When stimulus variability accelerates the learning of task knowledge in adults and school-aged children

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Abstract

Experience with instances that vary in their surface features helps individuals to form abstract task knowledge, leading to transfer of that knowledge to novel contexts. The current study sought to examine the role of this variability effect in how adults and school-aged children learn to engage cognitive control. We focused on the engagement of cognitive control in advance (proactive control) and in response to conflicts (reactive control) in a cued task-switching paradigm, and conducted four preregistered online experiments with adults (Experiment 1A: N = 100, Experiment 1B: N = 105) and 9- to 10-year-olds (Experiment 2A: N = 98, Experiment 2B: N = 97). It was shown that prior task experience of engaging reactive control makes both adults and 9- to 10-year-olds respond more slowly in a subsequent similar-structured condition with different stimuli in which proactive control could have been engaged. 9- to 10-year-olds (Experiment 2B) exhibited more negative transfer of a reactive control mode when uninformative cue and pre-target stimuli, which do not convey task-relevant information, were fixed, compared to when they were changed in each block. Furthermore, adults showed suggestive evidence of the variability effect both when cue and target stimuli were varied (Experiment 1A) and when uninformative cue and pre-target stimuli were varied (Experiment 1B). The collective findings of these experiments provide important insights into the contribution of stimulus variability to the engagement of cognitive control.

Key words

cognitive control, stimulus variability, task knowledge, proactive/reactive control, negative transfer, children

A fundamental question in cognitive psychology is how individuals engage cognitive control in a constantly changing environment. Cognitive control is defined as the ability to regulate one's thought and action to meet current goals (e.g., Banich, 2009; Miyake et al., 2000). An increasing number of studies are beginning to focus on learning long-term knowledge of engaging cognitive control through repeated experience. For both adults and children, these studies have paid attention to associations between control and stimulus-response mappings in adaptive control (e.g., Braem et al., 2019; Egner, 2007; Gonthier et al., 2021; Verguts & Notebaert, 2008) and cognitive skills or routines in cognitive control training (e.g., Gathercole et al., 2019; Taatgen, 2013). However, it remains unclear what constrains individuals' learning of long-term knowledge in cognitive control based on their prior experience. The current study examines the effect of stimulus variability as a potential constraint on how individuals generalize and transfer task experience to the engagement of cognitive control in novel task environments.

Transfer of a learned skill and the variability effect

Learning can be evaluated by not only how individuals improve their performance during repetitions of a task but also how they transfer a learned skill to different task contexts (Schmidt & Bjork, 1992). A primary determinant of such transfer that has been postulated is the similarity between the task context in a training phase and the different task context in a test phase (Medin et al., 1993; Schmidt, 1975). It has been proposed that the formation of a “schema” or abstract task knowledge[1] that captures the regularities of the task environment beyond specific contexts (e.g., specific stimulus-response contingencies) allows individuals to notice the similarities between the training and test phases and generalize a trained skill to the test phase (Schmidt, 1975; Wulf & Schmidt, 1988). This theory accounts for transfer effects in motor skill learning, in which generalized motor programs are hypothesized to control a class of actions with a similar overall structure and allow us to adapt to external task requirements flexibly (e.g., Schmidt, 1975; Wulf & Schmidt, 1989). Extending this theory, abstract task knowledge has been applied to explain transfer effects in memory (e.g., Bower et al., 1979; Schank & Abelson, 1977), category learning (Posner & Keele, 1968), and problem solving (Chen & Mo, 2004).

To establish the argument that abstract task knowledge underlies transfer effects, previous studies have highlighted the critical factors facilitating the construction of abstract task knowledge. One such factor is the opportunity to

[1] Note that a class of models have proposed a schema is not stored knowledge but is derived from the pool of episodic memory traces at the time of retrieval (Hintzman, 1986; Restle, 1961).

process multiple instances of diverse tasks that share a similar goal structure (Gick & Holyoak, 1983; Posner & Keele, 1968; Schmidt & Bjork, 1992; see Laviv et al., 2022 for a recent review). Exposure to instances that vary in surface features allows individuals to form task knowledge that is not restricted to overly specialized contexts (i.e., abstract task knowledge), thus facilitating transfer (Gick & Holyoak, 1983). Specifically, participants who experienced high variability patterns (e.g., variable stimulus) during learning exhibited better performance in a transfer task than those who observed low variability patterns. This variability effect has been demonstrated in many research areas including motor skill learning (e.g., Catalano & Kleiner, 1984; Schmidt & Bjork, 1992; Wulf & Schmidt, 1988), category learning (Posner & Keele, 1968), face recognition (Ritchie & Burton, 2017), problem solving (Chen & Mo, 2004), planning (Stokes et al., 2008; Vakil & Heled, 2016), and rule learning (Cole et al., 2011). Furthermore, previous developmental studies have also observed the variability effect from early childhood in the contexts of motor skill learning (e.g., Kerr & Booth, 1978; Shapiro & Schmidt, 1982; Yan et al., 1998) and vocabulary learning (Gómez, 2002). Given this, it can be argued that the variability effect provides direct evidence that abstract task knowledge underlies transfer effects from early childhood.

Cognitive control and abstract task knowledge

In cognitive control studies, it has been argued that abstract task knowledge underlies near transfer for adults and children (e.g., Bhandari & Badre, 2018; Collins & Frank, 2013; Kharitonova et al., 2009; Yanaoka et al., 2022). Researchers have mainly focused on two types of abstract task knowledge that are needed for solving a cognitive control task: knowledge of task representations and knowledge of task management, which are hierarchical and temporal aspects of task knowledge respectively (Yanaoka et al., 2022). First, knowledge of task representations is presumed to include hierarchical knowledge of a task goal and its associated stimulus–response mappings. For example, in some task-switching paradigms, individuals are asked to implement one of two task goals (e.g., a color and object identification task) where they classify one of a set of stimuli (e.g., blue bear, blue car, pink bear, and pink car) according to one of a set of stimulus-response mappings (e.g., in a color task they press the "R" key when a blue stimulus is presented and press the "U" key when a pink stimulus is presented). Acquired knowledge of task representations allows infants, preschoolers, and adults to then accommodate a novel set of task goals and stimulus–response mappings in a similarly-structured task, resulting in positive transfer to different task environments (e.g., Badre & Frank, 2012; Kharitonova & Munakata, 2011; Pereg et al., 2021; Shahar et al., 2018; Werchan et al., 2015, 2016).

In contrast, less attention has been paid to the extent to which individuals are aware that task environments have a dynamical structure, with events unfolding in a specific order, and with specific timings. However, individuals learn how to implement goal-directed behaviors in accordance with such temporal task structures. The second form of task knowledge therefore amounts to knowledge of task management, which is knowledge about which approach one takes to engage cognitive control. In particular, the current study focused on knowledge about the temporal structure of task goal activation, which differs between two distinct cognitive control modes, that is, proactive and reactive control (e.g., Braver, 2012; Chatham & Badre, 2015; Chatham et al., 2009; Munakata et al., 2012). Proactive control allows individuals to activate and maintain a task goal in a sustained way to prevent or minimize the effects of interference *before* it occurs. In contrast, reactive control is mobilized as needed to resolve interference *after* it occurs. Thus, engaging proactive control has been evidenced by deceased response times for resolving interference as compared to engaging reactive control (e.g., Chevalier et al., 2015, 2020). Specifically, in a cued task-switching paradigm, a proactive control mode requires activation of a task goal based on contextual cue information *before* the appearance of a bivalent stimulus, which is relevant to several tasks, whereas in a reactive control mode the task goal is activated based on the task cue *after* a bivalent stimulus appears. Thus, as individuals experience the cued task-switching paradigm repeatedly, they learn whether to engage control either proactively or reactively (i.e., activate a task goal before or after the appearance of a bivalent stimulus). Such task knowledge about the temporal structure of task goal activation affects how individuals transfer cognitive control modes to different task environments (Bhandari & Badre, 2018; Gonthier et al., 2021; Sabah et al., 2021; Yanaoka et al., 2024).

Specifically, previous studies (e.g., Bhandari & Badre, 2018; Yanaoka et al., 2024) have examined whether knowledge of task management underlies near "negative" transfer of prior experience of a cognitive control task to a novel setting. Yanaoka et al. (2024) examined proactive and reactive control in the cued task-switching paradigm (Chevalier et al., 2015). They used Chevalier et al.'s two conditions that differ in the timing of the cue appearance (see Figure 1). Specifically, in the "pre-cued" condition, the informative task cue was presented before target onset and remained visible after the target appeared, so that cue-based proactive preparation was possible but not necessary. In the "simultaneous-cued" condition, uninformative stimuli (i.e., 12 brown circles), instead of the informative task cue, appeared before target onset and then the task cue was presented at the same time as the target, so that proactive cue processing was impossible and participants would be required to engage in a reactive control mode. Their key finding was that prior experience of engaging reactive control in the "simultaneous-cued" condition made both adults and 9- to 10-year-olds respond more slowly, across both switch and no switch trials, in a subsequent "pre-cued" condition with different stimuli, in which proactive control could have been engaged, compared with those who first performed the "pre-cued" condition. Given that it is generally expected that prior task experience performance benefits subsequent similar-structured task performance (i.e., positive transfer or practice effects), this decrement suggests that individuals learn knowledge of task management (i.e., using reactive control) from prior task experience and negatively transfer it to similarly-structured situations with different stimuli.

However, one may criticize the above studies as there are alternative explanations for the apparent negative transfer effects observed in Yanaoka et al. (2024). Specifically, general slowing seen in the test phase could be caused by an element of surprise related to the transition from a training phase to a test phase (i.e., from the “simultaneous-cued” condition to the “pre-cued” condition). It is possible that the costs associated with becoming accustomed to a different task environment might therefore be reflected in negative transfer effects. In addition, when first starting the “pre-cued” condition, participants have not yet seen a trial where the cue information appeared before a target in advance, potentially leading to a temporary slowing down of participants’ responses. To overcome these limitations, one potential approach is to examine whether practices that promote learning of abstract task knowledge also lead to greater transfer effects in a cognitive control task. Following Schmidt and Bjork (1992), we focused on stimulus variability as a driving factor in learning knowledge of task management. If stimulus variability enlarges negative transfer effects, this would establish a direct link between negative transfer effects and knowledge of task management that cannot be explained by the alternative explanations outlined above.

Cognitive control and the variability effect

Few studies have provided consistent evidence of the variability effect in adults’ use of cognitive control (Karbach & Kray, 2009; Sabah et al., 2019, 2021). Sabah et al. (2019, 2021) manipulated the variability of task-switching training by introducing novel stimuli in each training block and showed that content variability produced higher transfer gains when compared to repeating the same stimuli. Karbach and Kray (2009) also observed similar findings that stimulus variability during a training phase may help adults construct more abstract task knowledge, leading to greater near transfer effects in a task-switching paradigm.

However, two critical issues remain to be addressed. First, to understand the precise mechanism underpinning how stimulus variability accelerates task knowledge in engaging cognitive control, it is important to specify what form of task knowledge (i.e., knowledge of task representations vs. knowledge of task management) individuals learn in a more abstract form when presented with varied stimuli. Previous work (e.g., Karbach & Kray, 2009; Sabah et al., 2019, 2021) has examined the effect of stimulus variability on “positive” transfer of prior task experience. Yet, it is difficult to specify what form of knowledge underlies such “positive” transfer as the positive transfer effect is confounded with any benefits from repetitive practice. Thus, the precise mechanism underlying the variability effect on cognitive control remains unclear. Following Yanaoka et al. (2024), the current study examined whether individuals exhibit “negative” transfer effects that are assumed to reflect learning knowledge about the temporal structure of task goal activation. Critically, we addressed the issue of whether any negative transfer of a reactive control mode is accelerated by stimulus variability during the training phase [2].

Second, as far as we know, there is only one developmental study that examined the variability effect among children in the context of cognitive control (Karbach & Kray, 2009). That study showed that stimulus variability hinders near transfer in children, in contrast to adults. However, Karbach and Kray's (2009) variable training was combined with verbal self-instruction training, in which participants were asked to verbalize the next task goal in each trial. Thus, it may be that the decreased transfer after variable training found in children is the result of an interaction between the variable training and the verbalizations performed during training. Given that the variability effect has been observed from early childhood in the context of motor skill learning and vocabulary learning (e.g., Gómez, 2002; Shapiro & Schmidt, 1982), one would expect to see the typical variability effect during cognitive control training in children. Thus, we also examined whether children showed a larger negative transfer of a reactive control mode when presented with variable stimuli during a training

[2] One might also predict a variability effect on the degree of positive transfer of a trained "proactive" control mode. However, because adults have a strong default tendency to use proactive control (Gonthier et al., 2016), further improvements in the use of proactive control may be difficult to detect. Thus, even if one finds positive transfer of the use of proactive control, finding a variability effect on the degree of that positive transfer is likely to be highly challenging. Given this, we instead focused on negative transfer of the use of "reactive" control.

phase than when presented with fixed stimuli, allowing us to explore developmental differences in the variability effect in the context of cognitive control.

Current study

Extending Yanaoka et al. (2024), we employed three participant groups in each study (see Figures 2 & 3) using Chevalier et al.'s two conditions of the cued task-switching paradigm. Participants in the varied simultaneous-cued training group first experienced the simultaneous-cued training phase, in which different materials were used for each block, and then subsequently performed a pre-cued test phase with different materials. Participants in the fixed simultaneous-cued training group experienced a similar training-test procedure but with a constant set of stimuli in each block of the training phase. Lastly, participants in the pre-cued training group first experienced a pre-cued training phase and then performed another pre-cued test phase with different materials. To examine any negative transfer of the use of reactive control it was necessary to conduct experiments with participants who would normally be expected to perform tasks using a proactive control approach. Thus, we selected 9- to 10-year-old children as the participants in our developmental experiments because they have been shown to rely on proactive control engagement when proactive preparation is possible, as do adults (e.g., Chatham et al., 2009, 2015).

Throughout all the four experiments, we tested three predictions (see Table 1). The first two predictions were prerequisites for testing the key prediction, which was prediction 3. First, we confirmed whether our manipulation of the timing of cue presentation would cause participants to engage reactive control more in the simultaneous-cued training phase relative than in the pre-cued training phase (prediction 1). Second, we predicted that prior experience of the “pre-cued” condition would improve participants’ overall performance in the subsequent “pre-cued” condition with different stimuli. Specifically, individuals in the pre-cued training group would respond more quickly (and potentially also more accurately) in the test phase than in the training phase (prediction 2).

Third, our key assumption was that prior experience of engaging a reactive control mode (assessed by prediction 1) would make individuals engage reactive control in a subsequent similar-structured condition in which proactive control could have been engaged, despite the fact that prior task experience generally yields positive transfer effects (assessed by prediction 2). Specifically, we tested whether individuals in the varied and fixed simultaneous-cued training group would show increased overall response times in the test phase when compared to individuals in the pre-cued group's performance in the training phase (a test that directly compares performance during individuals' first experience of the pre-cued condition). The more specific prediction was that individuals in the varied simultaneous-cued training group would show much slower responses, that is greater negative transfer effects, when compared to those in the fixed simultaneous-cued training group (prediction 3). Based on Schmidt and Bjork (1992), this prediction follows from our assumption that stimulus variability will increase learning of abstract knowledge about the temporal structure of task goal activation (i.e., exerting reactive control) through the experience of the simultaneous-cued training phase, resulting in greater negative transfer of a reactive control mode to the test phase.

