switch:  $M = 592$  msec,  $SD = 350$  msec).

12

### 13 **Figure 3.**

14 *Mean preparation times (left), mean response times (middle), and error rates (right) in*  
 15 *the self-paced task-switching paradigm of each condition.*



16

17 *Note.* In all panels, boxplots indicate the medians (central horizontal black lines) and  
 18 interquartile ranges, whiskers represent the range of the data (excluding outliers), and  
 19 white dots represent the condition means. In the left and middle panels, the kernel  
 20 probability density of the data at different proportions is also depicted.

21

### 22 **Task performance and cue reliability (prediction 2)**

1        Figure 3 (middle) depicts mean correct response times for each condition and  
 2        condition-difference plots are also provided in supplementary Figure S1 (middle). There  
 3        were two main findings. First, we found a significant main effect of cue reliability ( $b = -$   
 4         $0.18$ ,  $t = -14.98$ ,  $\chi^2(1) = 226.02$ ,  $p < .001$ ), reflecting faster responses in the reliable  
 5        condition ( $M = 627$  msec,  $SD = 221$  msec) than in the unreliable condition ( $M = 984$   
 6        msec,  $SD = 279$  msec). Second, there was a significant interaction between cue  
 7        reliability and trial type ( $b = -0.01$ ,  $t = -3.67$ ,  $\chi^2(1) = 13.49$ ,  $p < .001$ ). Specifically, there  
 8        were greater switch costs in the unreliable precue condition ( $b = 0.03$ ,  $t = 12.55$ ,  $p$   
 9         $<.001$ ) (switch:  $M = 1010$  msec,  $SD = 277$  msec, no-switch:  $M = 953$  msec,  $SD = 277$   
 10        msec) than in the reliable precue condition ( $b = 0.02$ ,  $t = 7.33$ ,  $p <.001$ ) (switch:  $M =$   
 11         $640$  msec,  $SD = 227$  msec, no-switch:  $M = 606$  msec,  $SD = 212$  msec). We also  
 12        conducted a secondary analysis using a linear mixed-effects model with log-  
 13        transformed response times to account for the skewed data distribution. In this model,  
 14        the interaction between cue reliability and trial type was not significant ( $b = -0.004$ ,  $t = -$   
 15         $1.84$ ,  $\chi^2(1) = 3.38$ ,  $p = .066$ ), although the main effect of cue reliability remained  
 16        significant ( $b = -0.24$ ,  $t = -14.14$ ,  $\chi^2(1) = 200.66$ ,  $p <.001$ ). This suggests that the  
 17        apparent reduction in switch costs observed in our initial analysis might be an artifact of  
 18        the overall speed increase in the reliable condition.

19        Figure 3 (right) depicts mean error rates for each condition and condition-  
 20        difference plots are also provided in supplementary Figure S1 (right). There was no  
 21        significant main effect of cue reliability ( $b = 0.12$ ,  $z = 1.52$ ,  $\chi^2(1) = 2.75$ ,  $p = .097$ ),  
 22        indicating no systematic differences in error rates between conditions (reliable:  $M =$   
 23         $0.03$ ,  $SD = 0.18$ , unreliable:  $M = 0.06$ ,  $SD = 0.23$ ). However, we found a significant  
 24        main effect of trial type ( $b = 0.13$ ,  $z = 2.71$ ,  $\chi^2(1) = 8.98$ ,  $p = .003$ ), indicating that adults

1 made more errors on switch trials than on no-switch trials in both conditions (switch:  $M$   
2  $= 0.05$ ,  $SD = 0.21$ , no-switch:  $M = 0.04$ ,  $SD = 0.19$ ).

### 3 **Task performance and preparation times (prediction 3)**

4 The analysis revealed that the expected three-way interaction was not significant  
5 ( $b = -0.002$ ,  $t = -0.36$ ,  $\chi^2(1) = 0.14$ ,  $p = .719$ ), although preparation times significantly  
6 interacted with trial types across conditions ( $b = -0.01$ ,  $t = -2.50$ ,  $\chi^2(1) = 6.20$ ,  $p = .013$ ).  
7 That is, switch costs were reduced when participants showed longer preparation times  
8 (mean + 1SD) ( $b = 0.02$ ,  $t = 6.70$ ,  $p < .001$ ) than when they showed shorter preparation  
9 times (mean - 1SD) ( $b = 0.03$ ,  $t = 12.42$ ,  $p < .001$ ). In addition, there was a significant  
10 interaction between preparation times and cue reliability ( $b = -0.04$ ,  $t = -7.73$ ,  $\chi^2(1) =$   
11  $61.00$ ,  $p < .001$ ); however, unexpectedly, preparation times did not predict response  
12 times in the reliable condition ( $b = 0.001$ ,  $t = 0.11$ ,  $p = .915$ ), whereas longer preparation  
13 times predicted longer response times in the unreliable condition ( $b = 0.12$ ,  $t = 10.41$ ,  $p$   
14  $< .001$ ).

15 These preregistered analyses focused at the level of each trial. Additionally, we  
16 conducted an exploratory analysis to examine the relationship between response times  
17 and preparation time for each individual. By aggregating preparation times, we isolated  
18 between-subject variance from trial-level fluctuations, revealing a stable strategic  
19 relationship that was otherwise masked in the granular multilevel model. This revealed  
20 a significant interaction between preparation times and cue reliability ( $b = -0.26$ ,  $t = -$   
21  $2.53$ ,  $\chi^2(1) = 6.41$ ,  $p = .013$ ). Specifically, longer preparation times were related to faster  
22 responses in the reliable condition ( $b = -0.30$ ,  $t = -4.49$ ,  $p < .001$ ), whereas a significant  
23 relation was not observed in the unreliable condition ( $b = -0.04$ ,  $t = -0.51$ ,  $p = .612$ ).

### 24 **Matched and unmatched trials in the unreliable condition (exploratory analysis)**

1           The unreliable condition consists of both matched trials, where the precue  
2 matches the upcoming task cue, and unmatched trials, where the precue does not match  
3 the upcoming task cue. Chevalier et al. (2020) evaluated the extent to which participants  
4 rely on precues (i.e., engaging proactive control) by examining performance differences  
5 between matched and unmatched trials. Specifically, proactive preparation on matched  
6 trials was expected to make response times faster, whereas proactive preparation on  
7 unmatched trials should lead participants to prepare for the wrong task and slow  
8 responses on those trials. Consequently, the greater participants' reliance on precues in  
9 the unreliable condition, the more pronounced the performance disparities between  
10 matched and unmatched trials are expected to be.

