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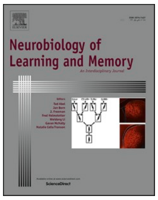

Transfer of learned cognitive control settings within and between tasks

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A B S T R A C T

Cognitive control is modulated based on learned associations between conflict probability and stimulus features such as color. We investigated whether such learning-guided control transfers to novel stimuli and/or a novel task. In Experiments 1 and 2, participants experienced an item-specific proportion congruence (ISPC) manipulation in a Stroop (Experiment 1) or Flanker (Experiment 2) task with mostly congruent (MC) and mostly incongruent (MI) colors in training blocks. During a transfer block, participants performed the same task and encountered novel transfer stimuli paired with MC or MI colors. Evidencing within-task transfer, in both experiments, responses were faster to incongruent transfer stimuli comprising an MI color compared with an MC color. In Experiment 3, we investigated between-task transfer from Stroop to Flanker. After training with an ISPC manipulation in the Stroop task, a Flanker task was completed with the same colors but without an ISPC manipulation (i.e., 50% congruent). Responses were faster to incongruent transfer stimuli paired with the previously-MI colors compared with the previously-MC colors. Additionally, transfer was evident in the first half of the Flanker task but not the second half. The evidence for within-task transfer, in combination with the novel evidence for between-task transfer, suggests learned control settings are flexibly retrieved and executed when predictive cues signaling these control settings are encountered in novel stimuli or a novel task. Theoretical implications are discussed alongside potential neural mechanisms mediating transfer of learning-guided control.

1. Transfer of learned cognitive control settings within and between tasks

The everyday environment consists of repeating patterns (i.e., regularities) that people learn and use to adjust behavior. Of present interest, people learn about external cues in the environment that predict attentional demands and associate cognitive control settings with these cues. Being exposed to the cues later can trigger the retrieval and execution of the control settings associated with the cues. Consider the following example. Imagine that you are driving while checking the map with online navigation on your phone. The map assigns different colors to different sections of your route depending on how crowded they are, such as assigning red to crowded sections and blue to uncrowded sections. As you follow the route, you experience high attentional demands in red sections, but low attentional demands in blue sections, and these differing demands would presumably lead you to engage control differently for different sections. Over time, these experiences may also lead you to associate a focused control setting (e.g., focus on stimuli related to the goal of driving while ignoring any distractors) with red and a relaxed control setting (e.g., reduced focus on the goal) with blue. The central question we researched in the present study is: to what extent do people transfer these learned control settings to novel stimuli and/or novel tasks? For example, imagine that you are now driving on a new road that you have not driven on previously. As you encounter the external cues (red and blue colors) on the map again, you might automatically retrieve the learned control settings associated with these cues and adjust your control settings accordingly. This would demonstrate transfer of learned control settings.

Cognitive control is the ability to dynamically regulate information processing to meet task demands (Miller & Cohen, 2001) such as when attention is adjusted to prioritize goal-relevant information over goal-irrelevant information. While cognitive control was traditionally considered slow, effortful, and strategic (Norman & Shallice, 1986; Posner & Snyder, 1975; Shiffrin & Schneider, 1977), growing evidence shows some forms of control are relatively fast and flexible, operating without awareness and relatively automatically (Hommel, 2007; Logan, 1988; for reviews, Bugg, 2012; Bugg & Crump, 2012). Much of the evidence stems from studies showing that people learn associations

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between stimulus features (e.g., color; referred to hereafter simply as “cues”) and conflict probability, leading to reactive cue-driven control adjustments, which is referred to generally as learning-guided control (Abrahamse, Braem, Notebaert, & Verguts, 2016; Braem & Egner, 2018; Bugg & Egner, 2021; Chiu & Egner, 2019; Crump & Milliken, 2009; Egner, 2014).

A widely used manipulation to observe learning-guided control is the item-specific proportion congruence (ISPC) manipulation (Jacoby, Lindsay, & Hessels, 2003; for the confound-minimized variant used herein, see Bugg, Jacoby, & Chanani, 2011). In a task such as Stroop (i.e., name ink color while ignoring a color-word), some items (e.g., colors blue and red) are presented as mostly congruent (MC; e.g., blue or red ink paired with word BLUE or RED, respectively, on most trials) while other items (e.g., colors green and white) are presented as mostly incongruent (MI; e.g., green or white ink paired with a conflicting word on most trials). The MC and the MI items are randomly intermixed in a 50% congruent list such that participants cannot predict the upcoming item type. This manipulation reliably produces an ISPC effect, which is the pattern whereby the congruency effect (i.e., slower, and sometimes less accurate responses on incongruent trials compared to congruent trials) is significantly reduced for the MI items compared to the MC items. According to the episodic retrieval account (Crump & Milliken, 2009), the ISPC effect can be explained as follows. During the Stroop task, participants learn to associate a more relaxed control setting with the MC items (because this setting is used most often when responding to the MC items which consist of blue or red colors) and a more focused control setting with the MI items (because this setting is used most often when responding to the MI items which consist of green or white colors). When the MC or the MI items are encountered on subsequent trials, the color acts as a cue that reactively triggers retrieval and execution of the associated control settings resulting in a smaller congruency effect when a focused control setting is retrieved (i.e., for the MI items) compared to when a relaxed control setting is retrieved (i.e., for the MC items). Because the adjustments are based on learned associations between a predictive cue (here, color) and conflict probability, the ISPC effect is considered an indicator of an item-specific form of learning-guided control (i.e., item-specific control; see Crump and Milliken (2009) for a location-specific form of learning-guided control).

While the ISPC effect itself is well established (see e.g., Bugg et al., 2011; Bugg & Dey, 2018; Chiu, Jiang, & Egner, 2017; Suh & Bugg, 2021), only a few studies have examined whether item-specific control transfers beyond training conditions (i.e., stimulus, task, etc. features that accompany the ISPC manipulation) in a near sense (e.g., to novel stimuli), and no studies, to our knowledge, have examined transfer in a far sense (e.g., to a novel task). Yet, examining transfer is important from a theoretical perspective because it directly informs questions regarding the flexibility of learning-guided cognitive control. The ISPC effect is often considered to reflect a flexible control mechanism because adjustments occur dynamically, item-by-item (i.e., stimulus-by-stimulus) contingent upon the learned demand for control (i.e., whether the item is MC or MI). That is, from one trial to the next in a task like Stroop, control varies from relatively focused to relatively relaxed depending on the demands associated with a given item. Transfer represents another indicator of flexibility. If the adjustments in control extend beyond stimuli encountered during training to novel stimuli that are accompanied by the predictive cue in the context of the same or a different task, then this is indicative of a flexible (as opposed to inflexible) control mechanism.

Two approaches have been used to examine transfer of item-specific control. One approach was to examine whether the learned adjustments in control generalize from training exemplars to novel, transfer exemplars that include the predictive cue (Bugg et al., 2011). In a training phase, participants were exposed to the ISPC manipulation in a picture-word Stroop task in which they named an animal in a picture while ignoring a superimposed animal word. The training stimuli were multiple pictures of bird and cat exemplars that were MC and multiple pictures of dog and fish exemplars that were MI. In the transfer phase, participants also encountered novel, 50% congruent exemplars (e.g., bird/cat/dog/fish exemplars that were not seen during training) that included the predictive cue (i.e., the exemplars were from the MC or MI animal category). It was found that the learning-guided adjustments in control transferred from the training stimuli to the transfer stimuli, as evidenced by an ISPC effect for the transfer stimuli, and this form of transfer proved to be highly robust to various manipulations designed to disrupt it (Bugg & Dey, 2018).

The second approach was to examine whether learned adjustments in control generalize from training stimuli to novel, transfer stimuli comprised of novel distractors paired with the predictive cue (Bugg & Hutchison, 2013, Experiment 2). In a training phase, participants were exposed to the ISPC manipulation in the color-word Stroop task so that they would have the opportunity to learn associations between to-be-named colors and their likelihood of conflict (e.g., blue and red = MC, green and white = MI), and thereby associate different control settings with different colors. Subsequently, in a transfer phase, they encountered novel stimuli consisting of the colors they responded to during training paired with novel distractor words not experienced during training (e.g., the word ORANGE in red ink or the word ORANGE in green ink).[1] The key finding was that participants that learned the association between colors and their conflict likelihood, as indicated by a positive ISPC effect during the training phase, transferred the learned control settings to the novel stimuli. More specifically, they were faster to respond to the incongruent transfer stimuli in the MI colors (e.g., ORANGE in green ink) compared to the MC colors (e.g., ORANGE in red ink).