Several task-switching studies, including our own, have shown that advance informative cue presentation reduces overall response times, rather than conferring a benefit that is specific to switch trials (Altmann, 2004a; Altmann, 2004b; Chevalier et al., 2015, 2020; Jin et al., 2020; Koch, 2001; Yanaoka et al., 2024). Given that the cognitive components of task switching consist not only of shifting processes but also monitoring processes such as identifying and maintaining a relevant task goal (Cepeda et al., 2001; Chevalier et al., 2015; De Baene, & Brass, 2014), these findings suggest that proactive control supports such monitoring on both switch and no switch trials alike. In fact, faster overall response times have been concurrently observed alongside more pronounced cue-locked posterior positivity measured by ERPs and greater cue-related pupil dilation, which are indices of the use of proactive control (Chevalier et al., 2015, 2020, Yanaoka et al., 2021). Therefore, we predicted that individuals in the pre-cued training group would respond more quickly in the training phase, regardless of trial type (switch or no switch) when compared to the varied and fixed simultaneous-cued group's performance in the training phase (prediction 1a). However, other task-switching studies have shown that any advance preparation in response to an increase in cue-stimulus intervals leads to a reduction in switch costs (e.g., Meiran, 2000; Monsell & Mizon, 2006; see Kiesel et al., 2010; Monsell, 2003 for reviews), suggesting that engaging proactive control can reduce switch costs. Therefore, an alternative hypothesis tested by prediction 1 would be that advance informative cue presentation would result in smaller switch costs (prediction 1b). Before conducting this experiment it was difficult to make strong predictions regarding the effect of switch costs, given previously inconsistent findings particularly when preparation time for processing cue information has been manipulated using a between-participant design (e.g., Altmann, 2004a; Altmann, 2004b; Chevalier et al., 2015, 2020; Yanaoka et al., 2024, but see Elchlepp et al. (2015)). Furthermore, in terms of the negative transfer effect, as in prediction 1, it is possible that individuals negatively transfer task knowledge regardless of trial type (prediction 3a) or switch costs would be mitigated when individuals negatively transfer task knowledge (prediction 3b).

Experiment 1A

We primarily examined whether adults exhibit negative transfer of a reactive control mode after the experience of simultaneous-cued training phase and whether the degree of this negative transfer is greater when the cue and target stimuli were varied, compared to when they were fixed. Specifically, we tested the three predictions outlined in Table 1.

Method

Participants

As specified in our preregistered plan (https://osf.io/hzv4y), our target sample was 96 adults (varied simultaneous-cued training group = 32, fixed simultaneous-cued training group = 32, pre-cued training group = 32). The participants were recruited to an online experiment and, given the possibility that some participants might respond randomly, we recruited 108 adults, aged between 19 and 30 years old, from a database of a research consulting company. All the participants were native Japanese speakers. All participants gave full informed consent before the experiment and were paid 1000 yen after completing all the task procedures. Four participants who did not complete all the sessions and four participants who performed less than minus 3SD score of the mean accuracy (i.e., below a cut off score of 71.3%) were excluded from the analyses.[3] Our final sample consisted of 33 adults in the varied simultaneous-cued training group (*M* = 27.30 years, *SD* = 2.39 years, 19 females and 14 males), 34 adults in the fixed simultaneous-cued training group (*M* = 25.85 years, *SD* = 3.05 years, 18 females and 16 males), and 33 adults in the pre-cued training group (*M* = 25.30 years, *SD* = 3.36 years, 18 females and 15 males). This and the subsequent experiments in this study were approved by the institutional review board of the University of Tokyo (Variability effect on learning task knowledge in cognitive control).

It was difficult to estimate the sample size needed to adequately detect any variability effect on degree of negative transfer. Thus, our target sample size was

[3] In the preregistration document, we stated that participants who scored less than 80% would be excluded from final analysis. However, we subsequently came to the conclusion that the 80% criterion was unhelpfully arbitrary and so deviated from the preregistration plan. Specifically, we used 3SD as the basis for determining who was excluded. However, even if we were to adopt the 80% criterion, the number of participants excluded would not differ.

decided following Yanaoka et al. (2024) (N = 64). This study successfully observed negative transfer of a reactive control mode by making a comparison between the training phase performance of the pre-cued training group and the test phase performance of the simultaneous-cued training group. To determine whether the sample size of that previous study was adequately powered to detect negative transfer and stimulus variability effects, we ran an additional sensitivity analysis with 1000 Monte Carlo simulations using the simr package in R (Brysbaert & Stevens, 2018; Green and MacLeod, 2016). This aimed to establish the minimal effect size that could be detected with 80% power at $\alpha = 0.05$. We systematically varied the effect of the parameters of interest and calculated power at each level to test which effect size we were able to detect with at least 80% power. Note that this approach is different from conducting a post-hoc power analysis, which simply yields a transformation of the observed *p*-value and is not informative (Levine & Ensom, 2001).

Given our sample of participants, the sensitivity analysis revealed that we would be able to detect a minimum effect size with 80% power of $\beta = 0.193$ (varied comparison), $\beta = -0.034$ (varied comparison × block), $\beta = 0.191$ (fixed comparison), $\beta = -0.034$ (fixed comparison × block) (see Table 1D in supplemental material D).

Procedure and experimental design

Our experiment was programmed in PsychoPy (Peirce et al., 2019) and exported and run as an PsychoJS experiment on Pavlovia (https://pavlovia.org/). The online experiment was run only with either Firefox or Chrome browsers. At the beginning of the experiment, participants provided information about their age and sex on a platform provided by the research consulting company, and were then informed about ethical information such as data confidentiality and their right to suspend the experiment. After they gave consent, they clicked on a link that took them to the main experimental task that was presented using Pavlovia. Participants were randomly assigned to one of the three experimental groups. They were introduced to the "Santa Claus Game", in which they were asked to help Santa Claus sort a set of gifts by either color or object, and performed two conditions of the cued task-switching paradigm. Critically, in the varied reactive training group, adults first experienced the simultaneous-cued training phase, in which different cue and target stimuli were used for each block (e.g., first block: colorful jagged patches on a blue circle and blue bear; second block: colorful circular patches on a green circle and light blue snowman; third block: colorful polygon patches on a dark red circle and orange airplane).

Santa Claus Game

The materials and task procedures were similar to Yanaoka et al. (2024), which replicated Chevalier et al. (2015) as precisely as possible. We had four sets of surrounding color circles, informative cues, and target stimuli (for details in supplemental material A). The surrounding color circle served as a placeholder for the informative or uninformative cues. The informative task cue signaled either a color identification task with 12 colorful patches (see Figure 1) or an object identification task with 12 gray geometrical shapes (see Figure 1). The target stimuli were 8 × 8 cm in size and varied on two dimensions (e.g., color: blue and pink; object: bear and car). To facilitate responding, four 2 × 2 cm unidimensional response pictures (e.g., a bear, a blue patch, a car, and a pink patch) and four response keys corresponding to each response picture (i.e., “R”, “T”, “O”, and “P”) were constantly presented in two horizontal rows at the bottom of the screen.

On each trial of the “Santa Claus Game”, a fixation cross within a color circle was displayed at the center of the screen for 1000 to 1200 msec, followed by a pre-target stimulus (i.e., brown wrapped gift box) that was presented within the same color circle for 1500 msec before target onset. Simultaneously, either informative or uninformative task cue stimuli were presented on the color circle.

The role of the pre-target was to prevent too much attention being paid to the task cue, which allowed us to examine whether participants endogenously processed informative cues. Subsequently, a target stimulus replaced the pre-target and remained until participants responded or for up to 10 seconds. Critically, as explained in the introduction section, the onset of informative cue presentation on the color circle was manipulated across conditions (see Figure 1).

The “Santa Claus Game” was composed of first practice, training, second practice, and test phases, each separated by a short break. In the first practice phase, participants were first instructed to sort bivalent gifts according to one of the tasks (either color or object identification) based on a task cue. Participants were also explicitly informed that the task cue would indicate which rule to use and were further explained about (un)informative cue, pre-target, and target in a figure depicting the structure of one trial (see Figure 1). However, participants were not instructed to when they activate a task goal based on the cue information in the pre-cued and the simultaneous-cued condition. They were asked to place four fingers (index and middle fingers of each hand) on four keys, which corresponded to unidimensional response pictures presented on the screen, and to respond with one of the four keys according to the current task. Participants completed four practice trials with this first task, and were then given instructions for, and performed four practice trials with, the second task. The presentation order of the tasks was counterbalanced across participants. Next, participants were presented with 10 practice trials in a pseudorandom sequence that included five color trials and five object trials. During these ten trials participants received feedback on their performance, and the sequence of ten trials was repeated if they made more than three errors.

Following Chevalier et al. (2015, 2020), the training phase contained three blocks of 21 trials separated by a short break; each block consisted of one start trial (not included in the analysis), 10 switch trials, and 10 non-switch trials. The switch and non-switch trials were intermixed in a pseudorandom order. In the varied simultaneous-cued training group, before starting a new block, participants were presented with a novel set of cue and target stimuli and instructed to sort the novel bivalent stimuli according to either a color or object identification task again. Any further practice trials were not performed. In contrast, one set of cue and target stimuli was used across all three blocks in the fixed simultaneous-cued training group and the pre-cued training group.

It is important to note that a different set of surrounding color circles, informative cues, and target stimuli from that used in the training phase was employed in the second practice and test phases. Thus, in the second practice phase, participants were first introduced to the novel stimuli and were presented with four practice trials for each of the color and object identification tasks. However, they did not practice with ten mixed trials. Then, in the test phase, participants in the three training groups all engaged in the "pre-cued" condition, in which the number of trials and the proportion of switch trials were the same as in the training phase. During the training and test phases, participants were provided with no feedback. The different sets of stimuli used in the training and test phases were counterbalanced across participants.

Data processing

The dependent measures were response times and correct response rates in the cued task-switching paradigm. Response times were examined for correct responses after discarding outliers, that is, values greater than median + 2.5 MAD (Median Absolute Deviation) and values lower than median – 2.5 MAD (Leys, Ley, Klein, Bernard, & Licata, 2013). 6.3% of correct responses were excluded from the analyses of response times.

Data analysis

The study design, hypotheses, and analytic plan were preregistered in the Open Science Framework (https://osf.io/hzv4y). Using the lme4 package (Bates, Maechler, Bolker, & Walker, 2015) in the R system (R Core Team, 2013), we conducted regression analyses with linear mixed-models for response times, which were not log-transformed.[4] We also conducted generalized mixed-models logistic regression analysis for correct response rates. The regression models used in this study was similar to Yanaoka et al. (2024).

To test the first and second predictions (see Table 1), the regression model included the factors of training group comparison (see below: varied simultaneous-cued training group vs. pre-cued training group and fixed simultaneous-cued training group vs. pre-cued training group), task phase (test phase, training phase), trial type (switch trial, no switch trial), block, and their interactions. As preregistered, the factor of training group was coded as two planned contrasts. More specifically, we report the effect of contrasting the pre-cued training group with the varied simultaneous-cued training group as a 'varied group' comparison and the effect of contrasting the pre-cued training group with the fixed simultaneous-cued training group as a 'fixed group' comparison. As random factors, random intercepts for participants were included in the models for response times and correct response rates. We compared the results of two

[4] When dealing with exponential or logarithmic RT data, it may be more appropriate to utilize generalized linear mixed effects modeling (GLMM) than linear mixed effects modeling. This approach was not specified in our preregistered analysis plan, but in supplemental material E we further report the result of another set of models in which we applied the GLMM approach with a gamma distribution and log link function. Overall, the findings from the GLMM are consistent with those reported in the main text.

regression models: one focal model containing the two-way interactions (varied group comparison × task phase, fixed group comparison × task phase) and another model without each interaction. In terms of the two-way interaction, we were interested in two planned comparisons. First, pairwise comparisons were conducted to examine whether in the training phase adults in the pre-cued training group would respond more quickly than adults in the varied and fixed simultaneous-cued training group (prediction 1). Second, a pairwise comparison was conducted to examine whether adults in the pre-cued training group respond more quickly (and potentially more accurately) in the test phase than in the training phase (prediction 2).

To test the key third prediction concerning negative transfer of a reactive control mode and the variability effect (prediction 3), we set up another model, including the factors of training group comparison (varied group comparison: the test phase performance in the varied simultaneous-cued training group vs. the training phase performance in the pre-cued training group; fixed group comparison: the test phase performance in the fixed simultaneous-cued training group vs the training phase performance in the pre-cued training group), trial type, block, and their interactions. Random intercepts for participants were also included in the model as random factors. We also compared the results of two regression models: one focal model containing the two-way interactions (varied group comparison × block, fixed group comparison × block) and another model without each interaction. Pairwise comparisons were conducted to examine whether adults in the varied and fixed reactive training groups would respond more slowly in the test phase than adults in the pre-cued training group respond in the training phase (throughout the blocks or in the earlier block) and whether such a decrement would be seen for a longer period in the varied reactive training group than in the fixed reactive training group. As indicated by Yanaoka et al. (2024), it is possible that negative transfer of a reactive control mode would transiently occur at the earlier trials of the test phase and rapidly decrease in the subsequent trials. Therefore, as specified in our preregistered analysis plan, if we did not find any clear negative transfer effects in earlier block(s), we considered 5 trials as one mini-block and analyzed again.

The significance of each predictor was represented by the standardized coefficient, chi-square, and *p*-value resulting from the likelihood ratio test. Holm-corrected *p*-values with a family wise alpha of .05 are used throughout to adjust for pairwise comparisons.

Result and Discussion

Cognitive control modes in the training phase and positive transfer effects of task knowledge (predictions 1 and 2)

Response times. Figure 4a depicts mean correct response times for each condition. The full results are summarized in Table 1A in supplemental material B.

Our focal comparison revealed a significant two-way interaction between the varied group comparison and task phase ($\beta = -0.19$, $t = -22.77$, $\chi^2 = 518.53$, $df = 1$, $p < .001$) and a significant two-way interaction between the fixed group comparison and task phase ($\beta = -0.16$, $t = -19.11$, $\chi^2 = 365.19$, $df = 1$, $p < .001$). There were also a significant three-way interaction between the varied group comparison, task phase, and block ($\beta = -0.05$, $t = -5.57$, $\chi^2 = 32.02$, $df = 1$, $p < .001$) and a significant three-way interaction between the fixed group comparison, task phase, and block ($\beta = -0.02$, $t = -2.29$, $\chi^2 = 5.43$, $df = 1$, $p = .021$), although we did not have any strong predictions about them and therefore do not discuss them in any detail. In terms of the first prediction, in the training phase participants in the pre-cued training group responded more quickly than those in the varied simultaneous-cued training group ($\beta = 0.59$, $t = 10.77$, $p < .001$) and those in the fixed simultaneous-cued training group ($\beta = 0.46$, $t = 8.27$, $p < .001$). Second, participants in the pre-cued training group responded more quickly in the test phase than in the training phase (β = -0.07, t = -6.18, p < .001).

We also found a main effect of trial type (β = 0.05, t = 6.58, χ^2 = 44.46, df = 1, p < .001) and its interaction with task phase (β = 0.02, t = 2.68, χ^2 = 6.79, df = 1, p = .009), indicating a switch cost in response times which was larger in the test phase. There were no significant interactions with trial type that were related to training group comparisons.

Correct response rates. Correct response rates were near ceiling (see Figure 5a), thus we did not consider them as a key measure for adults. We include the analysis for correct response rates in supplemental material C.

Negative transfer of a reactive control mode (prediction 3)

Response times. To test our key prediction concerning negative transfer of a reactive control mode, we examined the varied and fixed group comparisons described in the preceding data analysis section. These two comparisons have two purposes. The first one is to examine whether negative transfer is observed in the varied and fixed simultaneous-cued training groups. The second one is to examine whether the negative transfer effect behaves differently in the varied and fixed simultaneous-cued training groups.