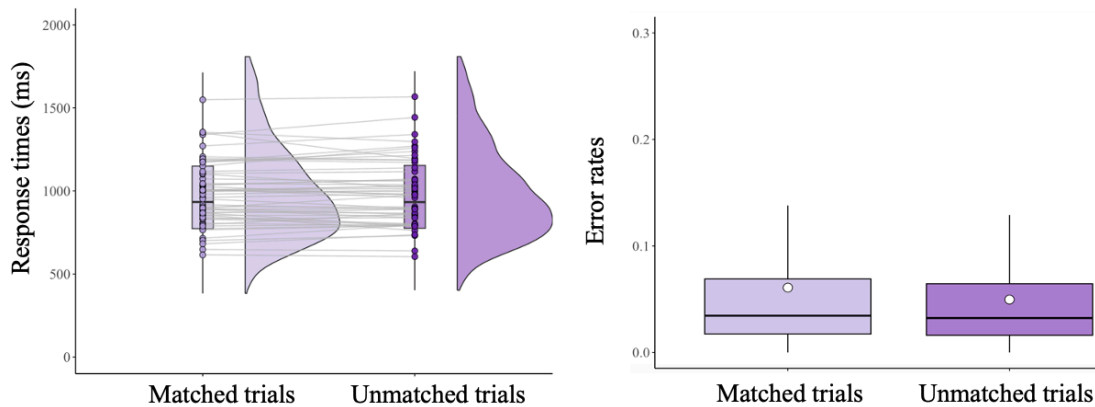
11           Accordingly, whilst not preregistered, we explored the impact of precue trial type  
12 on task performance in the unreliable condition; the reliable condition did not include  
13 unmatched trials and was therefore not included in this analysis. For response times, as  
14 shown in Figure 4 (left), there was no significant main effect of precue trial type ( $b = -$   
15  $0.001$ ,  $t = 0.33$ ,  $\chi^2(1) = 0.11$ ,  $p = .739$ ), reflecting no observable differences between  
16 matched and unmatched trials (unmatched:  $M = 985$  msec,  $SD = 279$  msec, matched:  $M$   
17  $= 983$  msec,  $SD = 279$  msec). Similarly, for error rates, there was also no significant  
18 main effect of precue trial type ( $b = -0.02$ ,  $z = -0.25$ ,  $\chi^2(1) = 0.06$ ,  $p = .806$ ), as illustrated  
19 in Figure 4 (right) (unmatched:  $M = 0.05$ ,  $SD = 0.22$ , matched:  $M = 0.06$ ,  $SD = 0.24$ ).  
20 This pattern is also clearly visible when examining condition-difference plots (see  
21 supplementary Figure S2). These results suggest that adults are not inclined to rely on  
22 precues in the unreliable condition. Further supporting this interpretation, a trial-by-trial  
23 analysis of matched trials within the unreliable condition revealed that longer  
24 preparation times were associated with longer response times ( $b = 0.10$ ,  $t = 5.92$ ,  $\chi^2(1) =$

1 73.69,  $p < .001$ ). This finding reinforces the idea that, even in matched trials,  
 2 participants in the unreliable condition may not fully leverage precues to enhance task  
 3 performance.

4

5 **Figure 4.**

6 *Mean response times (left) and error rates (right) on matched and unmatched trials in*  
 7 *the unreliable condition*



8

9 *Note.* In all panels, boxplots indicate the medians (central horizontal black lines) and  
 10 interquartile ranges, and whiskers represent the range of the data (excluding outliers). In  
 11 the left panel, small colored dots represent individual participant data points, with  
 12 connecting light gray lines representing paired differences in response times. The  
 13 surrounding shaded areas represent kernel probability density. In the right panel, large  
 14 white dots represent the condition means.

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## Discussion

17

We designed Experiment 1 to examine how contextual cue reliability affects the

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use of proactive control within a self-paced task-switching paradigm. We obtained two

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key findings. First, consistent with our prediction 1, adults spent more time in the

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precue phase preparing to respond to the target in the reliable condition compared to the

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unreliable condition. We also found that participants showed longer preparation times

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on switch trials than on no switch trials only in the reliable condition. Second, our

1 results supported prediction 2, replicating those of Chevalier et al. (2020). Specifically,  
2 adults exhibited faster responses as well as reduced switch costs in the reliable  
3 condition than in the unreliable condition. Note that the result of the reduced switch  
4 costs needs to be interpreted with a degree of caution because our secondary analysis  
5 with log-transformed response times yielded no significant effect of the interaction  
6 between cue reliability and trial type. These findings provided evidence of proactive  
7 preparation and behavioral outcomes achieved by the proactive preparation, suggesting  
8 that adults are more willing to engage proactive control in fully predictable  
9 environments than in completely unpredictable environments. Furthermore, although  
10 not preregistered, we found that response times did not differ significantly between  
11 matched and unmatched trials in the unreliable condition, suggesting that adults did not  
12 use the precue information to prompt the engagement of cognitive control in a totally  
13 unpredictable situation. Together, these findings offer further converging evidence  
14 directly linking proactive preparation with contextual cue reliability.

15       One might wonder whether preparation times solely reflect proactive control, or  
16 also include other metacontrol processes such as momentary breaks or hesitation. We  
17 believe that preparation times can function as a direct measure of proactive control  
18 engagement, but we acknowledge that they may also include these other processes.  
19 Looking at the relation between preparation times and response times in the reliable  
20 condition, trial-by-trial analyses revealed no significant association between preparation  
21 times and response times. This suggests that, on a trial-by-trial basis, extended  
22 preparation does not necessarily confer benefits, but that it also incurs no negative  
23 effects. In contrast, exploratory analyses at the participant level showed that longer  
24 average preparation times were associated with faster responses. This discrepancy may

1 be due to the trial-level variability in preparation time, which might indeed reflect  
2 various metacontrol processes such as momentary breaks or hesitation, obscuring the  
3 proactive preparation process itself. When these variances are aggregated and smoothed  
4 out at the participant level, preparation times come to reflect a more stable and  
5 consistent metacontrol process, that is, proactive control. As a result, the expected  
6 benefits of longer preparation times on response times become apparent. Thus, these  
7 two approaches provide complementary, rather than contradictory, insights into  
8 proactive control. That is, while proactive preparation may not manifest at the trial  
9 level, it functions as a consistent and beneficial strategy at the participant level.