While both approaches yielded evidence supporting the flexibility of item-specific control, in a recent consensus paper, researchers from opposing theoretical perspectives confidently recommended the second approach (transfer design of Bugg & Hutchison, 2013) as an effective way to study item-specific control while minimizing the influence of confounds (Braem et al., 2019).[2] However, the critical transfer findings from this study have not been replicated, and the original sample size was relatively small ($N = 20$; $N = 17$ who had a positive ISPC effect in training). These shortcomings led us to pursue Experiment 1 of the current study using the same color-word Stroop task, and a conceptual replication and extension in Experiment 2 using a color-based Flanker task.

In addition to informing theoretical questions regarding the flexibility of learning-guided control, investigating the transfer of control settings also has implications for a theoretical debate regarding the role of simple contingency learning in ISPC effects (i.e., Schmidt & Besner, 2008). According to the contingency learning account, participants use the irrelevant dimension of the stimulus (e.g., the distracting word in the Stroop task) to predict responses on high contingency trials (i.e., congruent trials for MC items; incongruent trials for MI items), leading to a speeding of reaction time in select conditions that results in a pattern of means corresponding to the ISPC effect in some designs (e.g., Jacoby et al., 2003). Informing this theoretical debate was a secondary goal in the current study. This goal was considered secondary because prior findings (e.g., the selective and/or more pronounced effect of the

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[1] To ensure that there was nothing about the transfer stimuli in isolation that could lead to differential adjustments in control, the transfer stimuli were 50% congruent such that the novel distractor words like ORANGE also appeared in their corresponding color (in this example, orange) half of the time. However, congruent trials were not informative with respect to the examination of transfer since they did not contain the predictive cue feature.

[2] This was in part because (unlike the design of Bugg et al., 2011, involving novel animal exemplars) the transfer stimuli in Bugg and Hutchison (2013) did not include training words that participants could theoretically associate with high contingency responses (but see Suh & Bugg, 2021, for evidence and arguments against such a contingency-based account of ISPC effects).

ISPC manipulation on incongruent compared to congruent trials; Bugg et al., 2011; Bugg & Dey, 2018; Suh & Bugg, 2021) from the confound-minimized ISPC design we employed here (i.e., overlapping sets design in which the relevant dimension signals proportion congruence [PC] and serves as the predictive feature; Bugg et al., 2011) have already provided evidence against this account (see Suh & Bugg, 2021 for discussion). Nonetheless, showing transfer of item-specific, learned control settings to novel stimuli and/or tasks in the current experiments would further dispute this account given that we assessed transfer by using novel stimuli that did not include the irrelevant words participants are assumed to associate with contingent responses, according to the contingency learning account.

1.1. *Current study*

In the current study, we conducted three pre-registered experiments to investigate whether item-specific control settings transfer to novel stimuli and/or a novel task. In each experiment, we examined training and transfer of learning-guided control. In the training phase, participants were exposed to the ISPC manipulation, thereby allowing them to learn the association between a predictive cue (color) and the probability of conflict. In a subsequent transfer phase, we assessed transfer of control by presenting the predictive cue (color) with novel stimuli in the same task (i.e., within-task transfer, Experiments 1 and 2) or novel stimuli in a different task (i.e., between-task transfer, Experiment 3) without manipulating conflict probabilities for the transfer stimuli. In other words, transfer stimuli were 50% congruent such that there was nothing about the transfer stimuli in isolation that could lead to differential adjustments in control. Finding transfer of learned control settings to novel stimuli and novel tasks would lend strong support to the flexibility of learning-guided control, and further challenge the contingency learning account. Failure to find transfer would demonstrate boundary conditions for the flexibility of learning-guided control.

2. Experiment 1

We aimed to replicate Experiment 2 of Bugg and Hutchison (2013) with a larger sample size. The replication of this study was particularly important because it is the only study to date showing the transfer of item-specific control settings to novel stimuli while controlling all frequency and contingency-learning confounds (Braem et al., 2019). During training, participants learned associations between specific colors and the likelihood of conflict in the Stroop task. For example, Stroop stimuli appearing in blue or red were MC (low likelihood of conflict) whereas green and white were MI (high likelihood of conflict). After training, participants encountered novel stimuli comprising the predictive cue (one of the four colors from training) paired with a new word not seen during training. If learning-guided control transfers to novel stimuli, then participants should be faster to respond to incongruent transfer stimuli in green or white ink (MI colors) compared to blue or red ink (MC colors) on the assumption that the colors green/white should trigger retrieval of a more focused control setting compared with blue/red.

2.1. *Method*

This experiment, including the power analysis, experimental design, exclusionary criteria, and analytic plan, was fully pre-registered on Open Science Framework (https://osf.io/9fwqj), and the data are publicly available (https://osf.io/xe49k).

2.1.1. *Participants*

To define the target sample size, we conducted separate power analyses for the training and the transfer items because they involved different designs (please see Design subsection) and unique analyses. A priori power analyses were conducted with Cohen's method using G*Power software (Faul, Erdfelder, Lang, & Buchner, 2007). For the training items, a sample size of 45 provides 0.99 power to detect an effect of 0.30 (η_p^2) with an alpha set at 0.05. For the transfer items, a sample size of 18 provides 0.99 power to detect an effect of 0.20 (η_p^2) with an alpha set at 0.05 for the planned analyses.[3] To be conservative, we aimed for 48 participants as our target sample size, which is slightly more than the sample size calculated for the training items. We collected data from 49 Washington University students who participated in the study to fulfill a credit as a partial requirement of Psychology courses.[4] Participants were native English speakers and reported that they had normal or corrected-to-normal vision and color vision. One participant was excluded due to having a scratch trial rate (see Procedure section) 3-standard deviations above the mean of all participants, resulting in 48 usable participants (29 females, 17 males, 2 not preferred to indicate, mean age = 19.72, SD = 1.18). The study was approved by the Institutional Review Board at Washington University in St. Louis. All participants provided informed consent.

2.1.2. *Design and stimuli*

We aimed to replicate the results of Experiment 2 from Bugg and Hutchison (2013) and therefore the procedure and design closely followed that experiment. The experiment consisted of four blocks, three training blocks and one transfer block. For the first three training blocks, we used a 2 (Proportion Congruence: Mostly Congruent vs. Mostly Incongruent) × 2 (Trial Type: Congruent vs. Incongruent) within-subject design. Four color-words (BLUE, RED, GREEN, WHITE) and their corresponding colors were used for the training blocks. The items were divided into two sets according to the color of the stimulus (blue and red vs. green and white); that is, the relevant dimension (color) served to signal the PC of the item (cf. Bugg et al., 2011). One set of colors (e.g., blue and red) was presented as MC while the other set (e.g., green and white) was presented as MI, and this was counterbalanced across participants. Following Bugg and Hutchison (2013), the colors in the MC set were 75% congruent (i.e., presented 36 times with the congruent word, 4 times with each of the three incongruent words) and the colors in the MI set were 25% congruent (i.e., presented 12 times with the congruent word, 12 times with each of the three incongruent words). The items in the first three blocks will be referred to as training items (please see Fig. 1). Each training block was comprised of 192 trials which were presented in a random order.

For the last block (i.e., transfer), we used a 2 (Proportion Congruence: Mostly Congruent vs. Mostly Incongruent) × 2 (Trial Type: Congruent vs. Incongruent) × 2 (Item Type: Training vs. Transfer) within-subject design. The training items continued to be presented in this block, but this block was unique in that it also included transfer items. The transfer items were comprised of novel color-words (PURPLE, BLACK, YELLOW) that participants were not exposed to in the training blocks, and were 50% congruent (i.e., 48 congruent trials with the matching transfer color [e.g., PURPLE in purple], and 48 incongruent trials with the training colors). Of primary importance were the incongruent transfer trials since they were paired with the training colors signaling item-specific PC. Half of these trials were presented in an MC training color (e.g., the word PURPLE in blue) whereas the other half were presented in an MI training color (e.g., the word PURPLE in green).

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[3] We selected the effect sizes based on Experiment 2 of Bugg and Hutchison (2013). They reported an effect size of 0.54 (η_p^2) for the Proportion Congruence x Trial Type interaction in RT (i.e., the ISPC effect) for the training items and an effect size of 0.20 (η_p^2) for the critical test of transfer, as indicated by the main effect of Proportion Congruence in RT for the transfer (incongruent) items. We used a smaller effect size for the power analyses for the training items to be more conservative.

[4] The stopping rule (i.e., the maximum number of participants we can collect data from unless the total sample size drops below the target sample size) was indicated as 52 participants in the pre-registration.