These results are summarized in Table 2. The varied group analysis found a significant main effect of the varied group comparison and a significant interaction between the varied group comparison and block. Pairwise comparisons with Holm correction demonstrated that participants in the varied simultaneous-cued training group responded more *slowly* in the first block of the test phase relative to the training phase performance of participants in the pre-cued training group (β = 0.22, t = 3.08, p = .008), whereas we did not observe such differences in the second and third block (Second block: β = 0.12, t = 1.75, p = .082; Third block: β = 0.15, t = 2.17, p = .064). The second fixed group analysis did not find a significant interaction between the fixed group comparison and block.

According to our preregistered analysis plan, we broke the first block into four mini-blocks (5 trials in each mini-block) and examined the simple effect of the fixed group comparison in each mini-block using Holm correction. We found a significant expected pattern only in the first mini-block where participants in the fixed simultaneous-cued training group showed slower responses in the test phase than did participants in the pre-cued training group in the training phase (β = 0.30, t = 3.57, p = .002), whereas no significant differences were observed in the second, third, and fourth mini-blocks (Second mini-block: β = 0.07, t = 0.87,

$p = .765$, Third mini-block: $\beta = 0.07$, $t = 0.88$, $p = .765$, Fourth mini-block: $\beta = 0.12$, $t = 1.47$, $p = .431$) (see Figure 6a).

We therefore observed slower responses in the test phase of the varied and fixed simultaneous-cued training group relative to those seen in the training phase performance of the pre-cued training group, that is, negative transfer of a reactive control mode. Critically, the varied and fixed simultaneous-cued training group differed in how long the negative transfer effects could be seen for. The varied simultaneous-cued training group showed negative transfer effects in the first block (i.e., first twenty trials), whereas the fixed simultaneous-cued training group showed them only in the first mini-block (i.e., first five trials). These findings that stimulus variability leads to more prolonged negative transfer effects.

We employed the varied and fixed group comparisons to focus on whether negative transfer is observed in the varied and fixed simultaneous-cued training groups. However, it might be argued that a direct comparison between the test phase performance of the varied simultaneous-cued training group and the test phase performance of the fixed simultaneous-cued training group (hereafter, the varied-fixed comparison) is a more appropriate and stricter test of variability manipulation. Thus, we ran another post-hoc (not preregistered) model, including the varied-fixed comparison. Note that this comparison indicates group differences in response times in the test phase, rather than negative transfer effects which instead emerge from the preceding analysis. Neither the main effect of the varied-fixed comparison (β = 0.08, t = 1.19, χ^2 = 1.41, df = 1, p = .234) nor its interaction with block (β = -0.002, t = -0.17, χ^2 = 0.03, df = 1, p = .867) were significant. Therefore, although the current experiment showed the expected pattern of a greater degree of negative transfer in the varied than the fixed simultaneous-cued training groups, there was not strong evidence that this difference in size of negative transfer was itself significant.

Correct response rates. We include the analysis for correct response rates in supplemental material C.

Experiment 1B

Experiment 1B aimed to further examine whether stimulus variability could accelerate learning knowledge of task management resulting in greater negative transfer of a reactive control mode. In the "simultaneous-cued" condition (see Figure 1), the most efficient control strategy is that individuals (a) ignore the uninformative cue and pre-target stimuli and then (b) activate a task goal based on the informative cue stimuli when it arrives, thereby processing the target reactively. To examine the variability effect, Experiment 1A focused on process (b) and presented different informative cue and target stimuli across each block of the varied simultaneous-cued training phase. We assumed that the variation of these informative cues and targets makes it even more apparent to participants that simultaneously presented informative cue information cannot be used to prompt proactive control, leading instead to the engagement of a reactive control mode. As another way of examining the variability effect, Experiment 1B focused on process (a) and employed a different set of uninformative cue and pre-target stimuli in each block of the training phase in the varied simultaneous-cued training group. To learn abstract task knowledge about activating a task goal, it might be effective to recognize that even if the uninformative cue and pre-target stimuli are changed, the temporal structure of task goal activation is not changed. The formation of such abstract knowledge would prompt adults to ignore uninformative cue information presented along with a pre-target stimulus and to activate a task goal reactively in the subsequent “pre-cued condition,” leading to greater negative transfer of a reactive control mode. Furthermore, we did not change the color of circles surrounding the target in the training phase to focus on the change of uninformative cue and pre-target stimuli. Specifically, we tested the three same predictions as in Experiment 1A (see Table 1).

Method

Participants

Consistent with Experiment 1A, we recruited 108 adults, whom were 19-year-olds to 30-year-olds who had not participated in Experiment 1A, from a database of a research consulting company. This decision was specified in our preregistered plan (https://osf.io/hzv4y). The logic behind a justification of the sample size is the same as for Experiment 1A. All the participants were native Japanese speakers, and they gave informed consent and were paid 1000 yen after completing all the task procedures. Consistent with Experiment 1A, most participants exhibited near perfect correct response rates, but two participants who performed less than minus 3SD score of the mean accuracy (i.e., below a cut off score of 79.8%) and one participant who did not complete all of the session were not included in the final analyses. Our final sample was 35 adults in the varied simultaneous-cued training group (M = 25.46 years, SD = 2.92 years, 20 females and 15 males), 35 adults in the fixed simultaneous-cued training group (M = 26.83 years, SD = 2.55 years, 16 females and 19 males), and 35 adults in the pre-cued training group (M = 25.83 years, SD = 3.13 years, 18 females and 17 males).

Materials and experimental design

In addition to materials used in the Experiment 1A, we added three sets of uninformative cues and pre-target stimuli for the varied simultaneous-cued training group. Although the uninformative cue stimuli had the same color circle, there were different patches on the circle (i.e., 12 brown circles, 12 green crosses, and 12 red hearts) and a different pre-target within the circle (i.e., one brown gift, one Christmas tree, and one Santa Claus), which were also all uninformative (see Figure 3).

Consistent with Experiment 1A, participants were assigned to three training groups (i.e., varied simultaneous-cued training, fixed simultaneous-cued training, and pre-cued training), and experienced the first practice, training, second practice, and test phases.

Santa Claus Game

The procedure, the sequence of each trial, and the composition of training and test phases were essentially the same as in Experiment 1A. One change was that before starting a new block, participants in the varied simultaneous-cued training group were instructed that a different set of uninformative cue and pre-target stimuli was used in the next block. Importantly, unlike in Experiment 1A, the informative cue and target stimuli were stable across the training phase. No further practice trials with novel uninformative cue and pre-target stimuli were included.

Data processing

The dependent measures were response times and correct response rates. Following the same procedure as Experiment 1A (Leys et al., 2013), we excluded 6.2% of correct responses from the analyses of response times.

Data analysis

The study design, hypotheses, and analytic plan were preregistered in the Open Science Framework (https://osf.io/hzv4y). We used the same analytic plan as in Experiment 1A.

Result and Discussion

Cognitive control modes in the training phase and positive transfer effects of task knowledge (predictions 1 and 2)

Response times. Figure 4b depicts mean correct response times for each condition and the full results of the analysis are summarized in Table 1B in supplemental material B. Our focal comparisons revealed a significant two-way interaction between the varied group comparison and task phase (β = -0.18, t = -19.21, χ^2 =371.44, df = 1, p < .001) and a significant two-way interaction between the fixed group comparison and task phase (β = -0.19, t = -20.30, χ^2 =

413.44, $df = 1$, $p < .001$). There were also a significant three-way interaction between the varied group comparison, task phase, and block ($\beta = -0.03$, $t = -3.98$, $\chi^2 = 16.40$, $df = 1$, $p < .001$) and a significant three-way interaction between the fixed group comparison, task phase, and block ($\beta = -0.02$, $t = -2.38$, $\chi^2 = 5.89$, $df = 1$, $p = .015$). Our planned pairwise tests for the two-way interactions demonstrated that in the training phase adults in the pre-cued training group responded more quickly than those in the varied simultaneous-cued training group ($\beta = 0.55$, $t = 10.10$, $p < .001$) and than those in the fixed simultaneous-cued training group ($\beta = 0.50$, $t = 9.19$, $p < .001$). We also found that adults in the pre-cued training group responded faster in the test phase than in the training phase ($\beta = -0.09$, $t = -8.20$, $p < .001$).

The main effect of trial type ($\beta = 0.06$, $t = 6.90$, $\chi^2 = 47.59$, $df = 1$, $p < .001$) and its interaction with block were also significant ($\beta = -0.02$, $t = -2.25$, $\chi^2 = 5.25$, $df = 1$, $p = .022$), indicating a switch cost in response times that was largest in the first block. There were no significant interactions with trial type that were related to any training group comparisons.

Correct response rates. In line with Experiment 1A, correct response rates were near ceiling (see Figure 5b), thus we did not consider them as a key measure for adults. We include the analysis for correct response rates in supplemental material C.

Negative transfer of a reactive control mode (prediction 3)

Response times. Table 3 provides the full results of the analysis. In terms of the varied group comparison, we observed its significant main effect and a non-significant interaction with block, indicating that participants in the varied simultaneous-cued training group responded more slowly throughout the test phase compared to the performance shown throughout the training phase by the pre-cued training group. In contrast, regarding the fixed group comparison, we did not observe its main effect or the expected significant interaction with block.

According to the preregistered analysis plan, we broke the three blocks into twelve mini-blocks and examined a simple effect of training group in first four mini-blocks using Holm correction. We found the same pattern as in Experiment 1A. That is, response times were slower in the test phase performance of the fixed simultaneous-cued training group than those seen in the training phase performance of the pre-cued training group only in the first mini-block ($\beta = 0.33$, $t = 3.95$, $p < .001$). In contrast, no significant differences were observed in the second, third, and fourth mini-blocks (Second mini-block: $\beta = 0.08$, $t = 0.95$, p

= .588, Third mini-block: β = 0.05, t = 0.63, p = .999, Fourth mini-block: β = 0.05, t = 0.56, p = .999) (see Figure 6b).

In line with Experiment 1A, we tested another post-hoc model including the varied-fixed comparison. This demonstrated that neither the main effect of the varied-fixed comparison (β = 0.06, t = 1.02, χ^2 = 1.05, df = 1, p = .305) nor its interaction with block (β = -0.01, t = -0.71, χ^2 = 0.62, df = 1, p = .430) were significant.

In sum, adults in the varied simultaneous-cued training group showed prolonged negative transfer of a reactive control mode throughout all three blocks of the test phase, whereas those in the fixed simultaneous-cued training group showed it only in the first mini-block. However, the direct comparison of test phase response times across these two groups was not statistically significant. Therefore, our findings are suggestive of the possibility that adults show a variability effect on learning knowledge of task management when uninformative cue and pre-target stimuli are varied in the training phase, without conclusively demonstrating this.

Correct response rates. In line with Experiment 1A, we include the analysis for correct response rates in supplemental material C.

Experiment 2A

Using the same paradigm as Experiment 1A, Experiment 2A aimed to examine whether 9- to 10-year-olds experience greater leaning from stimulus variability when learning knowledge of task management. We applied the same three predictions made for adults in Experiment 1A to children in Experiment 2A (see Table 1). Our specific prediction in this regard was that negative transfer of a reactive control mode would be greater in the varied simultaneous-cued training group than in the fixed simultaneous-cued training group (prediction 3).

Method

Participants

We specified the target sample in our preregistered plan (https://osf.io/4nxwb). Following Experiment 1A, our target sample was ninety-six 9-to 10-year-olds (i.e., thirty-two 9-to 10-year-olds in the varied simultaneous-cued training group, thirty-two 9-to 10-year-olds in the fixed simultaneous-cued training group, and thirty-two 9-to 10-year-olds in the pre-cued training group).[5] Considering that some participants might be excluded due

[5] Ideally we would have decided the sample size for Experiment 2A based on the power of key parameters observed in Experiment 1A. However, at the time of preregistration of this plan (January 25, 2021), we had not completed the analyses of Experiment 1A, which was preregistered on January 12, 2021. Thus, the sample size for Experiment 2A was determined using the same logic as for Experiment 1A.

to low levels of performance indicative of guessing or non-engagement, or from quitting the experiment midway through, we recruited one hundred eight parents of a 9-to 10-year-old child from a database of a research consulting company. The parents reported that all the children were native Japanese speakers and did not have any history of neurological disorders, and both parents and children gave informed consent before participation in this experiment. A total of ten children were excluded (6 children did not finish all the blocks; 4 parents failed to send in photographs of their child performing the task as evidence of their participation (see below)). Our final sample was 32 children in the varied simultaneous-cued training group (*M* = 10.03 years, *SD* = 0.57 years, 15 females and 17 males), 33 children in the fixed simultaneous-cued training group (*M* = 10.04 years, *SD* = 0.58 years, 18 females and 15 males), and 33 children in the pre-cued training group (*M* = 9.78 years, *SD* = 0.58 years, 17 females and 16 males). Parents were paid 2000 yen and a small gift of stationery was sent to the child as a reward. However, if children did not complete the training phase, they were not rewarded.

A sensitivity analysis was conducted to determine the minimal effect sizes that could be detected with 80% power with this sample size. The sensitivity analysis revealed that we would be able to detect a minimum effect size with

80% power of $\beta = 0.190$ (varied comparison), $\beta = -0.036$ (varied comparison × block), $\beta = 0.190$ (fixed comparison), $\beta = -0.036$ (fixed comparison × block) (see Table 2D in supplemental material D).

Materials and experimental design

The same materials used in the Experiment 1A were employed. As in Experiment 1A, children were randomly assigned to one of the three training groups.

Santa Claus Game

As in Experiment 1A, on a platform of the research consulting company, parents provided information about children's age, sex, and their history of neurological disorders, and then parents and their children were informed about ethical information. After providing informed consent, they clicked on a link that took them to the main experimental task that was presented using Pavlovia. We asked parents to stay at their children's side in case any technical difficulties arose. Children read through the instructions of the "Santa Claus Game" by themselves, and if they did not understand the instructions, we asked their parents to explain them verbally.

The sequence of each trial and the composition of the first practice, training, second practice, and test phases were the same as in Experiment 1A.

However, following the same procedure of Yanaoka et al. (2024), Experiment 2A included two additional procedures that were conducted by parents. First, we asked parents to take pictures of the PC screen and their children during a short break between blocks. Parents were instructed to take these pictures from behind the child to preserve anonymity. Given that each phase had three blocks, we asked parents to take four pictures in total (i.e., two pictures in the training phase and two pictures in the test phase) and then send the pictures to the first author after completing the experiment. The pictures were considered evidence of the children's participation in the experiment. Second, we asked parents to monitor that their children performed test trails until the end of the task, and after children completed the experiment, we also asked parents whether their children carried out all the blocks by themselves, noting that they could receive rewards even if it was reported that parents performed the task instead of their children. As mentioned above, six parents reported their children did not complete all the trials alone, one parent sent pictures depicting only PC screen, and three parents did not send their pictures. Data from these children were excluded from final analyses.

Data processing

The dependent measures were response times and correct response rates. Following the same procedure as Experiment 1A, response times greater than median + 2.5 MAD and values lower than median – 2.5 MAD were excluded (Leys et al., 2013), and 7.0% of correct responses were excluded from the analyses of response times.

Data analysis

The study design, hypotheses, and analytic plan were preregistered in the Open Science Framework (https://osf.io/4nxwb). We employed the same analytic plan as Experiment 1A.