10 Crucially, this beneficial relationship was observed only in the reliable condition.

11 In the unreliable condition, even on matched trials, longer preparation times were  
12 associated with longer response times in trial-by-trial analyses, whereas participant-  
13 level analyses revealed no significant relationship. Given the absence of differences  
14 between matched and unmatched trials in the unreliable condition, it is likely that  
15 participants did not rely on the precue. Thus, preparation times in the unreliable  
16 condition might not reflect proactive control engagement, and, by extension, goal  
17 identification and goal management. Instead, the relationship between longer  
18 preparation times and slower responses in this condition might be explained by general  
19 slowing. For instance, shorter preparation times may reflect an active strategy of  
20 skipping the precue phase due to low precue reliability, whereas longer preparation  
21 times may result from a passive response to stimuli. On trials where participants  
22 respond passively, their overall pace may be slower and more consistent. This  
23 interpretation aligns with patterns observed in previous studies (Longman et al., 2017;  
24 Meiran et al., 2002).

1           Our documentation of the relation between preparation times and response times  
2 underscores that preparation time is not merely a passive interval between events;  
3 rather, it is a context-dependent proactive process that is strategically deployed when it  
4 is most likely to be effective. In addition to the relation between preparation times and  
5 response times, an additional promising outcome was that longer preparation times were  
6 associated with a reduction in switch costs. This relationship was observed across both  
7 conditions, thus the beneficial effect on performance was not necessarily tied to the  
8 engagement of proactive control. However, the pattern of data was consistent with  
9 prediction 3 that the relationship between preparation times and the switch cost would  
10 be driven mostly by data from the reliable condition (see Figure S2 in supplementary  
11 material B). Specifically, in the reliable condition switch costs were significantly  
12 reduced when participants showed longer preparation times (mean + 1SD) relative to  
13 when they showed shorter preparation times (mean - 1SD). In contrast, this relationship  
14 was not seen in the unreliable condition. However, we acknowledge that firm  
15 conclusions cannot be drawn from this result alone because the relevant three-way  
16 interaction was not significant, due to a lack of statistical power (see the result of  
17 simulation-based sensitivity analysis in supplemental material). We therefore position  
18 the pattern as an additional indicative result that further supports our main conclusion  
19 that adults strategically adjust their preparatory processes based on environmental  
20 predictability.

21           In summary, Experiment 1 demonstrated that adults showed more advanced  
22 preparation, faster responses, and smaller switch costs in the fully predictable condition  
23 than in the completely unpredictable condition. In addition, several findings support the  
24 relation between advanced preparation and task performance. Specifically, longer

1 preparation times were associated with smaller switch costs across conditions and with  
2 faster responses in the fully predictable condition at the participant level.

## 3 4 **Experiment 2**

5 Experiment 2 moved beyond all previous work in the area to examine whether the  
6 decision to use proactive control is influenced by how predictable the environment is,  
7 not just whether the environment is fully predictable or totally unpredictable. Drawing  
8 on Stroop task data, Bugg and Smallwood (2016) suggested that the benefits of  
9 contextual cues were evident at 100% reliability but diminished when reliability was  
10 only 75%. Based on this, we designed two conditions varying in the proportion of trials  
11 with reliable task cues that were equidistant from a central, ambiguous point of 75%  
12 reliability: a more reliable condition (Correct task cues appear on 85% of trials) and a  
13 less reliable condition (Correct task cues appear on 65% of trials). We expected that  
14 adults would engage more proactive cognitive control in the more reliable condition  
15 than in the less reliable condition.

16 In Experiment 1, a within-participants design was employed, with the order of the  
17 two conditions counterbalanced across participants. A further exploratory analysis  
18 revealed a significant interaction between condition and order. Specifically, adults were  
19 less likely to use proactive control in the unreliable condition after experiencing the  
20 reliable condition than when initially performing the unreliable condition (see detailed  
21 results in supplementary material C). These findings suggest that the order in which  
22 conditions are experienced may influence the adoption of cognitive control modes. To  
23 account for this, Experiment 2 preregistered the decision to conduct analyses with the  
24 inclusion of a factor of task order factor. If we observed a significant interaction

1 between task order and condition, we planned to focus subsequent between-participants  
2 analyses on just the first condition that participants encountered.

3

4

## Method

### 5 **Participants**

6 The preregistered target sample was 200 adults who were aged between 19- and  
7 50-years olds. Given that a preliminary analysis of Experiment 1 showed an order  
8 effect, we decided to emphasise the first condition experienced by participants, which  
9 required a between-participant analysis. Based on a target effect size of Cohen's  $d=0.40$   
10 (consistent with the assumption of Experiment 1) and with a power of 80% and an alpha  
11 of 0.05, the minimum recommended sample size was 200 participants to detect the  
12 expected difference of preparation times between conditions in a between-participant  
13 comparison. As in Experiment 1, we collected data from a little more than the target  
14 sample (210 adults) on the assumption that some participants might respond randomly  
15 in an online experiment.

16 All the participants gave full informed consent before the experiment and were  
17 paid 750 yen after completing all the task procedures. We excluded 18 participants who  
18 did not complete all the sessions or performed outside 3SD of the mean for overall  
19 accuracy. Our final sample consisted of 192 adults, who were native Japanese speakers  
20 ( $M = 39.28$  years,  $SD = 7.02$  years, 116 females and 76 males).

### 21 **Procedure and experimental design**

22 The procedure of Experiment 2 closely paralleled that of Experiment 1, except for  
23 precue reliability in the self-paced task switching paradigm. Participants experienced  
24 both the more reliable and less reliable conditions, which were counterbalanced. As

1 seen in Figure 2, in the more reliable condition, 85% of precues accurately predicted the  
2 upcoming task cue (e.g., a shape precue preceding a shape cue), referred to as *matched*  
3 *trials*. The remaining 15% of precues did not correspond to the subsequent task cue  
4 (e.g., a shape precue preceding a color cue), classified as *unmatched trials*. Conversely,  
5 in the less reliable condition, 65% of precues were matched to the upcoming task cue,  
6 while the remaining 35% were unmatched.

### 7 **Data processing and data analysis.**

8 As outlined in our preregistration (<https://osf.io/xubzp>), Experiment 2 added three  
9 changes to the approach to data processing and data analysis used in Experiment 1.  
10 First, our target for analysis was correct trial sequences; that is, if there was an error on  
11 trial  $n$ , then the data for trial  $n+1$  were excluded. This is because trial  $n+1$  is a  
12 “recovery” trial, in which any task switch is more ambiguous because of the error on  
13 trial  $n$  (Monsell, 2003). Second, given that data from Experiment 1 suggested that  
14 performance on the second condition was influenced by the first condition, we  
15 incorporated a main effect of task order (first and second task experienced) and its  
16 related interactions to the model employed in Experiment 1. To account for individual  
17 differences in these order effects, the models testing Predictions 1-3 included task order  
18 as a random slope in addition to random intercepts for participants. Importantly, if any  
19 interaction with order emerged, we decided to confirm whether each prediction was  
20 supported when the analysis was restricted to just the first task experienced by  
21 participants in each group. However, the results of the pairwise comparisons for the  
22 second task experienced by participants, are detailed in supplemental material D. Third,  
23 we preregistered an analysis to assess the extent to which participants relied on precues  
24 (i.e., engaged in proactive control), focusing on performance differences between

1 matched and unmatched trials. As already noted, proactive preparation is expected to  
2 lead to performance differences between matched and unmatched trials. Unlike  
3 Experiment 1 however, both the more and less reliable conditions in this second  
4 experiment included matched and unmatched trials, thus we compared the differences  
5 between matched and unmatched trials across the two conditions. Specifically, we  
6 predicted that participants would show larger differences between matched and  
7 unmatched trials in the more reliable condition compared to the less reliable condition  
8 (Prediction 4).