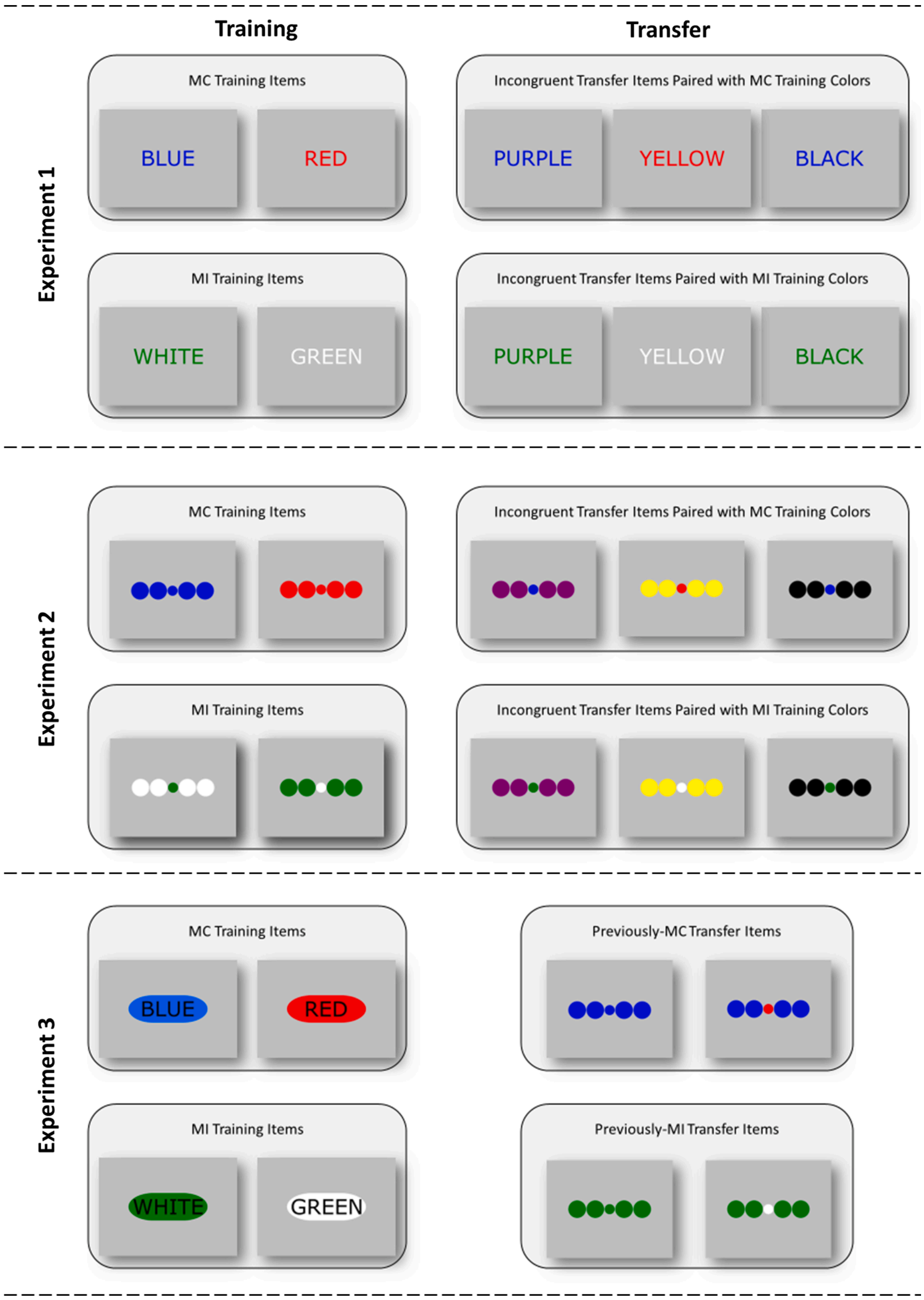

Fig. 1. Sample stimuli from the training (left column) and transfer (right column) phases in Experiments 1, 2, and 3. Note. In the training phases of Experiments 1 and 2, four color-words (the Stroop task) or colored circles (the Flanker task) were used. One set of the items (red and blue colors) was presented as MC (i.e., 75% congruent) while the other set (green and white colors) was MI (i.e., 25% congruent), counterbalanced across participants. In the transfer phase, the training items continued to be presented, but this block was unique in that it also included transfer items. The transfer items were comprised of novel color-words (PURPLE, BLACK, or YELLOW) or colored flanker circles (purple, black, or yellow circles) which were presented with MC and MI target colors equally frequently. Although not depicted here, there were also congruent versions of transfer items (e.g., PURPLE in purple ink or purple target circle with purple flankers) so that transfer items overall were 50% congruent. The training phase of Experiment 3 was similar to Experiment 1 except the Stroop stimuli were altered so that they were more similar to the Flanker stimuli participants encountered in the subsequent transfer phase. In the Flanker task, the same colors from the training phase were presented as equally congruent (50%), however, while half of the colors were previously-MC (during training), the other half were previously-MI colors. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The transfer trials were presented equally often in each of the MC and MI training colors (i.e., four presentations[5] of each transfer word in each of the incongruent colors blue, red, green, and white). The transfer block was comprised of 240 trials which were presented in a random order (please see Fig. 1). The stimulus frequencies are presented in Table 1.

2.1.3. Procedure

Each participant was tested individually. They were seated approximately 60 cm from the monitor and a standard microphone was used to record vocal responses. The experiment was programmed and presented on a 17-inch LCD monitor with the E-prime 2.0 software (Psychology Software Tools, Pittsburgh, PA). All stimuli were presented on a gray background. A color-word (BLUE, RED, GREEN, WHITE, PURPLE, BLACK, YELLOW; font: sans serif, font size: 30) was presented at the center of the screen in blue, red, green, white, purple, black, or yellow ink yielding congruent (i.e., the word and the color is matched) or incongruent (i.e., the word and the color is not matched) trials. Participants were asked to name the color of the stimulus while ignoring the word itself as quickly and accurately as possible. The color-word was presented on the screen until a vocal response was detected. The reaction time was automatically recorded when the microphone was triggered by a vocal response. After the response, the stimulus disappeared, and the experimenter coded the vocal response of the participant (i.e., what the participant said) using the keyboard (e.g., if the participant said “blue”, the experimenter pressed the key corresponding to blue) so that accuracy could be derived. Trials in which the microphone was triggered by extraneous noise or imperceptible speech were coded as scratch trials. Then, a fixation cross (250 ms) and a blank screen (250 ms) were presented, followed by the next stimulus. Participants completed 22 trials before starting the training blocks to practice the task. The stimulus organization during the practice block mimicked the proportion congruence of the items during the main task.

2.2. Results

Trials slower than 1500 ms or faster than 200 ms were excluded from all analyses (eliminated 2.36% of total trials).[6] Scratch trials were excluded from all analyses (eliminated 1.36% of total trials), and error trials (eliminated 4.03% of total trials) were excluded from the RT analyses. Mean RTs and error rates are presented in Table 2. To test our hypotheses, we examined performance separately for training (the first three blocks) and transfer (the last block).

2.2.1. Reaction time

2.2.1.1. Training blocks. First, we confirmed the ISPC effect was present in the training blocks (the first three blocks) with a 2 (Proportion Congruence: Mostly congruent vs. Mostly incongruent) × 2 (Trial type: Congruent vs. Incongruent) within-subject ANOVA. The main effect of trial type was significant, $F(1, 47) = 441.75$, $p < .001$, $\eta_p^2 = 0.90$, indicating slower responses for the incongruent ($M = 738$ ms) compared to the congruent ($M = 636$ ms) trials. A significant main effect of PC, $F(1, 47) = 18.92$, $p < .001$, $\eta_p^2 = 0.29$, indicated that the overall RT was slower for the MC items ($M = 694$ ms) compared to the MI items ($M = 679$ ms). Most importantly, the PC × Trial Type interaction was significant, $F(1, 47) = 77.54$, $p < .001$, $\eta_p^2 = 0.62$, showing an ISPC effect. The overall congruency effect was larger for the MC items ($M = 127$ ms) compared to the MI items ($M = 76$ ms).