Result and Discussion

Cognitive control modes in the training phase and positive transfer effects of task knowledge (predictions 1 and 2)

Response times. Figure 4c depicts mean correct response times for each condition and the full results of the analysis are provided in Table 1C of supplemental material B. Our focal comparisons demonstrated a significant two-way interaction between the varied group comparison and task phase (β = -0.15, t = -15.72, χ^2 =248.90, df = 1, p <.001) and a significant two-way interaction between the fixed group comparison and task phase (β = -0.11, t = -11.44, χ^2 = 131.06, df = 1, p <.001). There were also a significant three-way interaction between the varied group comparison, task phase, and block (β = -0.02, t = -2.27, χ^2 = 5.42, df = 1, p = .020) and a significant three-way interaction between the fixed group comparison, task phase, and block (β = -0.02, t = -2.57, χ^2 = 6.67, df = 1, p = .010). Our planned pairwise tests for the two-way interactions demonstrated that in the training phase children in the pre-cued training group responded more quickly than those in the varied simultaneous-cued training group (β = 0.41, t = 6.95, $p < .001$) and those in the fixed simultaneous-cued training group (β = 0.33, t = 5.68, $p < .001$). Furthermore, children in the pre-cued training group responded more quickly in the test phase relative to the training phase (β = -0.08, t = -5.56, $p < .001$).

A significant main effect of trial type also emerged (β = 0.07, t = 4.95, χ^2 = 24.52, df = 1, $p < .001$), indicating a switch cost in response times. There were no significant interactions with trial type.

Correct response rates. Figure 5c depicts correct response rates for each condition. There were no significant two-way interactions between task phase and the varied group comparison (*Odds ratio* = 0.95, z = -0.63, χ^2 = 0.38, df = 1, p = .536) or between task phase and the fixed group comparison (*Odds ratio* = -0.90, z = -1.31, χ^2 = 1.68, df = 1, p = .194). In terms of children in the pre-cued training group, an effect of task phase was significant (*Odds ratio* = 1.30, z =

4.87, $\chi^2 = 23.70$, $df = 1$, $p < .001$), thus they also showed a positive transfer effect on correct test phase response rates as a result of their experience of the training phase.

We also found a significant main effect of trial type (*Odds ratio* = 0.86, $z = -4.95$, $\chi^2 = 24.18$, $df = 1$, $p < .001$). However, there were not any significant interactions with trial type.

Negative transfer of a reactive control mode (prediction 3)

Response times. Table 4 summarizes the result of the analysis. There was no significant interaction between the varied group comparison and block. On the other hand, we found the expected significant interaction between the fixed group comparison and block, though pairwise comparisons with Holm correction demonstrated no significant group difference in all the three blocks (First block: $\beta = 0.14$, $t = 1.95$, $p = .163$, Second block: $\beta = 0.02$, $t = 0.30$, $p = .999$, Third block: $\beta = 0.03$, $t = 0.46$, $p = .999$).

As preregistered, we broke the three blocks into twelve mini-blocks and examined a simple effect of training group in the first four mini-blocks using Holm correction. Children in the fixed simultaneous-cued training group responded more slowly in the test phase in comparison to the training phase performance of the pre-cued training group but only in the first mini-block (β =

0.24, $t = 2.84$, $p = .020$); children in the varied simultaneous-cued training group did not show such a difference ($\beta = 0.13$, $t = 1.51$, $p = .531$). By the second mini-block, no significant group differences were observed in either the varied group comparison (Second mini-block: $\beta = 0.11$, $t = 1.28$, $p = .606$, Third mini-block: $\beta = 0.12$, $t = 1.07$, $p = .606$, Fourth mini-block: $\beta = 0.02$, $t = 0.28$, $p = .782$) or the fixed group comparison (Second mini-block: $\beta = 0.09$, $t = 1.04$, $p = .348$; Third mini-block: $\beta = 0.09$, $t = 1.36$, $p = .348$, Fourth mini-block: $\beta = 0.14$, $t = 1.65$, $p = .299$) (see Figure 6c).

We also tested a post-hoc model including a direct comparison between the test phase performance of the varied and fixed proactive impossible training groups. A main effect of the varied-fixed comparison was not significant ($\beta = -0.01$, $t = -0.11$, $\chi^2 = 0.01$, $df = 1$, $p = .910$), but its interaction with block was significant ($\beta = 0.03$, $t = 2.20$, $\chi^2 = 4.84$, $df = 1$, $p = .028$). However, pairwise comparisons with Holm correction demonstrated no significant group difference in all the three blocks (First block: $\beta = -0.05$, $t = -0.74$, $p = .461$, Second block: $\beta = 0.004$, $t = 0.07$, $p = .999$, Third block: $\beta = 0.02$, $t = 0.57$, $p = .999$).

These findings indicate that 9 to 10-year-olds in the fixed simultaneous-cued training group showed negative transfer effects only in the first mini-block. However, we failed to find our expected result that stimulus variability accelerates such negative transfer of a reactive control mode. Rather, when informative cue and target stimuli were varied in each block, negative transfer effects were not apparent.

Correct response rates. The main effect of the varied group comparison (*Odds ratio* = 1.46, z = 1.38, χ^2 = 1.82, df = 1, p = .177) and the fixed group comparison (*Odds ratio* = 1.60, z = 1.74, χ^2 = 2.92, df = 1, p = .087) were not significant, and they did not interact significantly with block (varied: *Odds ratio* = 0.80, z = -1.70, χ^2 = 2.80, df = 1, p = .094, fixed: *Odds ratio* = 0.90, z = -0.81, χ^2 = 0.62, df = 1, p = .429).

We found a significant main effect of trial type (*Odds ratio* = 0.86, z = -3.22, χ^2 = 10.06, df = 1, p = .002), indicating a switch cost in correct response rates. There were no significant interactions with trial type.

Experiment 2B

Experiment 2B used the same paradigm as Experiment 1B to examine whether 9 to 10-year-olds experienced greater leaning from stimulus variability induced by changing uninformative cue and pre-target stimuli when learning knowledge of task management. We applied the three predictions made for adults in Experiment 1B to school-aged children in Experiment 2B (see Table 1). The effect of block in the training/test phase was taken into account when conducting analyses of the positive and negative transfer effects, in line with our preregistered analysis plan (https://osf.io/hzv4y).

Method

Participants

Consistent with Experiment 2A, we recruited 108 children, whom were 9- to 10-year-olds who had not participated in Experiment 2A, from a database of a research consulting company. This decision was specified in our preregistered plan. All the children were native Japanese speakers and did not have any history of neurological disorders. Both parents and children gave informed consent. In total, 11 children were excluded (five children did not finish all the blocks; five parents failed to send in the child's photographs showing them performing the task; one parent reported that they performed a task instead of their child). Hence, our final sample was 32 children in the varied simultaneous-cued training group (M = 10.04 years, SD = 0.62 years, 16 females and 16 males), 33 children in the fixed simultaneous-cued training group (M = 9.93 years, SD = 0.54 years, 14 females and 19 males), and 32 children in the pre-cued training group (M = 9.98 years, SD = 0.58 years, 15 females and 17 males). Parents were paid 2000 yen and a small gift of stationery was sent to the child as a reward. However, if children did not complete the training phase, they were not rewarded.

Materials and experimental design

The materials were the same as in Experiment 1B. Children were randomly assigned to one of the three training groups.

Procedure and Santa Claus Game

The procedure, the sequence of each trial, and the composition of the first practice, training, second practice, and test phases were the same as in Experiment 2A. However, critically, as in Experiment 1B, before moving to a new block, children in the varied simultaneous-cued training group were instructed that a different set of uninformative cue and pre-target stimuli would be used in the next block and they then sorted the same bivalent stimuli as used in the previous block according to either the color or object identification rule.

Data processing

The dependent measures were response times and correct response rates. Following the same procedure as Experiment 1A (Levy et al., 2013), we excluded 7.4% of correct responses from the analyses of response times.

Data analysis

The study design, hypotheses, and analytic plan were preregistered in the Open Science Framework (https://osf.io/hzv4y). We employed the same analytic plan as in Experiment 1A.

Result and Discussion

Cognitive control modes in the training phase and positive transfer effects of task knowledge (predictions 1 and 2)

Response times. Figure 4d depicts response times for each condition and the full results of the analysis are provided in Table 1D of supplemental material B. Our focal comparisons demonstrated a significant two-way interaction between the varied group comparison and task phase (β = -0.15, t = -15.74, χ^2 =249.25, df = 1, p < .001) and the fixed group comparison and task phase (β = -0.19, t = -19.83, χ^2 = 393.04, df = 1, p < .001). There was also a significant three-way interaction between the varied group comparison, task phase, and block (β = -0.02, t = -2.35, χ^2 = 5.57, df = 1, p = .018). According to planned pairwise comparisons for the two-way interactions, in the training phase children in the pre-cued training group responded more quickly than children in both the varied and fixed simultaneous-cued training groups (varied: β = 0.45, t = 8.32, p < .001, fixed: β = 0.46, t = 8.42, p < .001). Second, children in the pre-cued training group responded more quickly in the test phase than in the training phase (β = -0.04, t = -3.30, p = .001).

A significant main effect of trial type was also observed (β = 0.07, t = 8.17, χ^2 = 68.35, df = 1, p < .001), indicating a switch cost in response times. There were no significant interactions with trial type.

Correct response rates. Figure 5d depicts correct response rates for each condition. Neither the varied or the fixed group comparison interacted significantly with training phase (varied: *Odds ratio* = 1.06, z = 0.78, χ^2 = 0.50, df = 1, p = .480, fixed: *Odds ratio* = 0.93, z = -0.91, χ^2 = 0.74, df = 1, p = .390). However, in relation to prediction 2, children in the pre-cued training group showed significantly higher correct response rates in the test phase than in the training phase (*Odds ratio* = 1.23, z = 4.00, χ^2 = 15.93, df = 1, p < .001). We further found a significant main effect of trial type (*Odds ratio* = 0.89, z = -3.40, χ^2 = 11.29, df = 1, p < .001), but no significant interactions with trial type.

Negative transfer of a reactive control mode (prediction 3)

Response times. Table 5 summarizes the result of the analysis. We found a significant main effect of the varied group comparison which interacted significantly with block. Pairwise comparisons with Holm correction demonstrated that children in the varied simultaneous-cued training group showed slower responses in the test phase compared to the training phase of the pre-cued training group in the first block (β = 0.18, t = 2.59, p = .033), but not in the second (β = 0.15, t = 2.21, p = .059) and third block (β = 0.07, t = 0.89, p = .374). In contrast, there was no significant main effect of the fixed group comparison and no significant interaction between the fixed group comparison and block.

Following the preregistered analysis plan, we broke each block into four mini-blocks and examined the first four mini-blocks. Using Holm correction, it was revealed that the fixed group comparison was not significant in any mini-blocks (First mini-block: β = 0.22, t = 2.02, p = .177, Second mini-block: β = -0.01, t = -0.17, p = .999, Third mini-block: β = 0.05, t = 0.77, p = .999, Fourth mini-block: β = -0.06, t = -0.97, p = .999) (see Figure 6d).

In line with Experiment 2A, we tested a post-hoc model to make a direct comparison between the test phase performance of the varied and fixed proactive impossible training groups. The interaction between the varied-fixed comparison and block was significant (β = -0.05, t = -3.74, χ^2 = 13.94, df = 1, p < .001), although a main effect of the varied-fixed comparison was not significant (β = 0.07, t = 1.18, χ^2 = 1.38, df = 1, p = .239). Given that the varied group comparison was significant only in the first block, we conducted a pairwise comparison for the first block, demonstrating that in the test phase children in the varied cued-simultaneous training group responded slower in the first block than those in the fixed cued-simultaneous training group ($\beta = 0.12$, $t = 2.05$, $p = .043$).

We therefore demonstrated that 9 to 10-year-olds in the varied and fixed simultaneous-cued training group showed negative transfer of a reactive control mode when different cue and target stimuli were employed in the test phase. Most importantly, these negative transfer effects were seen in the first full block of trials among children in the varied simultaneous-cued training group, but not in the fixed simultaneous-cued training group. The two groups were directly compared and founded to be significantly different.

Correct response rates. The analysis showed significant main effects of both the varied group comparison (*Odds ratio* = 2.23, $z = 2.87$, $\chi^2 = 7.72$, $df = 1$, $p = .005$) and the fixed group comparison (*Odds ratio* = 1.77, $z = 2.09$, $\chi^2 = 4.16$, $df = 1$, $p = .041$). Both factors did not interact significantly with factors of block and trial type. That is, children in the varied and fixed simultaneous-cued training groups showed better performance in the test phase compared to the training phase performance of the pre-cued training group.

Direct Comparisons Between Adults and School-aged Children

To explore potential developmental differences in the negative transfer of a reactive control mode and the variability effect, we made direct comparisons between the data for adults and school-aged children. The following analyses were preregistered as exploratory ones in our Open Science Framework submission (https://osf.io/hzv4y). We added a factor of experiment (i.e., Experiment 1A vs. 2A, Experiment 1B vs. 2B) and its related interactions to the above-mentioned regression model concerning the negative transfer effect. We compared the results of two regression models: one focal model containing the three-way interaction (experiment × training group × block) and another model without the interaction. A pairwise comparison of the interaction was conducted to examine whether adults differ from school-aged children in the degree of the negative transfer of reactive control and the variability effect. Response times were log-transformed prior to statistical analyses to control for age-related baseline differences (Meiran, 1996).

In terms of the comparison between Experiment 1A and Experiment 2A, a two-way interaction between the fixed group comparison and block was significant (β = -0.04, t = -3.62, χ^2 = 13.09, df = 1, p < .001), but did not interact with the experimental factor (β = 0.01, t = 1.02, χ^2 = 1.03, df = 1, p = .309), suggesting that the degree of negative transfer effects did not differ between adults and school-aged children when informative cue and target stimuli were fixed. We also found a significant two-way interaction between the varied group comparison and block (β = -0.02, t = -2.70, χ^2 = 7.29, df = 1, p = .007), but this did not interact with the experimental factor (β = -0.003, t = -0.36, χ^2 = 0.13, df = 1, p = .720). Pairwise comparisons revealed that the varied and fixed group comparisons were significant in the first block (varied: β = 0.14, t = 2.89, p = .012, fixed: β = 0.13, t = 2.67, p = .002), but not in the second and third block (Second block; varied: β = 0.05, t = 1.16, p = .248, fixed; β = 0.02, t = 0.36, p = .719, Third block; varied: β = 0.08, t = 1.71, p = .178, fixed; β = 0.05, t = 1.08, p = .567). Thus, the varied and fixed simultaneous-cued training group showed negative transfer effects in the first block. However, when adults and children are combined, the varied and fixed simultaneous-cued training group did not differ in how long the negative transfer effects could be seen for. This pattern was independent of any differences in age groups. Indeed, we tested another model including the varied-fixed comparison, which revealed that any interactions related to the experimental factor was not significant.

In terms of the comparison between Experiment 1B and Experiment 2B, neither a two-way interaction between the fixed group comparison and block (β = -0.001, t = -0.95, χ^2 = 0.91, df = 1, p = .341) nor a three-way interaction between the fixed group comparison, block, and the experiment factor (β = 0.001, t = 0.14, χ^2 = 0.02, df = 1, p = .890) was significant. In contrast, we found a significant two-way interaction between the varied group comparison and block (β = -0.04, t = -3.61, χ^2 = 9.29, df = 1, p = .002), but this did not interact significantly with the experimental factor (β = 0.02, t = 1.94, χ^2 = 3.75, df = 1, p = .053). We again tested a further model including the varied-fixed comparison, which revealed a significant three-way interaction between the varied-fixed comparison, block, and the experiment factor (β = 0.02, t = 2.61, χ^2 = 6.80, df = 1, p = .009). Pairwise comparisons revealed that the varied-fixed comparison significantly interacted with block in school-aged children (β = -0.04, t = -4.03, p < .001), but not in adults (β = -0.01, t = -0.54, p = .586). Thus, the comparison between Experiment 1B and Experiment 2B suggests potential developmental differences in the variability effect.