9

10

## Result

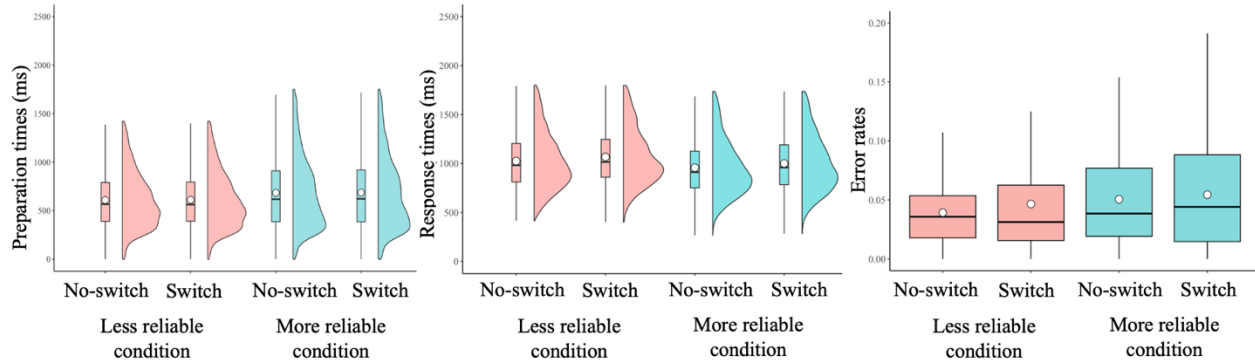
### 11 Preparation times and cue reliability (prediction 1)

12 The analysis revealed a significant interaction between cue reliability and order  
13 ( $b = -0.03$ ,  $t = -2.14$ ,  $\chi^2(1) = 4.57$ ,  $p = .033$ ). Our focal comparison for the first condition  
14 experienced by participants revealed that adults showed longer preparation times in the  
15 more reliable condition ( $M = 685$  msec,  $SD = 373$  msec) than in the less reliable  
16 condition ( $M = 611$  msec,  $SD = 286$  msec) ( $b = 0.05$ ,  $t = 2.54$ ,  $p = .013$ ) (see Figure 5  
17 left). Unlike Experiment 1, there was not significant interaction between trial type and  
18 cue reliability ( $b = 0.001$ ,  $t = 0.87$ ,  $\chi^2(1) = 0.75$ ,  $p = .387$ ).

19

20 **Figure 5.**

- 1 Mean preparation times (left), mean response times (middle), and error rates (right) for  
 2 each condition in the first experienced condition of the self-paced task-switching  
 3 paradigm.



- 4  
 5 Note. In all panels, boxplots indicate the medians (central horizontal black lines) and  
 6 interquartile ranges, whiskers represent the range of the data (excluding outliers), and  
 7 white dots represent the condition means. In the left and middle panels, the kernel  
 8 probability density of the data at different proportions is also depicted.  
 9

## 10 Task performance and cue reliability (prediction 2)

- 11 For response times, there was no significant two-way interaction between cue  
 12 reliability and order ( $b = 0.02$ ,  $t = 1.18$ ,  $\chi^2(1) = 1.39$ ,  $p = .238$ ), but the analysis revealed  
 13 a main effect of cue reliability ( $b = -0.02$ ,  $t = -4.53$ ,  $\chi^2(1) = 20.69$ ,  $p < .001$ ). Thus,  
 14 consistent with prediction 2, regardless of the first and second experienced conditions,  
 15 we found shorter response times in the more reliable condition ( $M = 943$  msec,  $SD =$   
 16  $265$  msec) than in the less reliable condition ( $M = 970$  msec,  $SD = 281$  msec) (see  
 17 Figure 5 middle). Unlike Experiment 1, there was not a significant two-way interaction  
 18 between cue reliability and trial type ( $b = -0.001$ ,  $t = -0.40$ ,  $\chi^2(1) = 0.49$ ,  $p = .483$ ),  
 19 despite a significant main effect of trial type ( $b = 0.02$ ,  $t = 19.24$ ,  $\chi^2(1) = 378.38$ ,  $p$   
 20  $< .001$ ).

1 For error rates, Figure 5 (right) depicts mean error rates for each condition. There  
 2 was no significant two-way interaction between cue reliability and order ( $b = 0.11, z =$   
 3  $1.85, \chi^2(1) = 3.51, p = .064$ ). A main effect of cue reliability was also not significant ( $b$   
 4  $= 0.01, z = 0.34, \chi^2(1) = 0.72, p = .395$ ), revealing no significant differences between the  
 5 more and less reliable conditions (more reliable:  $M = 0.06, SD = 0.23$ , less reliable:  $M =$   
 6  $0.04, SD = 0.21$ ). There was only a significant main effect of trial type ( $b = -0.16, z = -$   
 7  $7.32, \chi^2(1) = 53.55, p < .001$ ) (switch:  $M = 0.06, SD = 0.23$ , no-switch:  $M = 0.04, SD =$   
 8  $0.21$ ).

### 9 **Task performance and preparation times (prediction 3)**

10 The analysis revealed no interactions related to preparation times and cue  
 11 reliability (cue reliability  $\times$  preparation time:  $b = -0.03, t = -1.22, \chi^2(1) = 1.35, p = .245$ ,  
 12 cue reliability  $\times$  preparation time  $\times$  trial type:  $b = -0.001, t = -0.27, \chi^2(1) = 0.09, p$   
 13  $= .767$ ). They were not interacted with order (order  $\times$  cue reliability  $\times$  preparation time:  
 14  $b = 0.0001, t = 0.04, \chi^2(1) = 0.0003, p = .986$ , order  $\times$  cue reliability  $\times$  preparation time  
 15  $\times$  trial type:  $b = 0.002, t = 0.63, \chi^2(1) = 0.40, p = .527$ ). Instead, there was a main effect  
 16 of preparation times ( $b = 0.08, t = 14.48, \chi^2(1) = 249.49, p < .001$ ), revealing that longer  
 17 preparation times predicted longer response times.