2.2.1.2. Transfer blocks. As pre-registered, we excluded 3 participants from the transfer analysis that did not show a positive ISPC effect in the training phase. Bugg and Hutchison (2013) reasoned that those participants who did not show an ISPC effect in training would not be expected to show the transfer of item-specific control to novel items. We analyzed the remaining 45 participants. A one-tailed dependent samples *t*-test was conducted to compare the RT of the incongruent transfer items presented with the MC training colors and the incongruent transfer items presented with the MI training colors to test if the participants retrieve and execute the control setting associated with these colors when they are presented with novel words. We observed a significant difference, $t(44) = 5.44$, $p < .001$, $d = 0.81$, such that the transfer items presented with the MI colors ($M = 763$ ms) were responded to faster than the transfer items presented with the MC colors ($M = 808$ ms).[7]

2.2.2. Error rates

2.2.2.1. Training blocks. A 2 (Proportion Congruence: Mostly Congruent vs. Mostly Incongruent) × 2 (Trial Type: Congruent vs. Incongruent) repeated-measures ANOVA was conducted on the training blocks. The overall error rate was higher for the incongruent ($M = 6.14\%$) compared to the congruent ($M = 2.26\%$) trials, demonstrated by the main effect of trial type, $F(1, 47) = 53.99$, $p < .001$, $\eta_p^2 = 0.53$. The main effect of PC was not significant, $F(1, 47) = 1.69$, $p = .200$, $\eta_p^2 = 0.03$. The PC × Trial Type interaction was significant, $F(1, 47) = 5.23$, $p = .027$, $\eta_p^2 = 0.10$, showing an ISPC effect. The overall congruency effect was larger for the MC items ($M = 4.52\%$) compared to the MI items ($M = 3.22\%$).

2.2.2.2. Transfer blocks. Following the RT analysis, we excluded the 3 participants that did not show a positive ISPC effect in RT in the training phase from the transfer analysis and analyzed the remaining 45 participants.[8] A one-tailed dependent samples *t*-test was conducted to compare the error rates of the incongruent transfer items presented with the MC training colors and the incongruent transfer items presented with the MI training colors. We observed a significant difference, $t(44) = 4.00$, $p < .001$, $d = 0.60$, such that the transfer items presented with the MI colors ($M = 5.28\%$) were responded to more accurately compared to the transfer items presented with the MC colors ($M = 9.96\%$).

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[5] We increased the number of transfer items within the block (from 72 to 96 overall which created an increase from 36 to 48 for the critical incongruent transfer items presented with MC and MI training colors) compared to Bugg and Hutchison (2013) to have more data points, and consequently higher power for the transfer analyses.

[6] This trim deviates from the original study in that it is more conservative than that used by Bugg and Hutchison (2013) who excluded Stroop trials on which responses were faster than 200 ms or slower than 3000 ms. We pre-registered a more conservative trim because we expected faster RTs in the Flanker task (which we used in Experiment 2) compared with the Stroop task (which we used in Experiment 1; see also Bugg & Hutchison, 2013) and because we did not want to use different RT trims for different experiments (e.g., Experiment 1 vs. Experiment 2) or different tasks within a given experiment (Stroop and Flanker tasks in Experiment 3).

[7] Due to an error in the E-prime program, for half of the participants, three extra congruent trials for one of the MC *training* items were presented in the transfer phase (i.e., 36 congruent items [the word WHITE in white ink] instead of 33 congruent items). While we could not envision how this error would influence performance on the critical test of transfer, we confirmed that it did not by analyzing the data after excluding the participants who did not see the extra three congruent items. The transfer effect was again evident, $t(21) = 7.00$, $p < .001$, $d = 1.49$, and followed the same pattern. The transfer items presented with the MI colors ($M = 735$ ms) were responded to significantly faster than the transfer items presented with the MC colors ($M = 799$ ms).

[8] Please note that we defined the exclusion criteria based on RT because the primary indicator of the ISPC effect, thus the primary indicator of whether participants learned different control settings associated with the different colors, is RT.

Table 1
Frequency of Target-Distractor Pairings for Mostly Congruent (MC) and Mostly Incongruent (MI) Items in Experiments 1 and 2.

	Target				
Block	Distractor	Blue	Red	Green	White
Training	Blue	36	4	12	12
	Red	4	36	12	12
	Green	4	4	12	12
	White	4	4	12	12

	Target							
Block	Distractor	Blue	Red	Green	White	Purple	Black	Yellow
Transfer	Blue	33	1	9	9			
	Red	1	33	9	9			
	Green	1	1	9	9			
	White	1	1	9	9			
	Purple	4	4	4	4	16		
	Black	4	4	4	4		16	
	Yellow	4	4	4	4			16

Note. Target refers to the color of the word in the Stroop task, and to the color of the center circle in the Flanker task. Distractor refers to the meaning of the word in the Stroop task, and to the color of the flanker circles in the Flanker task. In this table, the targets (colors) blue and red are MC and green and white are MI; this was counterbalanced across participants during the experiments.

Table 2
Mean Reaction Times (RT) and Error Rates in Experiment 1.

Item Type	Proportion Congruence	Trial Type	Mean RT (SE)	Mean Error Rate (SE)
Training Items	Mostly Congruent	Incongruent	758 (13)	6.72 (0.74)
		Congruent	631 (10)	2.20 (0.36)
		Congruency Effect	127	4.52
	Mostly Incongruent	Incongruent	717 (12)	5.55 (0.59)
		Congruent	641 (12)	2.33 (0.39)
		Congruency Effect	76	3.22
Transfer Items	Mostly Congruent	Incongruent	808 (16)	9.96 (1.36)
	Mostly Incongruent	Incongruent	763 (15)	5.28 (0.81)
		Transfer Effect	45	4.68

2.3. *Discussion*

Replicating Bugg and Hutchison (2013), we found that item-specific control settings learned during training transferred to novel stimuli comprising the predictive cue (one of the four colors from training) paired with a new word (distractor) not seen during training. This within-task transfer effect was evidenced by significantly faster responses for incongruent transfer items paired with the MI training colors compared with those paired with the MC training colors. This suggests the learned control settings (i.e., more focused for MI training colors compared to more relaxed for MC training colors) were retrieved and executed when the predictive cues were encountered in novel incongruent stimuli, supporting the flexibility of learning-guided control. Since the transfer items were comprised of novel words that participants did not experience before and were presented equally congruent, this difference cannot be attributed to use of the word dimension to predict high contingency responses. That is, the finding is incompatible with the contingency learning account.

3. Experiment 2

We aimed to conceptually replicate and extend the results of Experiment 1 within a Flanker task (i.e., respond to the central target flanked by the distractors). Doing so was important for two main reasons. First, demonstrating within-task transfer of learned control settings with another common conflict task would show the generalizability of the transfer effect and provide converging evidence in support of the conclusions from Experiment 1. Second, because we planned to investigate transfer from one task (Stroop) to another (Flanker) in Experiment 3 (i.e., between-task transfer), it was critical to first establish that the within task transfer effect was observable in the Flanker task. We used a color version of the Flanker task with vocal responses rather than more traditional versions (e.g., arrows or letters with manual responses; Eriksen & Eriksen, 1974; Stoffels & Van der Molen, 1988) because we intended to use color as the predictive cue and require vocal responses in Experiment 3. The hypothesis was the same as in Experiment 1. If learning-guided control transfers to novel stimuli, then responses should be faster to incongruent transfer stimuli consisting of the MI predictive cue compared to those consisting of the MC predictive cue.

3.1. *Method*

This experiment, including the power analysis, experimental design, exclusionary criteria, and analytic plan, was fully pre-registered on Open Science Framework (https://osf.io/98hv4), and the data are publicly available (https://osf.io/7zqwx).

3.1.1. *Participants*

The same power analyses were conducted as in Experiment 1, and we again aimed for 48 participants as our target sample size. We collected data from 52 Washington University students who participated in the study to fulfill a credit as a partial requirement of Psychology courses.[9] All participants were native English speakers and reported that they have normal or corrected-to-normal vision and color vision. One participant was excluded from all analyses due to a high error rate (3-standard deviation above the mean of all participants), one due to a high scratch trial rate (3-standard deviation above the mean of all participants), and two due to not following the instructions (i.e., engaging in other activities during the task), resulting in 48 usable participants (35 females, 13 males, mean age = 19.35, SD = 1.11). All participants provided informed consent and the study was approved by the Institutional Review Board at Washington University in St. Louis.

3.1.2. *Design and stimuli*

The design was identical to Experiment 1 with the following exceptions. Instead of using color-word stimuli in a Stroop task, Experiment 2 used color flanker stimuli in a Flanker task. Five colored circles were presented in a row (cf. Diedrichsen, Ivry, Cohen, & Danziger, 2000; Kinder, Buss, & Tas, 2022). The center (target) circle was smaller than

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[9] The stopping rule was indicated as 52 participants in the pre-registration.

the outer (distractor) circles, and the target was presented 100 ms later than the distractors.[10] The stimulus was presented as either congruent (i.e., the color of the target and distractors are the same), or incongruent (i.e., the color of the target and distractors are different). As in Experiment 1, items were divided into two sets (an MC set and an MI set) according to the color of the relevant dimension (blue and red vs. green and white; counterbalanced across participants), which here refers to the color of the target circle (please see Fig. 1). The stimulus frequencies are presented in Table 1.