General Discussion

The current study investigated the effect of stimulus variability on the degree of learning of task knowledge seen in adults as well as school-aged children. A set of four preregistered experiments focused on examining whether stimulus variability promotes the learning of knowledge about the temporal structure of task goal activation, leading to greater transfer of that knowledge to different task environments relative to when stimuli were fixed. In these experiments, knowledge transfer was examined in terms of the negative transfer of a reactive, rather than proactive, approach to cognitive control. The experiments further explored whether such negative transfer is accelerated both when informative cue and target stimuli are varied (Experiments 1A and 2A) and when uninformative cue and pre-target stimuli are varied (Experiments 1B and 2B). Specific predictions and findings from all four experiments are summarized in Table 1.

Before moving to our primary issues, we note that all four experiments robustly demonstrated that our manipulation of the timing of cue presentation in a training phase, in which participants learnt an initial task, did have the predicted effects. In this training phase, participants in pre-cued training groups where proactive control was possible responded more quickly than those in varied and fixed simultaneous-cued training groups who were unable to engage proactive control. These findings confirm that both adults and 9 to 10-year-olds engage cognitive control proactively when cue-based proactive control is possible, but engage reactive control when the task cue is presented simultaneously with the target onset. The success of this manipulation confirms a key assumption of the current study (i.e., both adults and 9 to 10-year-olds engage proactive control when it is possible) and completely replicates previous evidence from adults (Yanaoka et al., 2024) and from children (Chevalier et al., 2015; Yanaoka et al., 2024).

Furthermore, we also observed clear positive transfer effects across training and test phases among the pre-cued training groups, which are again consistent with previous studies (e.g., Bhandari & Badre, 2018; Sabah et al., 2021; Yanaoka et al., 2024). Such positive transfer effects were seen in response times for adults (Experiments 1A and 1B) and in response times and correct response rates for 9 to 10-year-olds (Experiments 2A and 2B). These findings can be interpreted as showing that participants learn a collective body of task knowledge, which includes knowledge of task representations and task management, and then apply that knowledge to different task environments. Specifically, *knowledge of task representations* refers to knowledge about the task goal and its associated stimulus–response mappings in a given context (e.g., Cole et al., 2011; Collins & Frank, 2013), and *knowledge of task management* refers to knowledge about the temporal structure of task goal activation. Although we cannot specify which type of task knowledge underlies the observed positive transfer effects, it is clear that the transfer of this collective body of task knowledge, which is independent of any stimulus-response mappings, leads both adults and 9-to 10-year-olds to perform better on the task in the test phase than in the training phase.

The most critical finding of the current study was that 9- to-10-year-olds showed a clear variability effect on the degree of negative transfer of reactive control in Experiment 2B. Our preregistered analyses demonstrated that 9- to 10-year-olds in the varied and fixed simultaneous-cued training groups responded more slowly in the test phase compared to the training phase performance of the pre-cued training groups, despite the fact that this analysis compares two "pre-cued" conditions. This negative transfer was short-lived in the fixed simultaneous-cued training group (i.e., first five trials), whereas it continued for a longer period in the varied simultaneous-cued training group (i.e., one block or throughout all three blocks). This was especially true for school-aged children in Experiment 2B, where the claim for a meaningful difference in the size of the negative transfer effect was supported by a significant post-hoc comparison of the test phase performance of the varied and fixed cued-simultaneous training groups.

Adults also showed some suggestive evidence of a similar variability effect in Experiments 1A and 1B. However, the effect size of the key parameters observed in Experiments 1A and 1B was smaller than the effect that could be reliably detected with 80% power given our sample size (detailed information in supplemental material D). Thus, these findings are likely to be an over-estimation of the true effect size and should be interpreted with some caution due to the acknowledged lack of power. Indeed, we could not find meaningful differences between the test phase performance of the varied and fixed cued-simultaneous training groups in Experiments 1A and 1B. Thus, future studies should conduct more appropriate sample size planning based on the effect size observed in the current study to examine the impact of the variability effect on the degree of negative transfer of reactive control in adults.

Although previous studies have accounted for near transfer effects from the theoretical viewpoint of knowledge of task management (e.g., Bhandari & Badre, 2018; Gonthier et al., 2021; Yanaoka et al., 2024), they have not provided direct evidence linking these near transfer effects to such abstract task knowledge. Specifically, such near transfer effects could be partly attributed to adaptation to different experimental conditions in the test phase. However, given that stimulus variability promotes the formation of a "schema" (Schmidt & Bjork, 1992), the current findings demonstrate that stimulus variability during the first "simultaneous-cued" condition clearly helps participants learn task knowledge in a more abstract form. Specifically, they can learn abstract task knowledge about the temporal structure of task goal, which is not restricted to overly specialized contexts (e.g., pre-cue, pre-target, and stimulus-response mappings in the case of Experiments 1B and 2B). This enhanced abstract task knowledge encourages participants to continue engaging reactive control in the subsequent “pre-cued” condition, leading to greater negative transfer. Such variability effect cannot be explained by non-abstract processing explanations for the negative transfer. Thus, and moving beyond previous studies (e.g., Bhandari & Badre, 2018; Yanaoka et al., 2024), the current study provides the first evidence that leaning abstract knowledge of task management underlies near (negative) transfer effects by demonstrating the variability effect in school-aged children and potentially in adults. Furthermore, this is the first developmental evidence of the variability effect in the context of cognitive control. Previous studies with children have already observed the variability effect in motor skill acquisition (e.g., Kerr & Booth, 1978; Shapiro & Schmidt, 1982) and vocabulary learning (Gómez, 2002), but here we have extended those findings to the area of cognitive control.

However, the variability effect in cognitive control appeared not to be uniform. Among 9 to 10-year-olds, we observed a variability effect on learning knowledge of task management when uninformative cue and pre-target stimuli were varied (Experiment 2B), but not when informative cue and target stimuli were varied (Experiment 2A). One potential explanation for this inconsistency is that updating knowledge of task representations is cognitively demanding. In Experiment 2A, we assumed that the variation of informative cue and target stimuli helps participants learn that simultaneously presented informative cue information cannot be used to prompt proactive control, leading instead to the engagement of a reactive control mode. However, varying informative cues and targets, which are composed of goal-relevant features, also require children to update knowledge of task representations such as associations between informative cues, targets, and responses. It has been demonstrated that there are developmental improvements in the ability to build and maintain abstract task representations in working memory from early childhood to adolescence (e.g., Amso et al., 2014; Munakata et al., 2012). Thus, some 9 to 10-year-olds in Experiment 2A, due to their limited working memory capacity, might have had difficulty both updating knowledge of task representations and recognizing that engaging reactive control was still employed when different informative cue and target stimuli were introduced. These difficulties might have resulted in the absence of negative transfer of reactive control. Consistent with this possibility, previous studies have demonstrated that if the increased cognitive load associated with increased variability exceeds working memory limits, increased variability negatively affects learning and problem-solving performance (Chen et al., 2018; Likourezos et al., 2019). In contrast, in Experiment 2B, when different uninformative cue and pre-target stimuli were introduced, children did not need to update knowledge of task representations as uninformative cue and pre-target stimuli are composed of only goal-irrelevant features. Under such conditions varying uninformative cue and pre-target stimuli might make it relatively easier to recognize that any cue information that accompanies the appearance of a pre-target stimulus remains uninformative in the cued-simultaneous condition. This recognition helps the individual to understand the requirements of engaging cognitive control in the simultaneous-cued condition. Specifically, children might learn that it is better to reactively activate the task goal at the target onset rather than proactively on the presentation of any cue information, resulting in greater negative transfer of a reactive control mode even in the subsequent pre-cued condition. However, the current research did not provide direct evidence supporting this possibility. Therefore, future studies should address the relation between the variability effect, learning task knowledge, and working memory by manipulating the cognitive demands of a task, such as the number of stimulus-response mappings, along with varying goal-relevant stimuli.

One might wonder why adults, who are assumed to have higher working memory capacity than school-aged children, did not show clear evidence of the variability effect in Experiment 1B, in which different uninformative cue and pre-target stimuli were introduced. One potential explanation for this developmental difference is the extent to which individuals engage in metacognitive processes. Negative transfer effects were clearly present on earlier trials, but they reduced very quickly. One potential mechanism underlying this reduction is that participants monitor how task knowledge influences their task performance and switch to a more adaptive cognitive control mode (i.e., recognize that using reactive control is not the most adaptive strategy in the latter "pre-cued" condition and switch to using proactive control). The ability to engage in metacognitive processes, including judging whether to use a cognitive strategy depending on its effectiveness for solving a problem, develops with age (e.g., Chevalier et al., 2020; Niebaum et al., 2019, 2021; O'Leary & Sloutsky, 2017). It is therefore possible that even if stimulus variability accelerates learning knowledge of task management, adults, who have higher metacognitive abilities than children, might be more likely to monitor the disadvantage of reactive control and so switch to using proactive control more rapidly. As a result, the variability effect appears to be weaker in adults. However, this is one of a number of possible post-hoc interpretations. Our sensitivity analyses demonstrated that Experiments 1A and 1B were somewhat underpowered to reliably detect the negative transfer effect and the variability effect. Given this, one should further examine the developmental mechanisms underlying the variability effect on learning knowledge of task management among larger samples, including whether these developmental differences are robust.

The current study also provides evidence concerning the relation between leaning task knowledge and switch costs observed in a cued task-switching paradigm. Task-switching studies have shown that any advance preparation in response to an increase in cue-stimulus intervals leads to a reduction in switch costs (e.g., Meiran 2000; Monsell & Mizon, 2006; see Kiesel et al., 2010). Thus, if negative transfer effects, which are supported by knowledge of task management, lead participants to engage reactive control, one would also expect that negative transfer effects would increase switch costs. However, we did not observe any significant interactions involving the factor of trial type in the analyses of either response times or correct response rates. Critically, the manipulation of advance cue presentation in a training phase made overall response times faster, rather than specifically benefiting switch trials. We can infer that proactive control along with advance cue presentation may play a key role in monitoring processes, such as identifying and maintaining a relevant task goal, required for both trial types (e.g., Chevalier et al., 2015; De Baene, & Brass, 2014). However, one might wonder why the current study was not consistent with previous studies in terms of the effect of advance preparation on switch costs. One potential reason for the inconsistency might be the difference between between-participant and within-participant designs. A large number of studies (e.g., Meiran 2000; Monsell & Mizon, 2006) which demonstrate the effect of advance preparation on switch costs have employed a within-participant design, whereas studies using a between-participant design, including the current study, have generally failed to find such an effect on switch cost (Altmann, 2004a; Altmann, 2004b; Koch, 2001; Yanaoka et al., 2024). Therefore, the failure to find the effect of advance cue presentation on switch cost is not necessarily inconsistent with previous research. Furthermore, the number of trials per condition in the current study (i.e., 63 trials) was somewhat smaller than that in previous task-switching studies (e.g., 96 trials in Merian et al. (2000) and 144 trials in Monsell & Mizon (2006)). This may have reduced our ability to reliably detect any significant interactions involving switch costs. Given this, future work should examine the experimental design, the number of trials, and conditions under which advance preparation leads to the reduction of switch costs to further address whether variation in the contexts in which knowledge of task management is learned is reflected in switch costs.

Our findings are relevant to previous studies of cognitive control training. A large number of studies have already examined whether and how cognitive control training benefits adults and children (e.g., Fellman et al., 2020; Holmes et al., 2019; Thorell et al., 2009; Traut et al., 2021a; for a recent review Smid et al., 2020; Traut et al., 2021b). They have consistently reported the presence of near transfer effects (but limited far transfer effects) and have started to investigate the cognitive mechanism underlying such near transfer effects (e.g., Gathercole et al., 2019). However, although stimulus variability has been extensively investigated in a wide range of learning domains such as motor skill learning, face recognition, and category learning (e.g., Posner & Keele, 1968; Ritchie & Burton, 2017; Wulf & Schmidt, 1988), only a few studies have focused on the variability effect in the context of cognitive control training (Karbach & Kray, 2009; Sabah et al., 2019, 2021). Therefore, stimulus variability is likely to be a hidden factor underlying near transfer effects in previous studies with cognitive control training. Thus, existing meta-analysis studies may need to consider the possibility that the size of any near transfer effects on cognitive control can be moderated by whether and how the employed stimuli are varied (e.g., Sala &

Gobet, 2017, 2019). Moreover, such cognitive control training studies have not sufficiently investigated other potential factors such as scheduling of feedback (i.e., every 1 trial or 5 trials) and the organization of different tasks (i.e., blocked or random) during any training phase, which are also assumed to influence the degree of transfer (Schmidt & Bjork, 1992). Thus, to understand how individuals learn to engage cognitive control, we should go back to and learn from the classical work on skill learning (e.g., Schmidt, 1975) and integrate this evidence into any investigation of cognitive control training.

Conclusion

The current study provides a set of important findings. They confirm that prior task experience of engaging reactive control makes both adults and 9- to 10-year-olds respond more slowly in a subsequent similar-structured task with different cue and target stimuli, in which they could otherwise engage proactive control. However, they also go beyond all previous work in showing that among 9-to 10-year-olds, such transfer of the effects of prior experience was seen for a longer period when uninformative cue and pre-target stimuli were varied than when they did not change. This novel finding clearly demonstrates that stimulus variability helps individuals learn abstract knowledge of task management and, on occasions, leads to greater transfer of such knowledge. Furthermore, adults also showed suggestive evidence of this variability effect on the learning knowledge of task management both when cue and target stimuli were varied and when uninformative cue and pre-target stimuli were varied. This suggests potential developmental differences in learning regularities of cognitive control processes from variable environments. Taken together, these novel findings offer important insights into how adults and school-aged children learn to engage cognitive control, a key ability underpinning successful functioning in our ever-changing world.

References

Altmann, E. M. (2004a). Advance preparation in task switching: What work is being done?. *Psychological Science*, *15*, 616-622. https://doi.org/10.1111/j.0956-7976.2004.00729.x

Altmann, E. M. (2004b). The preparation effect in task switching: Carryover of SOA. *Memory & Cognition*, *32*, 153-163. https://doi.org/10.3758/BF03195828

Amso, D., Haas, S., McShane, L., & Badre, D. (2014). Working memory updating and the development of rule-guided behavior. *Cognition*, *133*, 201-210. https://doi.org/10.1016/j.cognition.2014.06.012

Badre, D., & Frank, M. J. (2012). Mechanisms of hierarchical reinforcement learning in cortico–striatal circuits 2: Evidence from fMRI. *Cerebral Cortex*, *22*, 527-536. https://doi.org/10.1093/cercor/bhr117

Banich, M. T. (2009). Executive function: The search for an integrated account. *Current Directions in Psychological Science*, *18*, 89-94. https://doi.org/10.1111/j.1467-8721.2009.01615.x

Bates, D., Maechler, M., Bolker, B., & Walker, S. (2015). lme4: Linear mixed-effects models using Eigen and S4. R package version 1.1-9. <https://CRAN.R-project. org/package=lme4>.