18 Further exploratory analysis examined the interindividual relation between  
 19 response times and preparation times at the level of the participant. This analysis  
 20 showed that longer preparation times were not related to response times ( $b = 0.06, t =$   
 21  $0.58, p = .561$ ) and this pattern did not interact with cue reliability ( $b = -0.02, t = -0.19, p$   
 22  $= .847$ ).

### 23 **Matched and unmatched trials in the more and less reliable conditions (prediction** 24 **4)**

1       The fixed effects in the model were cue reliability (reliable and unreliable  
2 conditions), matching (matched and unmatched trials), order (first and second task  
3 experienced), and all their interactions; random intercepts for participants and random  
4 slopes for matching were also included.

5       The analysis of response times revealed a significant three-way interaction  
6 between order, cue reliability, and matching ( $b = -0.01$ ,  $t = -2.37$ ,  $\chi^2(1) = 5.60$ ,  $p = .018$ ).  
7 The focal comparison for the first experienced condition demonstrated the expected  
8 significant two-way interaction between cue reliability and matching ( $b = 0.02$ ,  $t = 5.57$ ,  
9  $p < .001$ ). The difference in response times between matched and unmatched trials was  
10 significant in both the more reliable ( $b = 0.04$ ,  $t = 9.67$ ,  $p < .001$ ) and less reliable  
11 conditions ( $b = 0.01$ ,  $t = 2.16$ ,  $p < .001$ ). Importantly, consistent with prediction 4, the  
12 interaction indicated the differential influences of matching between the two conditions,  
13 suggesting a larger difference between matched and unmatched trials in the more  
14 reliable condition (unmatched:  $M = 1040$  msec,  $SD = 290$  msec, matched:  $M = 974$   
15 msec,  $SD = 280$  msec) than in the less reliable condition (unmatched:  $M = 1050$  msec,  
16  $SD = 279$  msec, matched:  $M = 1040$  msec,  $SD = 284$  msec) (see Figure 6).

17       For error rates, we found the three-way interaction between cue reliability, order,  
18 and matching ( $b = 0.09$ ,  $z = 2.33$ ,  $\chi^2(1) = 5.45$ ,  $p = .020$ ). The focal comparison for the  
19 first experienced condition produced the expected significant two-way interaction  
20 between cue reliability and matching ( $b = -0.26$ ,  $t = -6.19$ ,  $p < .001$ ). Specifically, in the  
21 first experienced condition, adults made more errors on unmatched trials than on  
22 matched trials in the more reliable condition ( $b = -0.54$ ,  $z = -9.40$ ,  $p < .001$ ) (unmatched:  
23  $M = 0.16$ ,  $SD = 0.36$ , matched:  $M = 0.05$ ,  $SD = 0.22$ ), but not in the less reliable

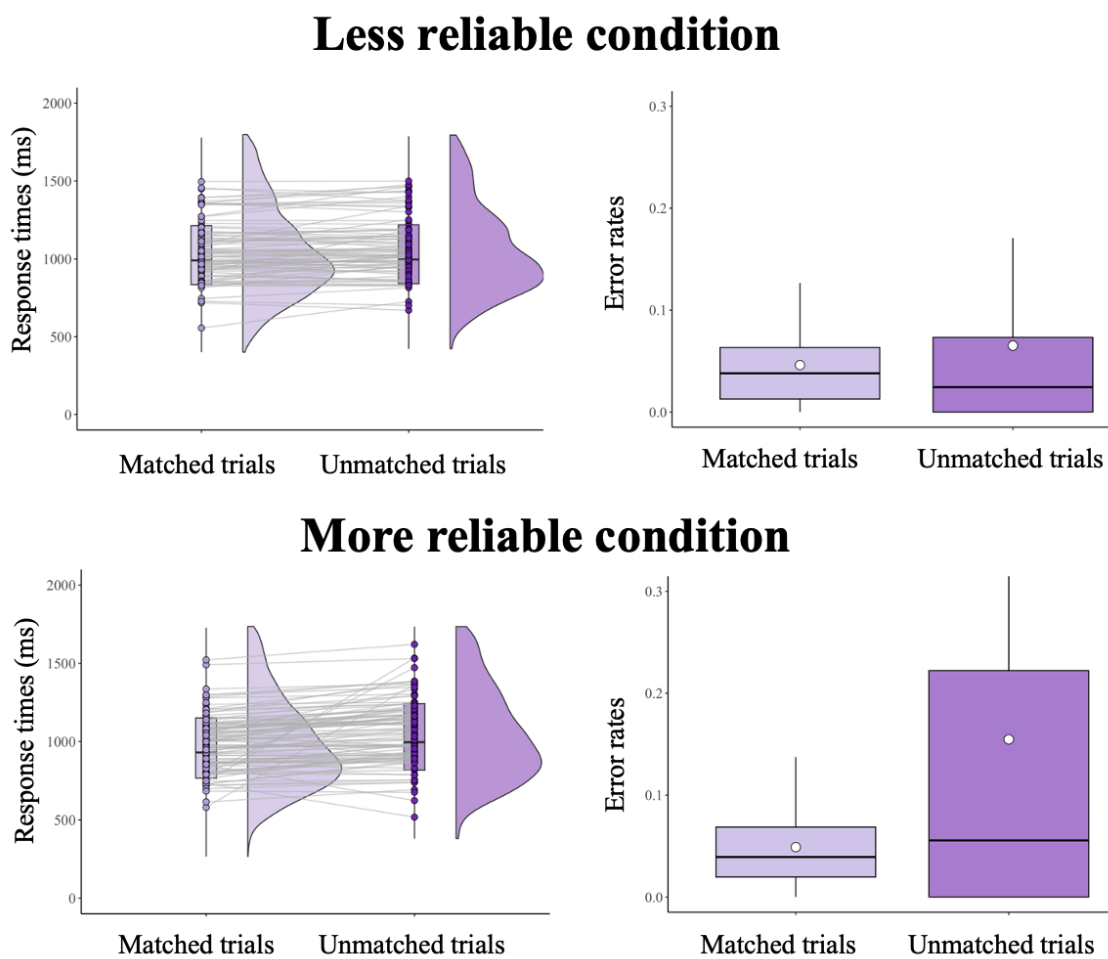
1 condition ( $b = -0.01, z = -0.17, p = .863$ ) (unmatched:  $M = 0.07, SD = 0.25$ , matched:  $M$   
 2  $= 0.05, SD = 0.21$ ) (see Figure 6).