3.1.3. *Procedure*

The same procedure was followed as in Experiment 1 except participants were instructed to name the color of the target (i.e., center circle) vocally and ignore the distractors (i.e., outer circles), and the target was presented 100 ms later than the distractors. Additionally, due to the pandemic, the responses of participants were recorded and coded by the experimenter after the experiment, rather than simultaneously (to eliminate the need for the experimenter to be in the small room with the participant).

3.2. *Results*

Trials slower than 1500 ms or faster than 200 ms were excluded from all analyses (eliminated 1.76% of total trials). Scratch trials were excluded from all analyses (eliminated 1.54% of total trials), and error trials (eliminated 1.37% of total trials) were excluded from the RT analyses. Mean RTs and error rates are presented in Table 3. To test our hypotheses, we examined performance in the training and transfer items separately.

3.2.1. *Reaction time*

3.2.1.1. Training blocks. A 2 (Proportion Congruence: Mostly Congruent vs. Mostly Incongruent) × 2 (Trial Type: Congruent vs. Incongruent) repeated-measures ANOVA was conducted on the training blocks (the first three blocks). The overall RT was slower for the incongruent (M = 574 ms) compared to the congruent (M = 510 ms) trials, demonstrated by the main effect of trial type, $F(1, 47) = 318.57$, $p < .001$, $\eta_p^2 = 0.87$. A significant main effect of PC, $F(1, 47) = 13.87$, $p = .001$, $\eta_p^2 = 0.23$, indicated that the overall RT was slower for the MC items (M = 548 ms) compared to the MI items (M = 536 ms). Most importantly, the PC × Trial Type interaction was significant, $F(1, 47) = 16.65$, $p < .001$, $\eta_p^2 = 0.26$, showing an ISPC effect. The overall congruency effect was larger for the MC items (M = 71 ms) compared to the MI items (M = 56 ms).

Table 3

Mean Reaction Times (RT) and Error Rates in Experiment 2.

Item Type	Proportion Congruence	Trial Type	Mean RT (SE)	Mean Error Rate (SE)
Training Items	Mostly Congruent	Incongruent	583 (10)	1.55 (0.29)
		Congruent	512 (10)	1.03 (0.19)
		Congruency Effect	71	0.52
	Mostly Incongruent	Incongruent	564 (10)	1.23 (0.23)
		Congruent	508 (10)	1.02 (0.20)
		Congruency Effect	56	0.21
Transfer Items	Mostly Congruent	Incongruent	635 (11)	2.91 (0.66)
	Mostly Incongruent	Incongruent	612 (10)	2.29 (0.66)
		Transfer Effect	23	0.62

3.2.1.2. Transfer blocks. As pre-registered, we excluded 13 participants from the transfer analysis that did not show a positive ISPC effect in the training phase and analyzed the remaining 35 participants. A one-tailed dependent samples t-test was conducted to compare the RT of the incongruent transfer items presented with the target circle in the MC training colors and the incongruent transfer items presented with the target circle in the MI training colors to test if the participants retrieve and execute the control setting associated with these colors when they are encountered again with novel distractors. A significant difference was observed, $t(34) = 3.54$, $p < .001$, $d = 0.60$. The transfer items presented with the MI colors (M = 612 ms) were responded to significantly faster than the transfer items presented with the MC colors (M = 635 ms).

3.2.2. *Error rates*

3.2.2.1. Training blocks. A 2 (Proportion Congruence: Mostly Congruent vs. Mostly Incongruent) × 2 (Trial Type: Congruent vs. Incongruent) repeated-measures ANOVA was conducted on the training blocks. Due to very low error rates (M = 1.20%), none of the main effects or the interaction were significant, $Fs < 2.85$. Following the RT analyses, the participants that did not show a positive ISPC effect in the training phase in RT were excluded from the transfer analysis, resulting in 35 participants. A one-tailed dependent samples t-test showed there was no difference between the incongruent transfer items presented with the target circle in the MI training colors (M = 2.29%) and the incongruent transfer items presented with the target circle in the MC training colors (M = 2.91%), $t(34) = 0.73$, $p = .237$, $d = 0.12$.

3.3. *Discussion*

The key finding of Experiment 2 was observing the transfer of learned control settings to novel stimuli within a color Flanker task, which replicates and extends the results of Experiment 1 with the color-word Stroop task (see also Bugg & Hutchison, 2013). This finding further demonstrates that predictive cues trigger the retrieval and execution of learned control settings for novel incongruent stimuli, provides additional evidence for the flexibility of learning-guided item-specific control settings, and challenges the contingency learning account. It is also notable that this study is the first to date to observe the standard ISPC effect (i.e., in the training phase) in a confound minimized design (Braem et al., 2019) with a Flanker task (see Bugg, 2015; Bugg & Gonthier, 2020, for evidence in designs that were not confound minimized).

4. Experiment 3

Having established transfer of control to novel stimuli within two color-based tasks (Stroop and Flanker), we aimed to investigate the transfer of learned control settings between tasks (from the Stroop task to the Flanker task), that is, under conditions in which the training and transfer stimuli differ as does the task goal during training and transfer phases. Returning to the example from the introduction, the question is whether you would retrieve the learned control settings associated with the red and blue map colors if you encountered these colors while performing a different task on your phone. During training, as in Experiment 1, participants learned associations between specific colors and the likelihood of conflict within the Stroop task. In a subsequent transfer

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[10] The use of a target circle that was smaller than distractor circles, and the presentation of the distractor circles for 100 ms prior to the onset of the target circle were determined based on pilot studies. In versions in which the target and distractor circles were of the same size and presented concurrently, the congruency effect was quite small thus raising concerns that the conflict was not sufficient, and it might be unlikely that an ISPC effect could be found.

phase, participants switched to the Flanker task, but critically, continued to encounter the predictive cues (i.e., the colors from the Stroop task). However, all colors were equally congruent in the transfer phase (Flanker task); that is, there was no ISPC manipulation. If learning-guided control transfers to a novel task, then participants should be faster to respond to transfer stimuli consisting of previously-MI colors compared to previously-MC colors. This would provide novel evidence suggesting learned control settings are flexibly retrieved and executed even when previously predictive cues (colors) are encountered in a different task.

Transfer of learned control settings from one task to another represents a farther form of transfer than the within-task transfer in Experiments 1 and 2. As noted above, there is less overlap between training and transfer trials in the present experiment compared to the preceding experiments (e.g., they comprise not just different distractors but stimuli that differ overall and the participants' goal differs across tasks). Based on the episodic retrieval account, it is reasonable to expect that the retrieval of control settings based on a predictive cue will be less potent (and/or more variable) to the extent that this overlap is reduced. This means the transfer effect in Experiment 3 should be smaller than that observed in the preceding experiments.

Perhaps less obvious is another change from the preceding experiments that should also contribute to a smaller transfer effect in Experiment 3. In Experiments 1 and 2 transfer trials were randomly intermixed with training trials in the transfer phase, but in Experiment 3, transfer trials were embedded in a transfer phase that did not include training trials and therefore was entirely unbiased (predictive color cues were 50% congruent for all items). This means that that there is no bottom-up support from training trials to maintain the learning about the predictive cues (maintain the cues' PC as mostly congruent vs. mostly incongruent) during the transfer phase in Experiment 3. Instead, participants can learn within the flanker task that the predictive cues are no longer predictive (i.e., all colors are 50% congruent). In other words, during the flanker task (transfer), participants are expected to unlearn the control settings they associated with the predictive cues during the Stroop task (training). Once the settings are fully unlearned, no transfer can be expected. The current literature on ISPC effects does not allow us to know exactly how quickly such unlearning will occur, but for this reason, we will examine transfer both within the first half and second half of the transfer phase.

4.1. Method

This experiment, including the power analysis, experimental design, exclusionary criteria, and analytic plan, was fully pre-registered on Open Science Framework (https://osf.io/trw52), and the data is publicly available (https://osf.io/p9qkh).

4.1.1. Participants

A priori power analysis was conducted with Cohen's method using the G*Power software (Faul et al., 2007). For the smallest effect we were interested in (the ISPC effect with the transfer items), a sample size of 102 provides 0.95 power to detect an effect of 0.115 (η_p^2) with an alpha set at 0.05.[11] We collected data from 113 Washington University students who participated in the study to fulfill a credit as a partial requirement of Psychology courses.[12] All participants were native English speakers and reported that they have normal or corrected-to-normal vision and color vision. Four participants were excluded from all analyses due to a high scratch trial rate (3-standard deviation above the mean of all participants), and two due to not following the instructions (one left the testing room for ~ 10 min in the middle of the experiment; one was falling asleep during the experiment), resulting in 107 usable participants (76 females, 31 males, mean age = 19.63, SD = 1.26). All participants consented to participate. The study was approved by the Institutional Review Board at Washington University in St. Louis.