Bhandari, A., & Badre, D. (2018). Learning and transfer of working memory gating policies. *Cognition*, *172*, 89-100. https://doi.org/10.1016/j.cognition.2017.12.001

Bower, G. H., Black, J. B., & Turner, T. J. (1979). Scripts in memory for text. *Cognitive Psychology*, *11*, 177-220. https://doi.org/10.1016/0010-0285(79)90009-4

Braem, S., Bugg, J. M., Schmidt, J. R., Crump, M. J., Weissman, D. H., Notebaert, W., & Egner, T. (2019). Measuring adaptive control in conflict tasks. *Trends in Cognitive Sciences*, *23*, 769-783. https://doi.org/10.1016/j.tics.2019.07.002

Braver, T. S. (2012). The variable nature of cognitive control: a dual mechanisms framework. *Trends in Cognitive Science*, *16*, 106-113. https://doi.org/10.1016/j.tics.2011.12.010

Brysbaert, M., & Stevens, M. (2018). Power analysis and effect size in mixed effect models: A tutorial. *Journal of Cognition*, *1*(1), https://doi.org/10.5334/joc.10

Catalano, J. F., & Kleiner, B. M. (1984). Distant transfer in coincident timing as a function of variability of practice. *Perceptual and Motor Skills*, *58*, 851-856. https://doi.org/10.2466/pms.1984.58.3.851

Cepeda, N. J., Kramer, A. F., & Gonzalez de Sather, J. (2001). Changes in executive control across the life span: examination of task-switching performance. *Developmental Psychology*, *37*, 715-730. https://doi.org/10.1037/0012-1649.37.5.715

Chatham, C. H., & Badre, D. (2015). Multiple gates on working memory. *Current Opinion in Behavioral Sciences*, *1*, 23-31. https://doi.org/10.1016/j.cobeha.2014.08.001

Chatham, C. H., Frank, M. J., Munakata, Y. (2009). Pupillometric and behavioral markers of a developmental shift in the temporal dynamics of cognitive control. *Proceedings of the National Academy of Sciences*, *106*, 5529-5533. https://doi.org/10.1073/pnas.0810002106

Chen, O., Castro-Alonso, J. C., Paas, F., & Sweller, J. (2018). Undesirable difficulty effects in the learning of high-element interactivity materials. *Frontiers in Psychology*, *9*, 1483. https://doi.org/10.3389/fpsyg.2018.01483

Chen, Z., & Mo, L. (2004). Schema Induction in Problem Solving: A Multidimensional Analysis. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 30*, 583-600. https://doi.org/10.1037/0278-7393.30.3.583

Chevalier, N. (2015). Executive function development: Making sense of the environment to behave adaptively. *Current Directions in Psychological Science*, *24*, 363-368. https://doi.org/10.1177/0963721415593724

Chevalier, N., Martis, S.B., Curran, T., Munakata, Y. (2015). Metacognitive processes in executive control development: the case of reactive and proactive control. *Journal of Cognitive Neuroscience, 27*, 1125-1136.

Chevalier, N., Meaney, J. A., Traut, H. J., & Munakata, Y. (2020). Adaptiveness in proactive control engagement in children and adults. *Developmental Cognitive Neuroscience*, *46*, 100870. https://doi.org/10.1162/jocn_a_00782

Cole, M. W., Etzel, J. A., Zacks, J. M., Schneider, W., & Braver, T. S. (2011). Rapid transfer of abstract rules to novel contexts in human lateral prefrontal cortex. *Frontiers in Human Neuroscience*, *5*, 142. https://doi.org/10.3389/fnhum.2011.00142

Collins, A. G. E., & Frank, M. J. (2013). Cognitive control over learning: Creating, clustering, and generalizing task-set structure. *Psychological Review*, *120*, 190-229. https://psycnet.apa.org/doi/10.1037/a0030852

De Baene, W., & Brass, M. (2014). Dissociating strategy-dependent and independent components in task preparation. *Neuropsychologia*, *62*, 331-340. https://doi.org/10.1016/j.neuropsychologia.2014.04.015

Egner, T. (2007). Congruency sequence effects and cognitive control. *Cognitive, Affective, & Behavioral Neuroscience*, *7*(4), 380-390. https://doi.org/10.3758/CABN.7.4.380

Elchlepp, H., Lavric, A., & Monsell, S. (2015). A change of task prolongs early processes: Evidence from ERPs in lexical tasks. *Journal of Experimental Psychology: General, 144*(2), 299–325. https://doi.org/10.1037/a0038740

Fellman, D., Jylkkä, J., Waris, O., Soveri, A., Ritakallio, L., Haga, S., Salmi, J., Nyman, T. J. & Laine, M. (2020). The role of strategy use in working memory training outcomes. *Journal of Memory and Language*, *110*, 104064. https://doi.org/10.1016/j.jml.2019.104064

Gathercole, S. E., Dunning, D. L., Holmes, J., & Norris, D. (2019). Working memory training involves learning new skills. *Journal of Memory and Language*, *105*, 19-42. https://doi.org/10.1016/j.jml.2018.10.003

Gick, M. L., & Holyoak, K. J. (1983). Schema induction and analogical transfer. *Cognitive Psychology*, *15*, 1-38. https://doi.org/10.1016/0010-0285(83)90002-6

Gomez, R. L. (2002). Variability and detection of invariant structure. *Psychological Science*, *13*, 431-436. https://doi.org/10.1111/1467-9280.00476

Gonthier, C., Ambrosi, S., & Blaye, A. (2021). Learning-based before intentional cognitive control: Developmental evidence for a dissociation between implicit and explicit control. *Journal of Experimental Psychology: Learning, Memory, and Cognition.* https://doi.org/10.1037/xlm0001005

Gonthier, C., Macnamara, B. N., Chow, M., Conway, A. R., & Braver, T. S. (2016). Inducing proactive control shifts in the AX-CPT. *Frontiers in Psychology*, *7*, 1822. https://doi.org/10.3389/fpsyg.2016.01822

Hintzman, D. L. (1986). "Schema abstraction" in a multiple-trace memory model. *Psychological Review, 93*, 411-428. https://psycnet.apa.org/doi/10.1037/0033-295X.93.4.411

Holmes, J., Woolgar, F., Hampshire, A., & Gathercole, S. E. (2019). Are working memory training effects paradigm-specific?. *Frontiers in Psychology*, *10*, 1103. https://doi.org/10.3389/fpsyg.2019.0110

Jin, X., Auyeung, B., & Chevalier, N. (2020). Positive emotion and reward motivation promote different cognitive control engagement strategies in children. *Developmental Cognitive Neuroscience*, *44*, 100806 https://doi.org/10.1016/j.dcn.2020.100806.

Karbach, J., & Kray, J. (2009). How useful is executive control training? Age differences in near and far transfer of task-switching training. *Developmental Science*, *12*, 978-990. https://doi.org/10.1111/j.1467-7687.2009.00846.x

Kerr, R., & Booth, B. (1978). Specific and varied practice of motor skill. *Perceptual and Motor Skills*, *46*, 395-401. https://doi.org/10.1177/003151257804600201

Kharitonova, M., & Munakata, Y. (2011). The role of representations in executive function: investigating a developmental link between flexibility and abstraction. *Frontiers in Psychology*, *2*, 347. https://doi.org/10.3389/fpsyg.2011.00347

Kiesel, A., Steinhauser, M., Wendt, M., Falkenstein, M., Jost, K., Philipp, A. M., & Koch, I. (2010). Control and interference in task switching—A review. *Psychological Bulletin*, *136*, 849-874. https://doi.org/10.1037/a0019842

Koch, I. (2001). Automatic and intentional activation of task sets. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *27*, 1474-1486. https://psycnet.apa.org/doi/10.1037/0278-7393.27.6.1474

Levine, M., & Ensom, M. H. (2001). Post hoc power analysis: an idea whose time has passed?. *Phamacotherapy: The Journal of Human Pharmacology* *and Drug Therapy*, *21*(4), 405-409. https://doi.org/10.1592/phoco.21.5.405.34503

Leys, C., Ley, C., Klein, O., Bernard, P., & Licata, L. (2013). Detecting outliers: Do not use standard deviation around the mean, use absolute deviation around the median. *Journal of Experimental Social Psychology*, *49*, 764-766. https://doi.org/10.1016/j.jesp.2013.03.013

Likourezos, V., Kalyuga, S., & Sweller, J. (2019). The variability effect: When instructional variability is advantageous. *Educational Psychology Review*, *31*, 479-497. https://doi.org/10.1007/s10648-019-09462-8

Medin, D. L., Goldstone, R. L., & Gentner, D. (1993). Respects for similarity. *Psychological Review, 100*, 254-278. https://doi.org/10.1037/0033-295X.100.2.254

Meiran, N. (1996). Reconfiguration of processing mode prior to task performance. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 22, 1423-1442. https://psycnet.apa.org/doi/10.1037/0278-7393.22.6.1423

Meiran, N. (2000). Reconfiguration of stimulus task sets and response task sets during task switching. In J. Driver & S. Monsell (Eds.), *Control of Cognitive*

Processes: Attention and Performance XVIII (pp. 377-399). Cambridge, MA: MIT Press.

Monsell, S., & Mizon, G. A. (2006). Can the task-cuing paradigm measure an endogenous task-set reconfiguration process? *Journal of Experimental Psychology: Human Perception and Performance, 32*, 493–516.

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., & Wager, T. D. (2000). The unity and diversity of executive functions and their contributions to complex “frontal lobe” tasks: A latent variable analysis. *Cognitive Psychology*, *41*, 49-100. https://doi.org/10.1006/cogp.1999.0734

Monsell, S. (2003). Task switching. *Trends in Cognitive Sciences*, *7*, 134-140. https://doi.org/10.1016/S1364-6613(03)00028-7

Munakata, Y., Snyder, H. R., & Chatham, C. H. (2012). Developing cognitive control: three key transitions. *Current Directions in Psychological Science, 21,* 71-77.

Niebaum, J.C., Chevalier, N., Guild, R.M., & Munakata, Y. (2019). Adaptive control and the avoidance of cognitive control demands across development. *Neuropsychologia, 123*, 152-158. https://doi.org/10.1016/j.neuropsychologia.2018.04.029.

Niebaum, J. C., Chevalier, N., Guild, R.M., & Munakata, Y. (2021). Developing adaptive control: age-related differences in task choices and awareness of proactive and reactive control demands. *Cognition, Affective, & Behavioral Neuroscience*, 21, 561-572. https://doi.org/10.3758/ s13415-020-00832-2.

O'Leary, A. P., & Sloutsky, V. M. (2017). Carving metacognition at its joints: protracted development of component processes. *Child Development*, *88*, 1015-1032. https://doi. org/10.1111/cdev.12644.

Peirce, J., Gray, J. R., Simpson, S., MacAskill, M., Höchenberger, R., Sogo, H., ... & Lindeløv, J. K. (2019). PsychoPy2: Experiments in behavior made easy. *Behavior Research Methods*, *51*, 195-203. https://doi.org/10.3758/s13428-018-01193-y

Pereg, M., Harpaz, D., Sabah, K., Ben-Shachar, M. S., Amir, I., Dreisbach, G., & Meiran, N. (2021). Learning the abstract general task structure in a rapidly changing task content. *Journal of Cognition*, *4*(1). 10.5334/joc.176

Posner, M. I., & Keele, S. W. (1968). On the genesis of abstract ideas. *Journal of Experimental Psychology, 77*, 353-363. https://doi.org/10.1037/h0025953

R Core Team. (2013). R: A language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing.

Raviv, L., Lupyan, G., & Green, S. C. (2022). How variability shapes learning and generalization. *Trends in Cognitive Sciences, 26*, 462-483. https://doi.org/10.1016/j.tics.2022.03.007

Restle, F. (1961). *Psychology of judgment and choice*. New York: Wiley.

Ritchie, K. L., & Burton, A. M. (2017). Learning faces from variability. *Quarterly Journal of Experimental Psychology*, *70*, 897-905. https://doi.org/10.1080/17470218.2015.1136656

Sabah, K., Meiran, N., & Dreisbach, G. (2021). Examining the Trainability and Transferability of Working-Memory Gating Policies. *Journal of Cognitive Enhancement*, 1-13. https://doi.org/10.1007/s41465-021-00205-8

Sabah, K., Dolk, T., Meiran, N., & Dreisbach, G. (2019). When less is more: costs and benefits of varied vs. fixed content and structure in short-term task switching training. *Psychological Research*, *83*, 1531-1542. https://doi.org/10.1007/s00426-018-1006-7

Sabah, K., Dolk, T., Meiran, N., & Dreisbach, G. (2021). Correction to: Enhancing task-demands disrupts learning but enhances transfer gains in short-term task-switching training. *Psychological Research*, *85*, 1473-1487. https://doi.org/10.1007/s00426-021-01557-8

Sala, G., & Gobet, F. (2017). Working memory training in typically developing children: A meta-analysis of the available evidence. *Developmental Psychology*, *53*, 671–685. https://doi.org/10.1037/dev0000265

Sala, G., & Gobet, F. (2019). Cognitive training does not enhance general cognition. *Trends in Cognitive Sciences*, *23*, 9–20. https://doi.org/10.1016/j.tics.2018.10.004

Schank, R., & Abelson, R. (1977). Scripts, plans, goals, and understanding. Hillsdale, NJ: Lawrence Erlbaum.

Schmidt, R. A. (1975). A schema theory of discrete motor skill learning. *Psychological Review, 82*, 225–260. https://doi.org/10.1037/h0076770

Schmidt, R. A., & Bjork, R. A. (1992). New conceptualizations of practice: Common principles in three paradigms suggest new concepts for training. *Psychological Science*, *3*, 207-218. https://doi.org/10.1111/j.1467-9280.1992.tb00029.x

Shahar, N., Pereg, M., Teodorescu, A. R., Moran, R., Karmon-Presser, A., & Meiran, N. (2018). Formation of abstract task representations: Exploring dosage and mechanisms of working memory training effects. *Cognition*, *181*, 151-159. https://doi.org/10.1016/j.cognition.2018.08.007

Shapiro, D. C., & Schmidt, R A. (1982). The schema theory: Recent evidence and developmental limitations. In J. A. S. Kelso & J. E. Clark (Eds.), *The development of movement control and coordination* (pp. 113-150). New York: Wiley.

Smid, C. R., Karbach, J., & Steinbeis, N. (2020). Toward a science of effective cognitive training. *Current Directions in Psychological Science*, *29*(6), 531-537. https://doi.org/10.1177%2F0963721420951599

Stokes, P. D., Lai, B., Holtz, D., Rigsbee, E., & Cherrick, D. (2008). Effects of practice on variability, effects of variability on transfer. *Journal of Experimental Psychology: Human Perception and Performance, 34*, 640-659. https://doi.org/10.1037/0096-1523.34.3.640

Taatgen, N. A. (2013). The nature and transfer of cognitive skills. *Psychological Review, 120*, 439–471. https://doi.org/10.1037/a0033138

Thorell, L. B., Lindqvist, S., Bergman Nutley, S., Bohlin, G., & Klingberg, T. (2009). Training and transfer effects of executive functions in preschool children. *Developmental Science*, *12*, 106-113. https://doi.org/10.1111/j.1467-7687.2008.00745.x

Traut, H. J., Chevalier, N., Guild, R. M., & Munakata, Y. (2021a). Understanding and supporting inhibitory control: Unique contributions from proactive monitoring and motoric stopping to children's improvements with practice. *Child Development*. https://doi.org/10.1111/cdev.13614

Traut, H. J., Guild, R. M., & Munakata, Y. (2021b). Why Does Cognitive Training Yield Inconsistent Benefits? A Meta-Analysis of Individual Differences in Baseline Cognitive Abilities and Training Outcomes. *Frontiers in Psychology*, *12*. 10.3389/fpsyg.2021.662139

Vakil, E., & Heled, E. (2016). The effect of constant versus varied training on transfer in a cognitive skill learning task: The case of the Tower of Hanoi Puzzle. *Learning and Individual Differences*, *47*, 207-214. https://doi.org/10.1016/j.lindif.2016.02.009

Verguts, T., & Notebaert, W. (2008). Hebbian learning of cognitive control: Dealing with specific and nonspecific adaptation. *Psychological Review, 115*, 518-525. https://doi.org/10.1037/0033-295X.115.2.518

Werchan, D. M., Collins, A. G., Frank, M. J., & Amso, D. (2015). 8-month-old infants spontaneously learn and generalize hierarchical rules. *Psychological Science*, 26, 805-815. 10.1177/0956797615571442

Werchan, D. M., Collins, A. G., Frank, M. J., & Amso, D. (2016). Role of prefrontal cortex in learning and generalizing hierarchical rules in 8-month-old infants. *Journal of Neuroscience*, *36*, 10314-10322. https://doi.org/10.1523/JNEUROSCI.1351-16.2016