3

4 **Figure 6.**

5 *Mean response times (left) and error rates (right) on matched and unmatched trials in*

6 *the first experienced condition of the self-paced task-switching paradigm.*



7

8 *Note.* In all panels, boxplots indicate the medians (central horizontal black lines) and  
 9 interquartile ranges, and whiskers represent the range of the data (excluding outliers). In  
 10 the left two panels, small colored dots represent individual participant data points, with  
 11 connecting light gray lines representing paired differences in response times. The  
 12 surrounding shaded areas represent kernel probability density. In the right two panels,  
 13 large white dots represent the condition means.

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## Discussion

Experiment 2 extended the findings from Experiment 1 by investigating whether gradual increases in predictability influence the decision to implement proactive control. Specifically, we compared a more reliable condition, where the precue correctly conveys the upcoming task cue on 85% trials, to a less reliable condition, where the precue correctly conveys it on 65% trials.

Three key findings emerged to support the view that adults can detect small differences in cue reliability and adjust their proactive control accordingly. First, in terms of preparation times, adults stayed longer during the precue phase in the more reliable than in the less reliable condition, supporting prediction 1. Second, consistent with prediction 2, adults showed faster responses in the more reliable than in the less reliable condition. Third, prediction 4 was supported in that the differences in response times and error rates between matched and unmatched trials, reflecting the degree to which participants rely on the information conveyed by precues, were larger in the more reliable than in the less reliable condition. Taken together, these results suggest that adults are more likely to rely on the precues and exhibit faster responses in more predictable situations.

Although the relation between advanced preparation and task performance was contrary to our prediction 3, the findings mirrored the pattern observed in the unreliable condition of Experiment 1. Across the more reliable and less reliable conditions, longer preparation times were associated with longer response times when analyzed at the trial level. However, when analyzed at the participant level, preparation times did not correlate significantly with response times. This discrepancy may appear contradictory,

1 as we observed longer preparation times and shorter response times in the more reliable  
 2 condition compared to the less reliable condition. This suggests that longer preparation  
 3 times and shorter response times do not occur simultaneously. We will address this  
 4 issue in the General Discussion.

## 6 **Integrating Experiment 1 with Experiment 2**

7 To explore whether proactive preparation improves incrementally with increasing  
 8 cue reliability, we combined the data from Experiment 1 and Experiment 2 and tested  
 9 the effect of varying cue reliability on preparation times and task performance. We put  
 10 together the following four conditions: the 100% reliable and 50% reliable conditions  
 11 from Experiment 1 when these were the first conditions experienced by participants,  
 12 and the 85% reliable and 65% reliable conditions from Experiment 2 when these were  
 13 the first conditions experienced by participants. We analyzed correct trial sequences and  
 14 excluded trials with response times that were either faster than 200 ms or more than 3  
 15 MAD from the mean. We conducted planned three comparisons, namely a 50/65  
 16 contrast (50 % v.s. 65%), a 65/85 contrast (65 % v.s. 85%), and an 85/100 contrast  
 17 (85 % v.s. 100%), thus the model included three contrasts with forward difference  
 18 coding<sup>1</sup>.

19 First, the analysis of preparation times revealed that the 65/85 contrast was  
 20 significant ( $b = -0.09$ ,  $t = -1.98$ ,  $\chi^2(1) = 3.90$ ,  $p = .048$ ), whereas the 50/65 and 85/100  
 21 contrasts were not significant (50/65 :  $b = 0.04$ ,  $t = 0.61$ ,  $\chi^2(1) = 0.38$ ,  $p = .540$ ,

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<sup>1</sup> For the 50/65 contrast (50 % v.s. 65%), the 50 % reliable condition was coded 3/4 and the other conditions were coded -1/4. For the 65/85 contrast (65% v.s. 85%), the 50 % and 65% reliable conditions were coded 1/2 and the other conditions were coded -1/2. Finally, for the 85/100 contrast (85% v.s. 100%), the 100 % reliable condition was coded -3/4 and the other conditions were coded 1/4.

1 85/100 :  $b = -0.06$ ,  $t = -0.99$ ,  $\chi^2(1) = 0.97$ ,  $p = .324$ ). This indicates that preparation  
2 times are longer when cue reliability increases from 65% ( $M = 657$  msec,  $SD = 348$   
3 msec) to 85% ( $M = 724$  msec,  $SD = 413$  msec) and that they are not statistically  
4 different when cue reliability is 85% as opposed to 100% ( $M = 792$  msec,  $SD = 402$   
5 msec) (see Figure 7).

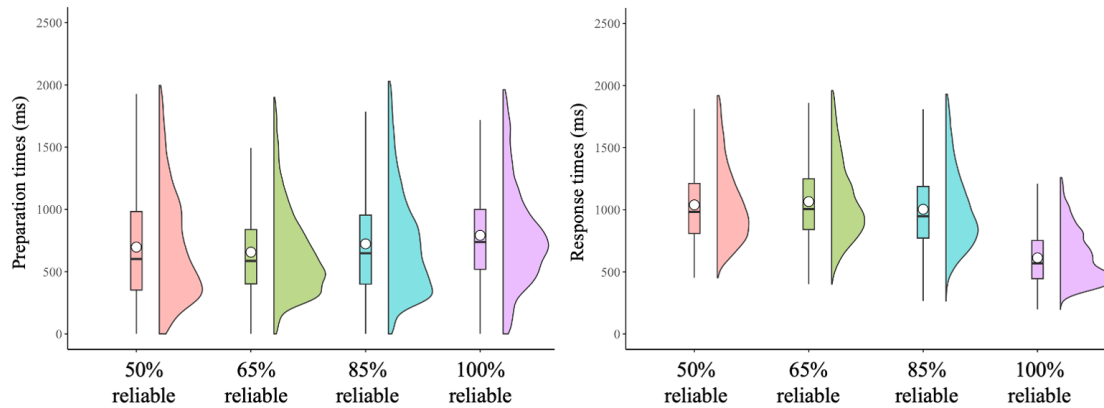
6 The analysis of response times revealed significant effects of the 65/85 contrast ( $b$   
7  $= 0.07$ ,  $t = 2.31$ ,  $\chi^2(1) = 5.35$ ,  $p = .021$ ) and the 85/100 contrast ( $b = 0.39$ ,  $t = 9.51$ ,  $\chi^2(1)$   
8  $= 90.37$ ,  $p < .001$ ), but not the 50/65 contrast ( $b = -0.03$ ,  $t = -0.52$ ,  $\chi^2(1) = 0.38$ ,  $p = .471$ ).  
9 Thus, response times are shorter when cue reliability increases from 65% ( $M = 1070$   
10 msec,  $SD = 309$  msec) to 85% ( $M = 1000$  msec,  $SD = 312$  msec) and also sharply drop  
11 from 85% to 100% ( $M = 613$  msec,  $SD = 207$  msec) (see Figure 7).