4.1.2. Design and stimuli

The experiment consisted of three blocks, two training blocks with the color-word Stroop task and a transfer block with the color flanker task.[13] For the first two training blocks, as in Experiment 1, we used a 2 (Proportion Congruence: Mostly Congruent vs. Mostly Incongruent) × 2 (Trial Type: Congruent vs. Incongruent) within-subject design. However, the color-word Stroop task was modified from Experiment 1 to better mimic some of the properties of the flanker task used in the (subsequent) transfer block (i.e., the color flanker task used in Experiment 2). Four color-words (BLUE, RED, GREEN, WHITE) and a shape filled with their corresponding colors were used to create congruent trials (the color of the shape and the color-word are the same) and incongruent trials (the color of the shape and the color-word are different) during the training blocks (please see Fig. 1). As in the prior experiments, the items were divided into two sets according to the color of the relevant dimension (blue and red vs. green and white shapes). The to-be-named colored shape (i.e., the relevant dimension of the stimulus) was presented 100 ms later than the distractor word presented in black ink (i.e., the irrelevant dimension of the stimulus). One set of colors (e.g., blue and red) was MC (i.e., 75% congruent; 36 times with the congruent word, 4 times with each incongruent word), and the other set (e.g., green and white) was MI (i.e., 25% congruent; 12 times with the congruent word, 12 times with each incongruent word), and this was counterbalanced across participants.

For the transfer block, we used a 2 (Previous Proportion Congruence: Mostly Congruent vs. Mostly Incongruent) × 2 (Trial Type: Congruent vs. Incongruent) within-subject design with the flanker task. We used the same color flanker task that we used in Experiment 2 (i.e., target circle smaller than distractors, to-be-named color shape presented 100 ms later than the distractor circles). Importantly, the same colors were used for the Stroop task in the training blocks and the flanker task in the transfer blocks. However, critically, while the colors were MC or MI in the Stroop task, all colors were 50% congruent in the Flanker task and hence we refer to the design factor as "Previous" Proportion Congruence. The stimulus frequencies are presented in Table 4.

4.1.3. Procedure

The same procedure was followed as in Experiments 1 and 2, with noted exceptions. The participants were instructed to respond to the color of the stimulus while ignoring the word in the training blocks and instructed to respond to the color of the target circle while ignoring the color of the distractor circles for the transfer block. To make the transition between tasks as seamless as possible, participants were instructed

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[11] We selected the effect size for the power analysis based on an unpublished study in our lab that found a significant ISPC effect in a transfer block using a distinct but similar design (Colvett et al., in progress). Since no prior study to our knowledge has examined transfer of item-specific control from one task to a new task, we deemed this study to be the closest approximation to the current experiment. Note that it is significantly smaller than the effect size we used to power Experiments 1 and 2, reflecting that Experiment 3 investigated far (between-task) transfer, which would likely be much smaller than near (within-task) transfer.

[12] The stopping rule was indicated as 120 participants in the pre-registration.

[13] As is apparent from the results of Experiments 1 and 2, the ISPC effect in the training phase was larger with the Stroop task (M = 51 ms, η_p^2 = 0.62) compared to the Flanker task (M = 15 ms, η_p^2 = 0.26). This may suggest that the modulation of control settings depending on the experienced conflict is more pronounced for the Stroop task. Since we aimed to test whether participants would continue to retrieve and execute learned control settings when the task changed in Experiment 3, we decided to use the Stroop task in the training and the Flanker task in the transfer blocks, to create a stronger manipulation (and stronger learning) in the training block.

Table 4
Frequency of Target-Distractor Pairings for Mostly Congruent (MC) and Mostly Incongruent (MI) Items in Experiment 3.

	Target				
Block	Distractor	Blue	Red	Green	White
Training	Blue	36	4	12	12
	Red	4	36	12	12
	Green	4	4	12	12
	White	4	4	12	12
	Target				
Block	Distractor	Blue	Red	Green	White
Transfer	Blue	24	8	8	8
	Red	8	24	8	8
	Green	8	8	24	8
	White	8	8	8	24

Note. Target refers to the color of the word in the Stroop task, and to the color of the center circle in the Flanker task. Distractor refers to the meaning the word in the Stroop task, and to the color of the flanker circles in the Flanker task. In this table, the targets (colors) blue and red are MC and green and white are MI; this was counterbalanced across participants during the experiments.

that they will continue with the same task (i.e., a conflict task) with slightly different rules. In Experiment 3, the vocal responses of the participants were coded by the experimenter after each response as in Experiment 1.

4.2. Results

Trials slower than 1500 ms or faster than 200 ms were excluded from all analyses (eliminated 1.13% of total trials). Scratch trials were excluded from all analyses (eliminated 1.38% of total trials), and error trials (eliminated 1.90% of total trials) were excluded from the RT analyses. Mean RTs and error rates are presented in Table 5. To test our hypotheses, we examined performance in training and transfer items separately.

4.2.1. Reaction time

4.2.1.1. Training blocks (Stroop Task). A 2 (Proportion Congruence: Mostly Congruent vs. Mostly Incongruent) × 2 (Trial Type: Congruent vs. Incongruent) repeated-measures ANOVA was conducted on the training blocks (the first two blocks). Participants responded slower to the incongruent ($M = 626$ ms) compared to the congruent ($M = 545$ ms) trials, indicated by the main effect of trial type, $F(1, 106) = 758.43$, $p < .001$, $\eta_p^2 = 0.88$. The main effect of PC was significant, $F(1, 106) = 18.24$, $p < .001$, $\eta_p^2 = 0.15$, indicating slower RTs for the MC items ($M = 591$ ms) compared to the MI items ($M = 580$ ms). Most importantly, the PC × Trial Type interaction was significant, $F(1, 106) = 73.48$, $p < .001$, $\eta_p^2 = 0.41$, showing a significant ISPC effect. The overall congruency effect was larger for the MC items ($M = 96$ ms) compared to the MI items ($M = 66$ ms).

Table 5
Mean Reaction Times (RT) and Error Rates in Experiment 3.

Item Type	Proportion Congruence	Trial Type	Mean RT (SE)	Mean Error Rate (SE)
Training Items (Stroop)	Mostly Congruent	Incongruent	639 (8)	3.76 (0.43)
		Congruent	543 (6)	0.93 (0.08)
		Congruency Effect	96	2.83
	Mostly Incongruent	Incongruent	613 (7)	2.80 (0.24)
		Congruent	547 (7)	0.78 (0.14)
		Congruency Effect	66	2.02
Transfer Items (Flanker)	Mostly Congruent	Incongruent	578 (7)	2.08 (0.24)
		Congruent	526 (6)	1.92 (0.25)
		Congruency Effect	52	0.16
	Mostly Incongruent	Incongruent	573 (7)	1.83 (0.30)
		Congruent	526 (7)	1.51 (0.21)
		Congruency Effect	47	0.32
		Transfer Effect	5	0.25

4.2.1.2. Transfer block (Flanker Task). As pre-registered, we excluded 20 participants from the transfer analysis that did not show a positive ISPC effect in the training phase and analyzed the remaining 87 participants.[14] A one-tailed dependent samples *t*-test was conducted to compare the RT of the incongruent transfer items which were previously MC training colors and the incongruent transfer items which were previously MI training colors.[15] We observed a significant difference such that the previously MI-incongruent transfer items ($M = 573$ ms) were responded to faster than the previously MC-incongruent transfer items ($M = 578$ ms), $t(86) = 2.09$, $p = .020$, $d = 0.22$.

Additionally, as pre-registered for this experiment, a 2 (Previous Proportion Congruence: Mostly Congruent vs. Mostly Incongruent) × 2 (Trial Type: Congruent vs. Incongruent) repeated-measures ANOVA was conducted on the transfer block to examine whether the participants continue to modulate control settings based on the previous PC the colors signaled (i.e., to test whether there would be an ISPC effect in the transfer task).[16] The overall RT was slower for the incongruent ($M = 576$ ms) compared to the congruent ($M = 526$ ms) trials, demonstrated by the main effect of trial type, $F(1, 86) = 462.24$, $p < .001$, $\eta_p^2 = 0.84$. The main effect of PC was not significant, $F < 1$. While the overall congruency effect was larger for the MC items ($M = 52$ ms) compared to the MI items ($M = 47$ ms), the PC × Trial Type interaction was not significant, $F(1, 86) = 3.67$, $p = .059$, $\eta_p^2 = 0.04$. Because we anticipated that the transfer effect might dissipate as participants learn the new PC (50% congruent) of the training colors during the transfer block, we analyzed the first and the second half of the transfer block separately, as pre-registered.