Wulf, G., & Schmidt, R. A. (1988). Variability in practice: Facilitation in retention and transfer through schema formation or context effects?. *Journal of Motor Behavior*, *20*, 133-149. https://doi.org/10.1080/00222895.1988.10735438

Wulf, G., & Schmidt, R. A. (1989). The learning of generalized motor programs: Reducing the relative frequency of knowledge of results enhances memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *15*, 748-757. https://doi.org/10.1037/0278-7393.15.4.748

Yan, J. H., Thomas, J. R., & Thomas, K. T. (1998). Children's age moderates the effect of practice variability: A quantitative review. *Research Quarterly for Exercise and Sport*, *69*, 210-215. https://doi.org/10.1080/02701367.1998.10607686

Yanaoka, K., van ’t Wout, F., Saito, S., & Jarrold, C. (2022). Prior task experience increases five-year-old children's use of proactive control: Behavioral and pupillometric evidence. *Developmental Science*, *25*, e13181. https://doi.org/10.1111/desc.13181

Yanaoka, K., van ‘t Wout, F., Saito, S., & Jarrold, C. (2024). Evidence for positive and negative transfer of abstract task knowledge in adults and school-aged children. *Cognition*, *242*, 105650. https://doi.org/10.1016/j.cognition.2023.105650

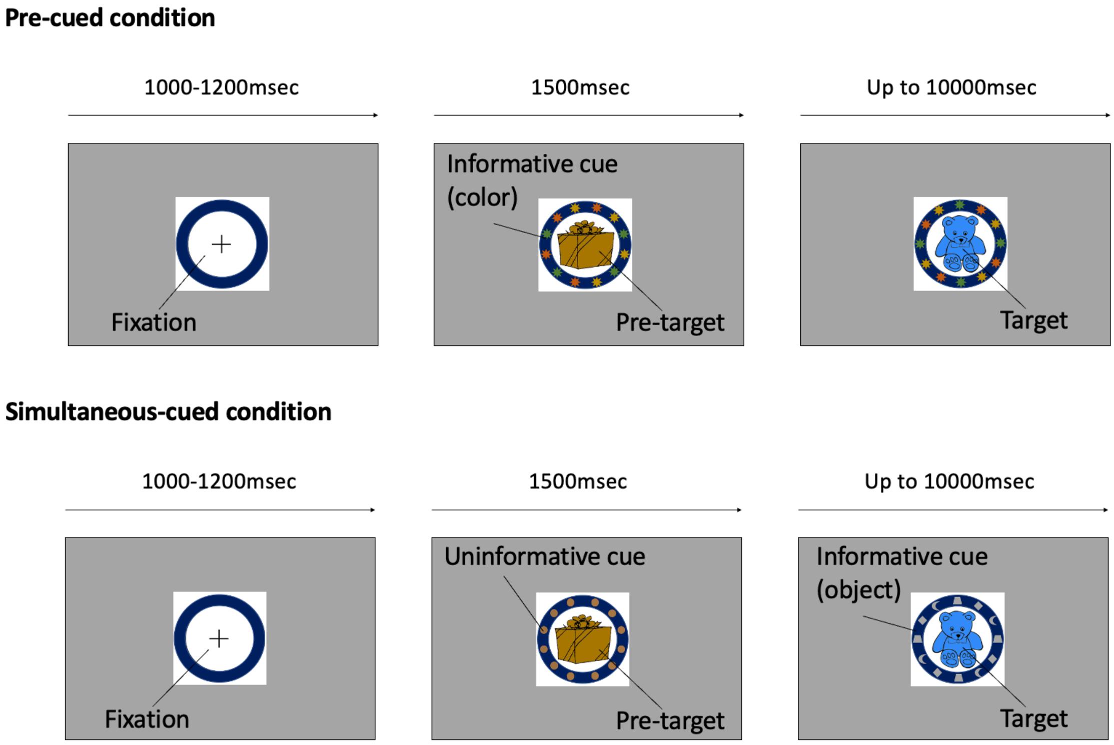


Figure 1. Illustration of the cue task-switching paradigm used in each condition. In the “pre-cued” condition, the informative cue appeared before the target. In the “simultaneous-cued” condition, the uninformative cue appeared along with the pre-target and then the informative cue was presented on target onset.

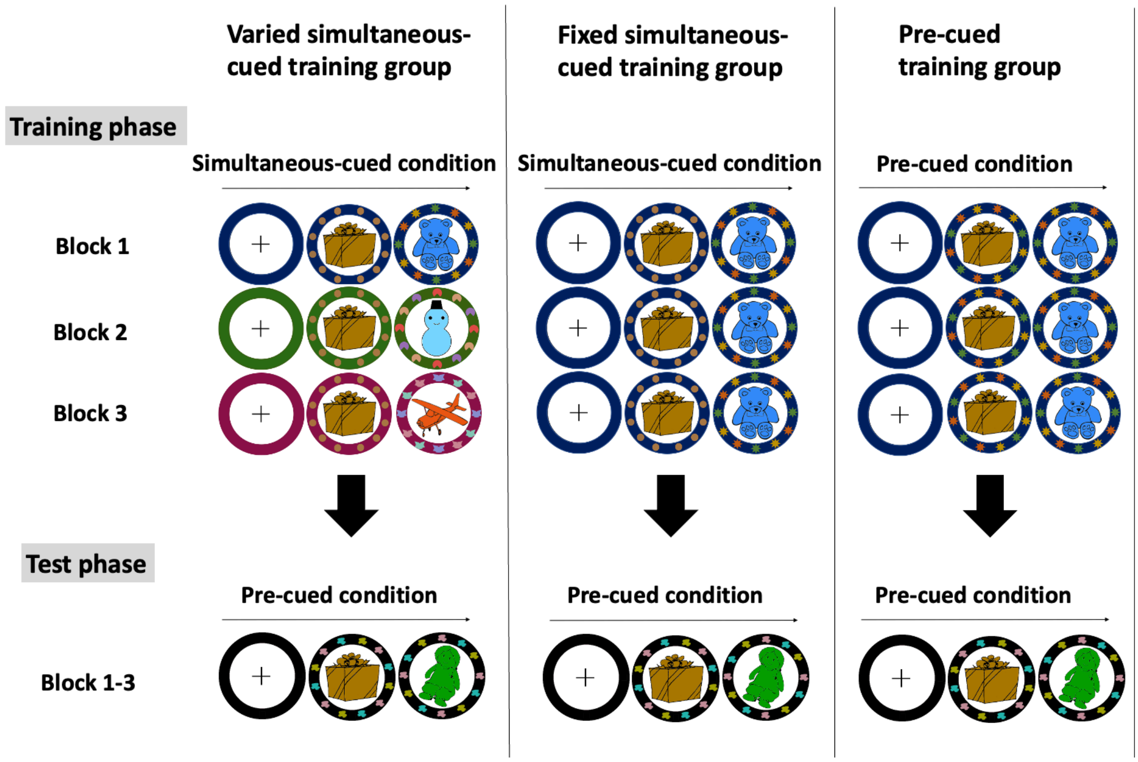


Figure 2. Illustration of the procedure for each training group in Experiments 1A and 2A. Different stimuli were used between the training and test phases. Informative cue (e.g., color cue) and target stimuli (e.g., blue bear) were changed in each block during the training phase for the varied simultaneous-cued training group.

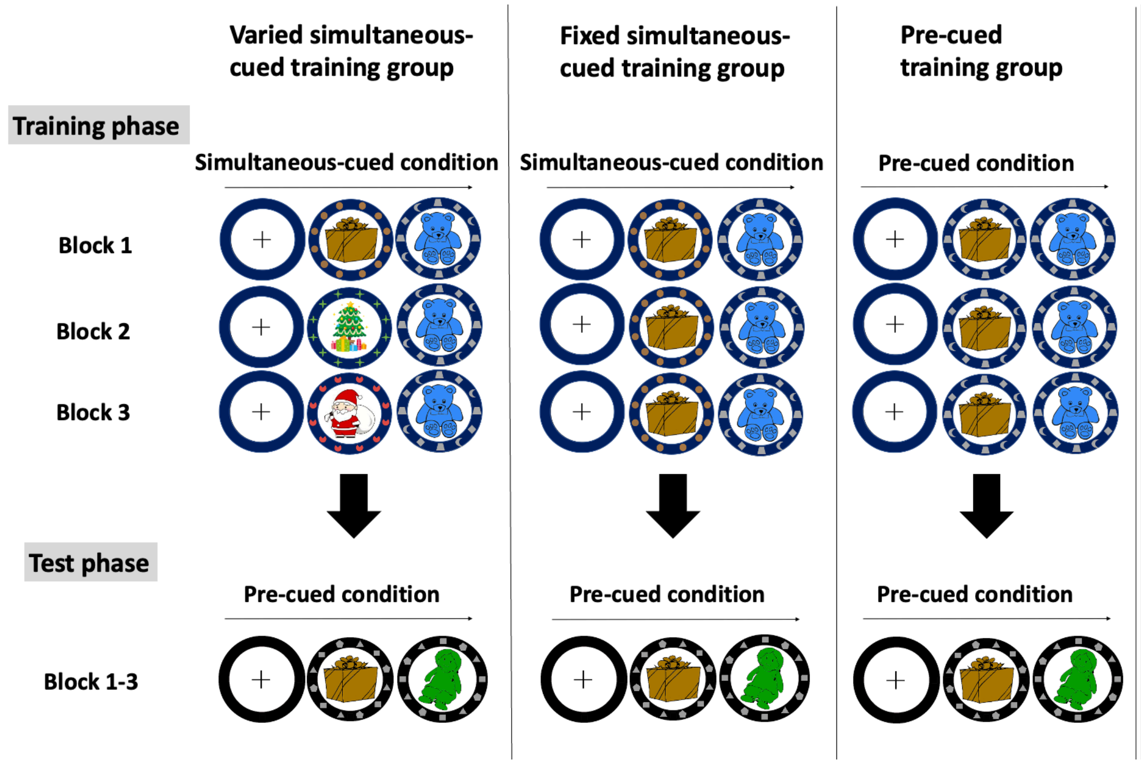
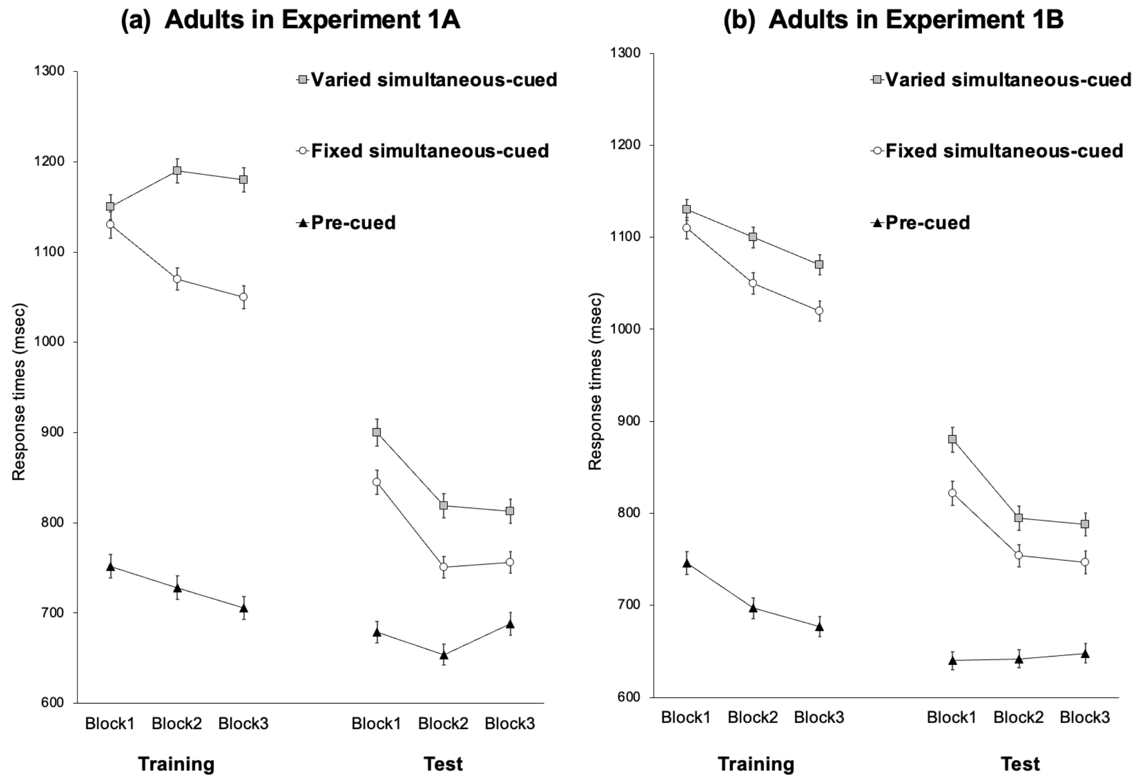
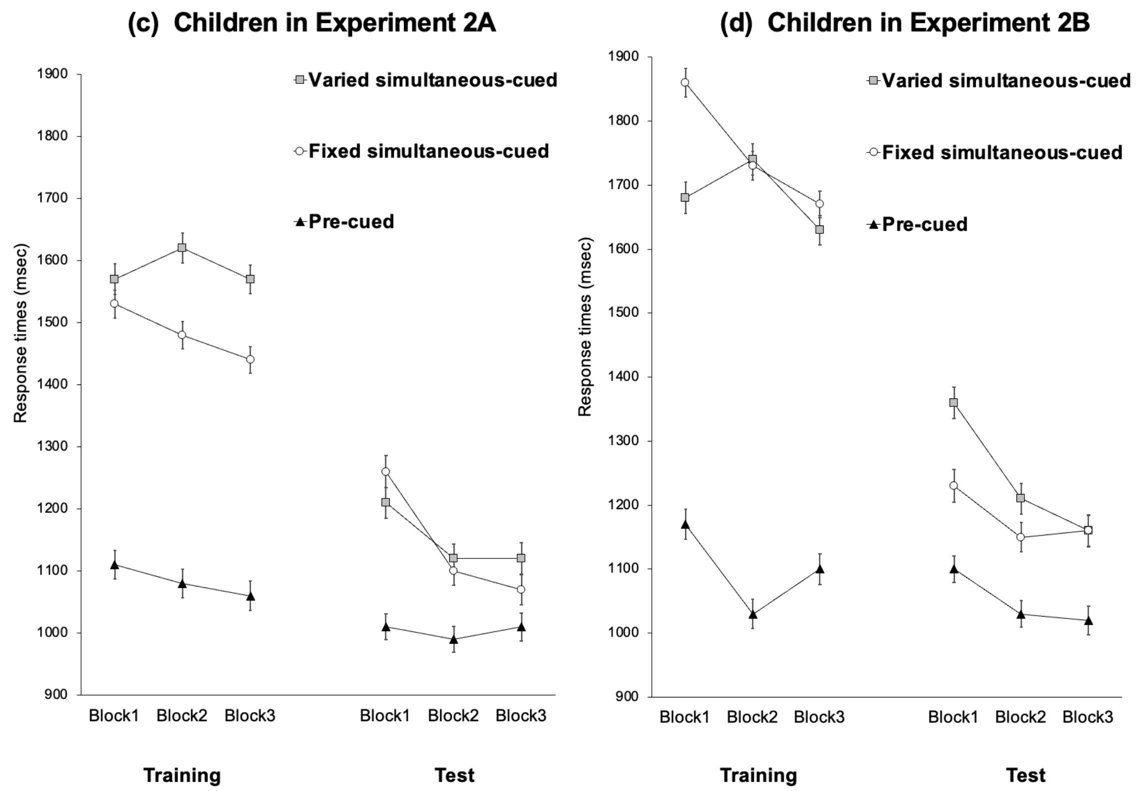


Figure 3. Illustration of the procedure of each training group in Experiments 1B and 2B. Different stimuli were used between the training and test phases. Uninformative cue (e.g., object cue) and pre-target stimuli (e.g., brown gift box) were changed in each block during the training phase for the varied simultaneous-cued training group.