12 In summary, the integrated analysis combining all four reliability conditions  
13 (50%, 65%, 85%, and 100%) revealed a nuanced relationship between cue reliability  
14 and proactive control. We focus on two key patterns. First, preparation times increased  
15 as reliability rose from 65% to 85%. Second, response times decreased as reliability  
16 rose from 65% to 85%, and they decreased dramatically when reliability rose from 85%  
17 to 100%. We interpret these two key findings in the General Discussion section.

18

19 **Figure 7.**

20 *Mean preparation times (left) and mean response times (middle) in the self-paced task-*  
21 *switching paradigm of each condition in Experiment 1 and 2.*



1

2 *Note.* In all panels, boxplots indicate the medians and interquartile ranges, whiskers  
 3 represent the range of the data (excluding outliers), and white dots represent the  
 4 condition means. The kernel probability density of the data at different proportions is  
 5 also depicted.

6

7

### General Discussion

8

It is well established that individuals can adapt their cognitive control mode

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flexibly in response to environmental features (e.g., Braem et al., 2019; Braver, 2012;

10

Bugg & Smallwood, 2016; Egner, 2023). One key factor influencing cognitive control

11

mode is the predictability of the environment (Braver, 2012; Chevalier et al., 2020;

12

Munakata et al., 2023). When upcoming conflicting events are predictable, engaging

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cognitive control proactively is advantageous as it enables quicker and more accurate

14

responses to the events. A recent study empirically supported this possibility by

15

manipulating cue reliability in a cued task-switching paradigm, in which a precue

16

stimulus presented ahead of target onset predicted either a color or shape task rule and

17

participants sorted the target based on the relevant task rule (Chevalier et al., 2020).

18

One key finding was that adults showed faster responses, reflecting the use of proactive

19

control, when the precue always correctly predicted the upcoming task than when the

20

precue randomly predicted it (Chevalier et al., 2020). The present study replicated and

1 extended this finding, showing that adults showed reduced switch costs as well as faster  
2 responses when the precue reliability was 100%, as compared to 50%. These findings  
3 confirm a relation between the adaptiveness of proactive control engagement and  
4 environmental predictability.

5       The current study further elucidates the precise mechanism underlying how  
6 environmental predictability affects proactive control engagement. First, we highlighted  
7 preparatory processes by using a self-paced task-switching paradigm (Chevalier &  
8 Blaye, 2016; Longman et al., 2017), in which individuals have the opportunity to  
9 prepare for the target response while precues are presented. This paradigm allowed us to  
10 examine whether or not participants spontaneously use proactive control. While  
11 previous research, such as Chevalier et al. (2020), has used physiological measures  
12 (e.g., ERPs and pupil dilation) to assess proactive preparation, our study provides  
13 converging evidence from a different direct method (self-paced preparation time) that  
14 preparation is influenced by cue reliability. Our two experiments demonstrated that  
15 preparation times were longer in conditions with high precue reliability, suggesting that  
16 adults spontaneously spend more time processing reliable information that predicts the  
17 upcoming task than unreliable information. This finding, combined with our results on  
18 task performance outcomes (faster responses and reduced switch costs), strengthens the  
19 evidence that cue reliability influences the engagement of spontaneous advance  
20 preparation. Thus, our findings contribute substantially to the understanding that adults  
21 selectively engage proactive control based on environmental predictability, as  
22 evidenced both by control processes and task performance outcomes.

23       Next, we compared more predictable to less predictable environments, moving  
24 beyond the simple dichotomy of predictable versus unpredictable. Combining the

1 findings from Experiment 2 and the comparison of the four conditions across  
2 Experiments 1 and 2 (i.e., 50% reliable, 65% reliable, 85% reliable, 100% reliable  
3 conditions), we found two potential thresholds that govern the relationship between cue  
4 reliability and proactive control engagement. The first threshold concerns the decision  
5 to engage proactive control. In Experiment 2, we found that adults showed longer  
6 preparation times and faster responses when the precue reliability was 85% compared to  
7 65%. We also demonstrated that when the precue reliability was 85%, there were larger  
8 differences in both response times and error rates between "matched" trials (where the  
9 cue correctly predicted the task) and "unmatched" trials (where the cue incorrectly  
10 predicted the task), as compared to when the precue reliability was 65%. By integrating  
11 the findings from Experiment 1 and 2, we found differences in preparation times and  
12 response times between the 65% and 85% reliable conditions, but not between the 50%  
13 and 65% reliable conditions. These findings suggest that the threshold in the cued-task  
14 switching paradigm for the decision to implement proactive control lies between the  
15 65% reliable and 85% reliable conditions. Crossing this threshold, adults tend to take  
16 more time to process contextual cues and engage cognitive control proactively based on  
17 the information from the cues. This is consistent with the results of Bugg and  
18 Smallwood (2016), suggesting that there may be a threshold between 75% and 100%  
19 reliability that is necessary to encourage to use proactive control

20 The second threshold concerns the benefits gained from proactive control  
21 engagement. Although there was no significant difference in preparation times between  
22 85% and 100% reliable conditions, response times were notably faster in the 100%  
23 reliable condition. These findings suggest that adults engage proactive preparation in  
24 both conditions, but that the advantages of this preparation are more pronounced in the

1 100% reliable condition. In other words, the effectiveness of proactive control  
2 engagement may be maximized in the 100% reliable condition, with a boundary lying  
3 between the 85% and 100% reliable conditions. However, it is also plausible that the  
4 effectiveness of proactive control engagement would be particularly high in the 100%  
5 reliable condition compared to the 85% reliable condition, rather than there being a  
6 threshold somewhere between these two conditions. This suggests that the advantage of  
7 proactive control may be undermined even if only a few unmatched trials are included.  
8 Indeed, a recent study showed that adults modulate their proactive preparation even in  
9 uncertain situations with 10% unreliable information (Chai et al., 2024). Collectively,  
10 adults are highly sensitive to how predictable the environment is when deciding whether  
11 they use proactive control to maximize its the benefits

12 In the self-paced task switching paradigm, it has been demonstrated that longer  
13 preparation times are associated with greater accuracy and faster responses (Chevalier  
14 et al., 2020) and with a reduction in switch costs (Longman et al., 2017). Consistent  
15 with these findings, our participant-level analysis in the 100% reliable condition  
16 revealed that individuals who spent longer on average preparing also showed faster  
17 responses. This finding is also compatible with traditional task-switching studies, which  
18 have shown that advance preparation in response to an increase in cue-stimulus  
19 intervals (CTIs) leads to faster responses and a reduction in switch costs (e.g., Meiran,  
20 2002; Monsell & Mizon, 2006). However, this relationship was not observed in the  
21 trial-by-trial analysis in the present study. We suggest this discrepancy may be due to  
22 the variability inherent in the self-paced task-switching paradigm. While CTI-  
23 manipulation studies typically use fixed intervals of around 1000 msec, our self-paced  
24 preparation times showed a much wider range, with some exceeding 2000 msec. These

1 longer preparation times may include processes beyond pure task-goal preparation, such  
2 as hesitation or other cognitive processes, which could add noise and obscure the direct  
3 relationship between preparation time and response time at the trial level.