4.2.1.2.1. First half of the transfer block. We observed a significant difference between the incongruent transfer items presented with the MC and the MI colors, $t(86) = 1.93$, $p = .029$, $d = 0.21$, just as in the overall transfer block analysis. The incongruent transfer items presented with the MI colors ($M = 562$ ms) were responded to faster than the incongruent transfer items presented with the MC colors ($M = 568$ ms).

A 2 (Previous Proportion Congruence: Mostly Congruent vs. Mostly Incongruent) × 2 (Trial Type: Congruent vs. Incongruent) repeated-measures ANOVA was conducted on the first half of the transfer block and showed the main effect of trial type, $F(1, 86) = 331.59$, $p < .001$, $\eta_p^2 = 0.79$, showing the RT was slower for the incongruent ($M = 565$ ms) compared to congruent ($M = 518$ ms) trials. The main effect of PC was

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[14] One of the participants had a 0.24 ms ISPC effect which was rounded to 0 and not included in the transfer analyses. However, when we include this participant, the analyses yielded the same critical results (i.e., significant difference between incongruent items presented with the MC and the MI training colors, $t(87) = 2.02$, $p = .023$, $d = 0.22$; and the non-significant ISPC effect, $F(1, 87) = 3.39$, $p = 0.069$, $\eta_p^2 = 0.04$.

[15] Please note that we refer to the color of the target circle since it is the relevant dimension of the stimulus.

[16] This analysis is unique to Experiment 3. This analysis was not applicable to Experiments 1 and 2 because only the incongruent transfer trials, and not the congruent transfer trials, included the predictive cue (i.e., colors that were predictive of PC during the training phase). That is, in Experiments 1 and 2, the congruent transfer trials comprised not only novel words but also novel transfer colors (i.e., purple, black, and yellow) as the relevant dimension. As such, these colors, did not signal any information about the PC; thus, there were no theoretically guided predictions regarding performance for the congruent transfer trials in those experiments. In Experiment 3, however, the congruent transfer trials also comprise the previously MC and MI colors.

not significant, $F < 1$. Most critically, the two-way interaction between PC and trial type was significant, $F(1, 86) = 4.63$, $p = .034$, $\eta_p^2 = 0.05$, indicating an ISPC effect based on previous proportion congruency. The overall congruency effect was larger for the MC items ($M = 51$ ms) compared to the MI items ($M = 42$ ms).

4.2.1.2.2. Second half of the transfer block. The same analyses were repeated for the second half of the transfer block. Unlike in the first half analyses, the incongruent transfer items presented with the MC ($M = 588$ ms) and the MI ($M = 585$ ms) training colors were responded to with a similar RT, $t(86) = 1.10$, $p = .137$, $d = 0.12$. The 2 × 2 repeated-measures ANOVA showed a main effect of trial type, $F(1, 86) = 360.49$, $p < .001$, $\eta_p^2 = 0.81$, indicating slower RT for the incongruent ($M = 587$ ms) compared to the congruent ($M = 533$ ms) trials. Neither the main effect of PC nor the two-way interaction between PC and trial type was significant, $Fs < 1$. In contrast to the first half of the transfer block, the congruency effect was similar for the MC ($M = 54$ ms) and the MI items ($M = 52$ ms) in the second half.

4.2.2. Error rates

4.2.2.1. Training blocks (Stroop task). A 2 (Proportion Congruence: Mostly Congruent vs. Mostly Incongruent) × 2 (Trial Type: Congruent vs. Incongruent) repeated-measures ANOVA was conducted on the training blocks. The overall error rate was lower for the congruent ($M = 0.85\%$) compared to the incongruent ($M = 3.28\%$) trials, demonstrated by the main effect of trial type, $F(1, 106) = 63.88$, $p < .001$, $\eta_p^2 = 0.38$. A significant main effect of PC, $F(1, 106) = 8.32$, $p = .005$, $\eta_p^2 = 0.07$, showed lower error rates for the MI items ($M = 1.79\%$) compared to the MC items ($M = 2.34\%$). The PC × Trial Type interaction was significant, $F(1, 106) = 4.54$, $p = .035$, $\eta_p^2 = 0.04$, showing an ISPC effect. The overall congruency effect was larger for the MC items ($M = 2.83\%$) compared to the MI items ($M = 2.02\%$).

4.2.2.2. Transfer block (Flanker task). Following the RT analyses, we excluded the 20 participants that did not show a positive ISPC effect in RT in the training phase from the transfer analysis and analyzed the remaining 87 participants. A one-tailed dependent samples *t*-test found no difference between incongruent transfer items presented with the MC ($M = 2.08\%$) and MI ($M = 1.83\%$) training colors, $t(86) = 0.65$, $p = .259$, $d = 0.07$. A 2 × 2 repeated-measures ANOVA showed that none of the main effects or the interaction was significant, $Fs < 1.74$.

4.3. Discussion

We extended the results of Experiments 1 and 2 by demonstrating the transfer of learned control settings between tasks. In line with the previous experiments, participants had the opportunity to learn associations between colors and their likelihood of conflict in the training blocks (i.e., the Stroop task). However, after training, they switched to a novel task (i.e., the Flanker task) during the transfer block. Critically, the transfer stimuli included the predictive cue (i.e., color) from the training task but all colors were equally congruent in the transfer task. There were two key findings, both of which suggest that far transfer can occur such that control settings learned in one task (the Stroop task) are generalized to a novel task (the Flanker task) when the predictive cue reappears. The first was that, as in Experiments 1 and 2, response times were significantly faster for the incongruent transfer items in the flanker task consisting of a previously-MI target color compared with those consisting of a previously-MC target color. The second is that, in the flanker task, there was an ISPC effect even though all colors were 50% congruent. Both effects were present in the first half but not the second half of the transfer block and, the transfer effects in this experiment were much smaller than those observed in the preceding experiments, which we further discuss in the General Discussion. In sum, the findings of Experiment 3 provide novel and converging evidence for the flexibility of the retrieval and execution of learned, item-specific control settings.

5. General discussion

The goal of the current study was to examine the transfer of learned item-specific control settings to novel stimuli and tasks. Using a larger sample, we replicated the results of Bugg and Hutchison (2013) showing within-task transfer in the color-word Stroop task (Experiment 1) and extended this finding for the first time to a color Flanker task (Experiment 2). Additionally, we provided novel evidence for between-task transfer from the Stroop task to the Flanker task (Experiment 3). Collectively, these results point to a control mechanism that generalizes beyond training conditions to novel stimuli and tasks in the presence of a predictive cue that triggers retrieval and execution of learned, item-specific control settings. This evidence thus supports the flexibility of this control mechanism, and further challenges the contingency learning account of the ISPC effect.

Retrieval and execution of learned item-specific control settings can be understood through the lens of the episodic retrieval account (Brosowsky & Crump, 2018; Crump & Milliken, 2009). Hommel (2004) suggested that perceiving an event (e.g., such as when responding to a Stroop stimulus) causes the brain to create an “event file”, which is a network of bindings that includes not only the physical stimulus and response features but also more abstract external cues in the environment (cf. Logan, 1980). Subsequently, the episodic retrieval account posited that these event files can also include more abstract features or internal states such as attentional control settings like those linked to color in the present paradigm (see also Dignath, Johannsen, Hommel, & Kiesel, 2019; Egner, 2014). When people encounter a component of an event file (e.g., a stimulus feature such as the color), it leads to the retrieval of the other components of the file. The retrieval of event files can explain both within-task (Experiments 1 and 2) and between-task (Experiment 3) transfer. After binding external cues (i.e., color) to internal states (i.e., learned control settings), being exposed to external cues in novel stimuli or novel tasks retrieved and executed the bound internal states. Not unexpectedly, the transfer effect (i.e., the difference in performance for the incongruent transfer trials with previously MC compared to previously MI predictive cues) was smaller when transfer was examined between tasks (Experiment 3, $d = 0.22$) than within-tasks (Experiment 1, $d = 0.81$; Experiment 2, $d = 0.60$). This suggests that the learned control settings may be more likely to be retrieved and executed when episodes of prior responding are more similar across the training and transfer trials than when the transfer trials do not map very well onto prior episodes.