(a) Adults in Experiment 1A
Varied simultaneous-cued
Fixed simultaneous-cued
Pre-cued
Response times (msec)
1300
1200
1100
1000
900
800
700
600
Block1 Block2 Block3 Block1 Block2 Block3
Training
Test
(b) Adults in Experiment 1B
Varied simultaneous-cued
Fixed simultaneous-cued
Pre-cued
Response times (msec)
1300
1200
1100
1000
900
800
700
600
Block1 Block2 Block3 Block1 Block2 Block3
Training
Test

1


(c) Children in Experiment 2A
Varied simultaneous-cued
Fixed simultaneous-cued
Pre-cued
Response times (msec)
1900
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
Block1 Block2 Block3 Block1 Block2 Block3
Training
Test
(d) Children in Experiment 2B
Varied simultaneous-cued
Fixed simultaneous-cued
Pre-cued
Response times (msec)
1900
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
Block1 Block2 Block3 Block1 Block2 Block3
Training
Test

2

Figure 4. Mean response times in each condition. Error bars indicate standard errors. Figure 4a shows performance in adults in Experiment 1A (upper left graph) and Figure 4b shows performance in adults in Experiment 1B (upper right graph). Figure 4c shows performance in school-aged children in Experiment 2A (lower left graph) and Figure 4d shows performance in school-aged children in Experiment 2B (lower right graph).

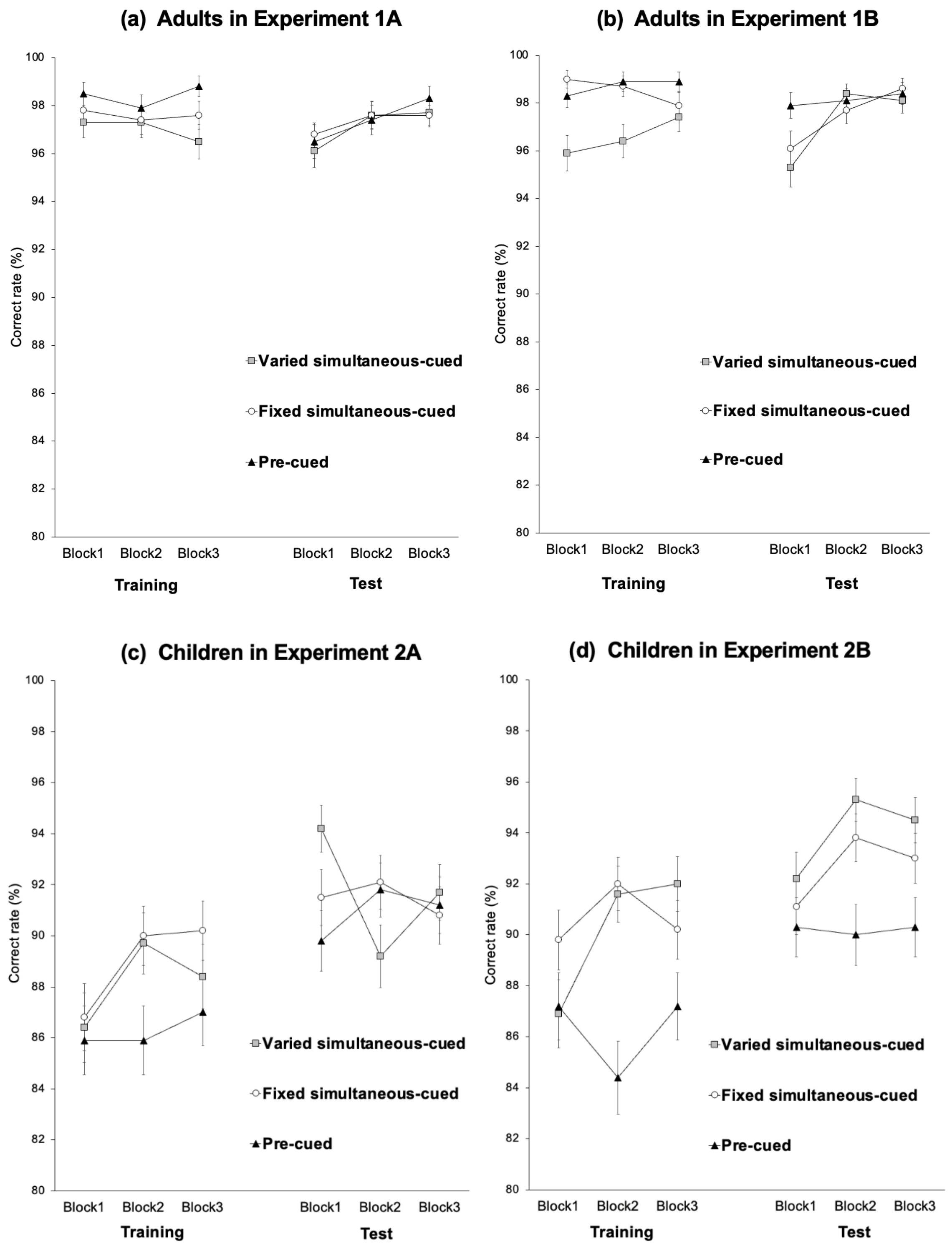


Figure 5. Mean correct response rates in each condition. Error bars indicate standard errors. Figure 5a shows performance in adults in Experiment 1A (upper

left graph) and Figure 5b shows performance in adults in Experiment 1B (upper right graph). Figure 5c shows performance in school-aged children in Experiment 2A (lower left graph) and Figure 5d shows performance in school-aged children in Experiment 2B (lower right graph).

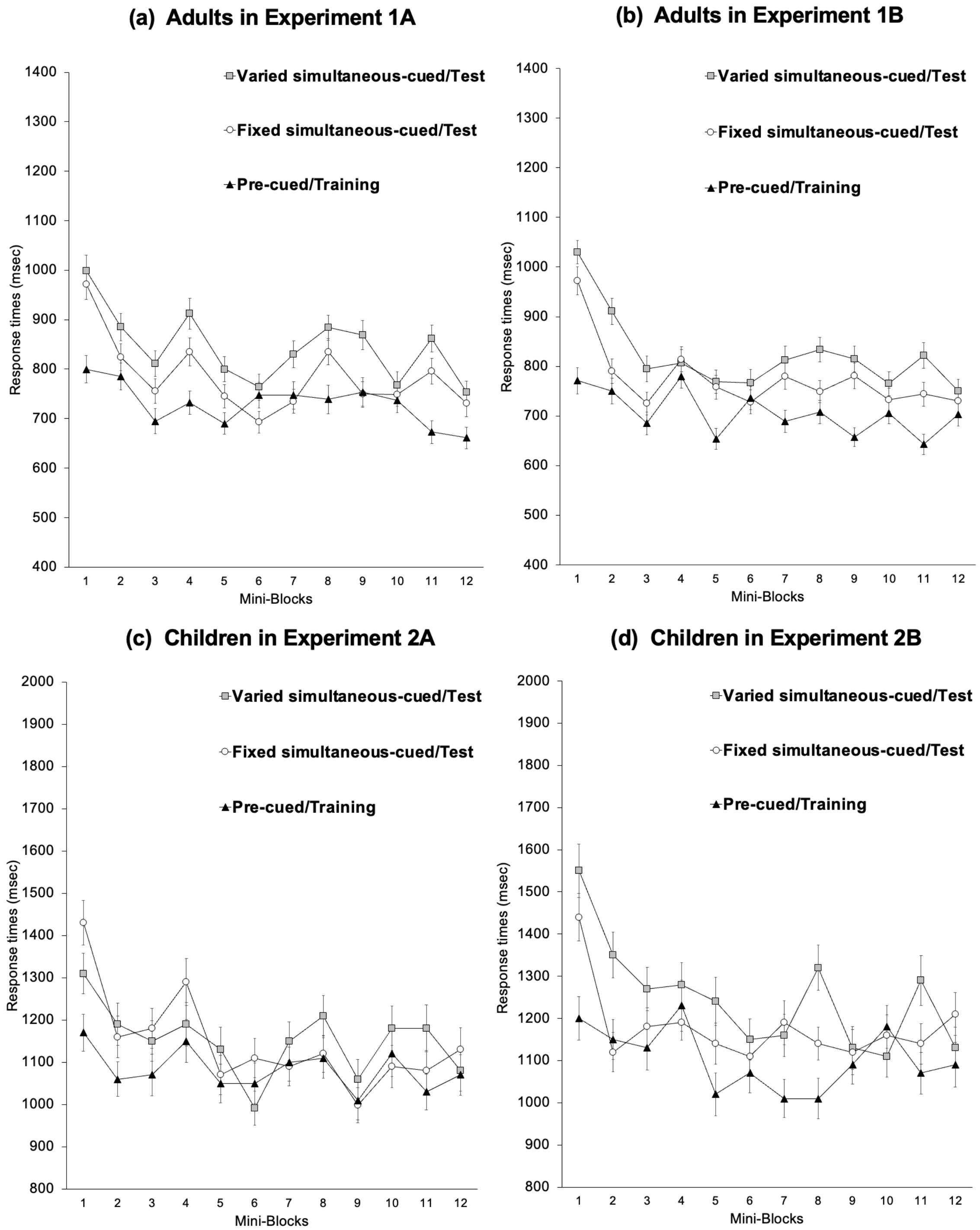


Figure 6. Mean response time s for each mini-block. Error bars indicate standard errors. As shown in figure 6a (upper left: Experiment 1A) and figure 6b (upper

right: Experiment 1B), adults showed slower responses in the test phase of the varied and fixed simultaneous-cued training group compared to the training phase performance of the pre-cued training group. A similar result was obtained in 9 to10-year-olds (see, figure 6c, lower left: Experiment 2B). In contrast, figure 6d (lower right: Experiment 2A) shows that only 9-to 10-year-olds in the fixed simultaneous-cued training group showed slower responses in the test phase compared to the training phase performance of the pre-cued training group.

Table 1. Summary of predictions and findings from all four experiments

	Predictions	Adults	Children
		Experiment 1A	Experiment 2A
Informative cue and target stimuli were changed	**Prediction 1** **Cognitive control mode effect** **(Response times (RTs) in a training phase)** Prediction 1a, 1b Interaction with a trial type Varied simultaneous cued/training (overall RTs) > Pre-cued/training (overall RTs)	✓	✓
	Fixed simultaneous cued/training (overall RTs) > Pre-cued/training (overall RTs)	✓	✓
	Prediction 2 **Positive transfer effect** **(RTs across training and test phases)** Pre-cued/training > Pre-cued/test	✓	✓
	Prediction 3 **Variability effect on negative transfer (RTs)** Prediction 3a, 3b Interaction with a trial type Varied simultaneous cued/test (overall RTs) > Pre-cued/training (overall RTs)	✓ (First block)	×
	Fixed simultaneous cued/test (overall RTs) > Pre-cued/training (overall RTs)	✓ (First "mini" block)	✓ (First "mini" block)
	Varied simultaneous cued/test (overall RTs) > Fixed simultaneous cued/test (overall RTs)	×	×
		Experiment 1B	Experiment 2B
Uninformative cue and pre-target stimuli	**Prediction 1** **Cognitive control mode effect** **(RTs in a training phase)** Prediction 1a, 1b Interaction with a trial type Varied simultaneous cued/training (overall RTs) > Pre-cued/training (overall RTs)	✓	✓
	Fixed simultaneous cued/training (overall RTs) > Pre-cued/training (overall RTs)	✓	✓

were changed	**Prediction2** **Positive transfer effect** **(Response times across training and test phases)** Pre-cued/training > Pre-cued/test	✓	✓
	Prediction3 **Variability effect on negative transfer (RTs)** Prediction 3a, 3b Interaction with a trial type Varied simultaneous cued/test (overall RTs) > Pre-cued/training (overall RTs)	✓ (All blocks)	✓ (First block)
	Fixed simultaneous cued/test (overall RTs) > Pre-cued/training (overall RTs)	✓ (First "mini" block)	×
	Varied simultaneous cued/test (overall RTs) > Fixed simultaneous cued/test (overall RTs)	×	✓ (First block)

Note. "✓" represents that each prediction is supported and "×" represents that each prediction is not supported

Table 2. Summary of the results of analysis for negative transfer and the variability effect in Experiment 1A.

Predictors	β	t	χ^2	p
Varied comparison	0.163	2.41	5.78	.016
Fixed comparison	0.084	1.23	1.52	.218
Trial type	0.063	5.87	34.01	<.001
Block	-0.093	-8.62	74.87	<.001
Varied comparison × Trial type	0.018	1.40	1.95	.163
Varied comparison × Block	-0.026	-2.08	4.47	.035
Fixed comparison × Trial type	0.008	0.65	0.42	.519
Fixed comparison × Block	-0.024	-1.92	3.74	.053
Trial type × Block	-0.027	-2.51	6.25	.012
Varied comparison × Trial type × Block	-0.010	-0.81	0.66	.417
Fixed comparison × Trial type × Block	-0.003	-0.23	0.05	.815

Table 3. Summary of the results of analysis for negative transfer and the variability effect in Experiment 1B.

Predictors	*β*	*t*	χ^2	*p*
Varied comparison	0.179	2.56	6.51	.010
Fixed comparison	0.108	1.53	2.35	.126
Trial type	0.048	4.76	22.30	<.001
Block	-0.101	-9.95	99.64	<.001
Varied comparison × Trial type	-0.009	-0.75	0.58	.447
Varied comparison × Block	-0.013	-1.10	1.28	.258
Fixed comparison × Trial type	-0.012	-0.99	1.00	.318
Fixed comparison × Block	-0.005	-0.39	0.17	.684
Trial type × Block	-0.030	-2.98	8.80	.003
Varied comparison × Trial type × Block	-0.008	-0.71	0.50	.480
Fixed comparison × Trial type × Block	-0.005	-0.43	0.18	.669

Table 4. Summary of the results of analysis for negative transfer and the variability effect in Experiment 2A.

Predictors	*β*	*t*	χ^2	*p*
Varied comparison	0.055	0.81	0.65	.420
Fixed comparison	0.062	0.93	0.86	.355
Trial type	0.078	6.63	43.83	<.001
Block	-0.077	-6.51	43.73	<.001
Varied comparison × Trial type	0.017	1.28	1.63	.202
Varied comparison × Block	-0.012	-0.91	0.80	.370
Fixed comparison × Trial type	-0.004	-0.29	0.08	.778
Fixed comparison × Block	-0.042	-3.10	9.46	.002
Trial type × Block	-0.013	-1.17	1.33	.248
Varied comparison × Trial type × Block	0.006	0.44	0.20	.659
Fixed comparison × Trial type × Block	0.014	0.99	0.98	.321

Table 5. Summary of the results of analysis for negative transfer and the variability effect in Experiment 2B.

Predictors	*β*	*t*	χ^2	*p*
Varied comparison	0.130	1.99	3.92	.048
Fixed comparison	0.057	0.89	0.78	.376
Trial type	0.078	6.55	42.71	<.001
Block	-0.086	-7.25	52.46	<.001
Varied comparison × Trial type	0.003	0.25	0.06	.812
Varied comparison × Block	-0.048	-3.41	11.81	<.001
Fixed comparison × Trial type	-0.005	-0.33	0.11	.735
Fixed comparison × Block	-0.003	-0.02	0.002	.967
Trial type × Block	-0.001	-0.11	0.02	.894
Varied comparison × Trial type × Block	-0.010	-0.73	0.54	.463
Fixed comparison × Trial type × Block	-0.008	-0.58	0.33	.563