4 In contrast, longer preparation times were not associated with faster responses  
5 even in the 85% reliable condition, despite participants clearly using proactive control  
6 in this condition. The absence of a clear relationship between preparation times and  
7 response times may be related to the second threshold mentioned earlier. Indeed, the  
8 pattern of the association between preparation times and response times differed  
9 between the 100% reliable and the other conditions. One possible explanation for this  
10 discrepancy is that the advantage of proactive control may be constrained by the need  
11 for attentional monitoring, even on matched trials. For example, in the 85% reliable  
12 condition, participants were able to predict the task cue correctly on most trials based on  
13 the precue. However, because the precue was unexpectedly inaccurate on 15% of trials,  
14 they might have still engaged in some form of verification process to ensure that the  
15 task cue aligned with the precue before responding. As a result, even when participants  
16 extended their preparation time, the expected facilitative effect on response times may  
17 have been diminished. This could explain why no clear relationship between  
18 preparation time and response time emerged at the participant level. Moreover, the trial-  
19 by-trial analysis did not show the expected association across all conditions. This  
20 highlights the need for future research to explore different tasks (e.g., Reimer et al.,  
21 2021) and conditions that more directly link preparation times and response times, such  
22 as situations where shorter response times, supported by proactive preparation, lead to  
23 rewards.

1        We outline possible directions for future research on cognitive control in light of  
2 our results. First, the present study’s use of explicit instructions regarding cue reliability  
3 provides a valuable lens for understanding the adaptive nature of proactive control.  
4 Based on Chevalier et al. (2020), we explicitly informed participants about the relative  
5 reliability levels to allow them to bypass the potentially long and variable process of  
6 learning statistical regularities. In this regard, our approach provides a unique test of  
7 theories such as the Expected Value of Control (EVC) theory (Shenhav et al., 2013).  
8 The EVC theory posits that cognitive control is engaged based on the expected benefits  
9 versus costs of that effort. Our findings align with this framework, as participants used  
10 the explicit reliability information to make a strategic decision to invest more time in  
11 proactive preparation in the reliable condition (or less time in the unreliable condition).  
12 This suggests that the adaptive engagement of proactive control is driven not only by  
13 implicit learning of environmental statistics but also by explicit knowledge of the  
14 predictive value of a cue. Future studies could test this possibility by manipulating  
15 whether cue reliability is conveyed explicitly or not.

16        Second, building on Chevalier et al. (2020), the current study intentionally  
17 isolated a single dimension—the reliability of a specific visual cue—to examine its  
18 direct impact on proactive control. However, environmental reliability is a multifaceted  
19 construct (Munakata et al., 2023). For example, previous studies have focused on the  
20 probability of the task switch (i.e., whether a switch or a repeat is likely to occur),  
21 demonstrating that proactive preparation is engaged when the probability of task-switch  
22 was high (e.g., Dreisbach & Haider, 2006; Kang & Chiu, 2021; Schneider & Logan,  
23 2006). In contrast, our research focuses on the predictability of the cue that signals the  
24 upcoming task. The observation that participants spontaneously spend more time

1 preparing when a cue is fully reliable, even when the overall switch probability is not  
2 manipulated, suggests that individuals are sensitive to more fine-grained aspects of  
3 environmental reliability. This finding expands our understanding of proactive control  
4 by showing that it is not only modulated by the statistical properties of task transitions  
5 but also by the local reliability of the predictive information available on a trial-by-trial  
6 basis. Therefore, our study complements and extends to the literature on switch  
7 probability, highlighting that the multidimensionality of environmental reliability plays  
8 a crucial role in how we adaptively engage cognitive control. In future study,  
9 considering how the multidimensionality of environmental reliability influences  
10 cognitive control would provide a more comprehensive understanding of how  
11 individuals adapt their cognitive control to the complex and dynamic nature of real-  
12 world environments.

13 In conclusion, the current study provides substantial methodological and  
14 theoretical contributions to our understanding of how environmental predictability  
15 affects the adaptiveness of proactive control engagement. The self-paced task switching  
16 paradigm allowed us to find that increasing cue reliability facilitates the engagement of  
17 spontaneous proactive preparation as well as outcomes that follow from proactive  
18 preparation. Furthermore, our work moves beyond the predictable/unpredictable  
19 dichotomy and suggests that adults adjust their decision to use proactive control and  
20 optimize its benefits depending on the degree of predictability. These novel findings  
21 provide a basis for future research addressing which factors, such as life history,  
22 development, and social interactions, shape and change the thresholds of predictability  
23 that determine whether or not we engage in proactive control.

24

## **Declarations**

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### **Conflicts of interest**

The authors have no competing interests to declare that are relevant to the content of this article.

### **Ethics approval**

The experiments reported in this article were approved by the Institutional Review Board of Osaka Kyoiku University (24001: Environmental Predictability and Cognitive Control Modes).

### **Consent to participate**

Informed consent was obtained from all individual participants included in the study.

### **Consent for publication**

Consent for publication was also obtained from all individual participants included in the study.

### **Availability of data and materials**

All datasets for the current study are available at the Open Science Framework repository (<https://osf.io/8sd6v/>) once finalized.

### **Code availability**

All datasets for the current study are available at the Open Science Framework repository (<https://osf.io/8sd6v/>) once finalized.

### **Author's contributions**

**Kaichi Yanaoka:** Conceptualization, Methodology, Software, Validation, Formal analysis, Resources, Data curation, Writing – Original Draft, Writing – Review & Editing, Visualization. **Hiroyuki Tsubomi:** Conceptualization, Methodology, Writing – Original Draft, Writing – Review & Editing. **Félice van 't Wout:** Conceptualization, Methodology, Writing – Original Draft, Writing – Review & Editing. **Christopher Jarrold:** Conceptualization, Methodology, Writing – Original Draft, Writing – Review & Editing. **Satoru Saito:** Conceptualization, Methodology, Writing – Original Draft, Writing – Review & Editing, Project administration, Funding acquisition. **John Nicholas Towse:** Conceptualization, Methodology, Writing – Original Draft, Writing – Review & Editing, Project administration.

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