Another pattern from the current study that can be interpreted through the lens of the episodic retrieval account is the finding that the transfer effect in Experiment 3 was significant in the first half but not in the second half of the transfer phase. According to this account, participants retrieve the control setting that has been historically associated with the predictive cue in the past, that is, the setting most often used to respond to stimuli that were presented in blue, for example. In the transfer phase in Experiment 3, all stimuli (regardless of color) were 50% congruent. Accordingly, participants could re-learn about the predictive cues (e.g., learn that blue/red are no longer MC and green/white are no longer MI, but all are instead 50% congruent). Assuming such re-learning occurs, then the control setting historically associated with the predictive cue should shift over time toward an “intermediate” control setting (Diede & Bugg, 2017) for all colors (reflecting that they are now 50% congruent). It is unclear how long such re-learning takes, or how a control setting (formerly relevant vs. currently relevant) is selected once re-learning begins, but presumably this could be based on recency (i.e., more recent experiences within the transfer phase are weighted more heavily than previous experiences during the training phase; cf. Botvinick et al., 2001) or task-relevance (i.e., the experiences with the flanker task are weighted more heavily because there is greater overlap between the event files formed during the flanker task and subsequent trials within the same task). In other words, existing episodes (event files) are likely updated or replaced by new ones that become associated with the predictive cues in the transfer phase. This can explain both why the transfer effect was not found in the second half of the transfer block in Experiment 3, and why the transfer effect was smaller in Experiment 3 than Experiments 1 and 2. Uniquely in Experiments 1 and 2, transfer trials were randomly intermixed with training trials during the transfer phase, and consequentially, the training trials may have provided bottom-up support to maintain the learning about the predictive cues (maintain the cues' PC as mostly congruent vs. mostly incongruent) and accordingly, the potency of these cues in flexibly triggering control adjustments.

The present findings stimulate an overarching theoretical question: What type of control setting did participants learn that was generalizable across stimuli and tasks? Bugg and Hutchison (2013) considered the possibility that the item-specific control mechanism in the Stroop task works as an abstract word-reading filter (Jacoby, McElree, & Trainham, 1999; Jacoby et al., 2003), such that the predictive cue retrieves the filter and the filter is generalizable to novel words (e.g., an MI color like green may become associated with a strong filter whereas an MC color like blue may be associated with a weaker filter). This explanation can accommodate the results of Experiment 1. Similarly, for Experiment 2, there might be a spatial filtering mechanism to ignore the flankers that is retrieved in response to the predictive cue and is generalizable to novel flankers. However, such "conflict-specific" filters cannot accommodate the results of Experiment 3 because the training task and transfer task involved different types of conflict. The Stroop task required the selection of a color while ignoring a word and its meaning whereas the Flanker task required the selection of a color while ignoring flanking colors. The fact that transfer was still observed suggests that the learned control settings were not specific to a certain type of conflict (e.g., a word or spatial filter); rather, possibly, what was learned may be a more abstract mechanism such as changing the weight of the relevant and/or irrelevant dimension during response selection depending on the predictive cue. Future research is needed to pinpoint precisely what type of mechanism is at play.

Theoretically speaking, our findings may also inform the question of whether the retrieval/execution of learned control settings is relatively automatic. One indicator of automaticity is whether a process continues to operate even under concurrent demands, that is, when attentional resources are directed elsewhere (Moors & De Houwer, 2006). Suh and Bugg (2021) investigated the automaticity of item-specific control by examining whether the ISPC effect was affected by a concurrent working memory task. Providing evidence for automaticity, they found that the ISPC effect was just as robust under a high load condition compared to a low load condition across multiple experiments using different working memory loads (verbal storage, spatial storage, updating loads imposed by an n-back task; see Spinelli, Krishna, Perry, & Lupker, 2020, for a similar conclusion using an alternative ISPC design). Transfer of learned control settings, as observed in the present experiments, may represent another indicator of automaticity. If the mere presence of a predictive cue triggers retrieval/execution of learning-guided adjustments in control, then this is indicative of a relatively automatic control mechanism. The near transfer of learned control settings to novel stimuli as observed in Experiment 1 and 2 and possibly more so, the far transfer of learned control settings to a novel task (i.e., novel stimuli, novel goal) in Experiment 3, further imply that learning-guided control has properties of automaticity.

5.1. Boundary conditions for transfer

Another important avenue for future research is to investigate the boundary conditions for between-task transfer. As already noted, the transfer effect observed for a novel task in Experiment 3 was much smaller than the transfer effects observed for novel stimuli in Experiments 1 and 2, and this was not surprising for the reasons discussed above. This begs the question of what features are most critical for observing between-task transfer. Experiment 3 was designed such that the Stroop and Flanker tasks, though differing in many ways, shared the relevant dimension (i.e., color), and this may have been critical for observing transfer of learned control settings between these tasks. The relevant dimension is somewhat obligatorily attended to achieve the task goal (name the color), and one would not expect transfer in the Flanker task if participants did not attend to color since color was the predictive cue from the training (Stroop) task (i.e., one would not expect the learned control settings associated with a given color to be retrieved if color was not attended). If the irrelevant dimension instead served as the predictive cue, there may have been a lower probability that participants would attend to the cue (distractor) on any given trial resulting in no transfer.

A finding supporting the importance of the repetition of the relevant dimension when investigating transfer comes from Wühr, Duthoo, and Notebaert (2015). They investigated transfer of the list-wide proportion congruence (LWPC, i.e., manipulating PC across blocks rather than items) effect across dimensions and tasks. The critical observation they made was that sharing the relevant dimension was a necessary condition for transfer, and the transfer effect disappeared when the relevant dimension was not shared across tasks. They argued that this boundary condition for transfer is consistent with the proposal of Funes et al. (2010a, 2010b), who suggested that adaptation to conflict frequency is mostly related to changes in the attentional weights for the relevant dimension of the stimulus, rather than the irrelevant dimension.

What remains an open question is how similar the predictive cue must be between tasks for transfer to be observed. In Experiment 3, the relevant dimension looked different in the Stroop (the color of a large shape) and Flanker (the color of a small circle) tasks (please see Fig. 1), but perhaps this perceptual difference was relatively minimal and the "broad feature similarity" (Cochrane & Pratt, 2022b, p. 2) allowed for transfer. Using the picture-word Stroop task described in the introduction, and the approach of looking at transfer to novel exemplars from animal categories, Cochrane and Pratt (2022b) found that the ISPC effect transferred to visually similar exemplars from the same animal category (e.g., from retrievers to other retrievers), visually dissimilar exemplars from the same animal category with broadly similar features (e.g., from retrievers to bulldogs), and visually dissimilar exemplars from different animal categories with broadly similar features (e.g., from retrievers to cats). They concluded that conflict signals transferred to novel stimuli based on broad feature similarity. Notably, in the latter case (transfer from retrievers to cats), participants were instructed to respond to the cat by saying "dog", just like they responded to the retriever. This may suggest that overlapping responses are important for facilitating transfer (see Bugg & Dey, 2018); that is, the response stored within the event file may be a key element that binds to and thus triggers associated control settings, which would also explain why transfer was observed in Experiment 3 (i.e., participants responded e.g., "red", "blue", "green", or "white" to the color of the large shape in Stroop and the color of the small circle in Flanker).

Another factor that may have been critical for observing transfer between tasks relates to our use of an atypical version of the Flanker task. Not only was this version atypical in that color was the relevant dimension (as opposed to more typical variants that use letters or arrows), but it was also atypical because we asked participants to make vocal responses (as opposed to more typical variants that use manual responses). We elected to use this version so that we could hold response modality constant across the Stroop (training) and Flanker (transfer) tasks in Experiment 3. Preliminary evidence from our lab suggests that the compatibility between the response modalities (between training and transfer) might also be a critical factor for observing transfer of learning-guided control (Colvett, Wetz, & Bugg, 2022).

Finally, with respect to potential boundary conditions, much prior research has studied between-task transfer of control by examining whether the congruency sequence effect (i.e., CSE, pattern whereby congruency effects are reduced following incongruent as compared to congruent trials) is observed when trial n-1 represents a different task than trial n. Such effects have been difficult to observe (Egner, 2008). Much more research is needed to determine the stability of between-task transfer of learning-guided control, but there are two important differences that may make it easier to observe. One is that, in the CSE paradigm, each control adjustment is driven primarily by the preceding trial (but see Jiménez & Méndez, 2013; Jiménez & Méndez, 2014; and see Colvett, Nobles, & Bugg, 2020, for evidence that a few trials back may contribute to control adjustments) whereas item-specific control adjustments are learned across many trials (but see Cochrane & Pratt, 2022a), and thus may be relatively more robust and more likely to survive changes in stimuli, tasks, etc. when transfer is assessed. The second is that, in the CSE paradigm, each trial used to examine between-task transfer is a task switch, whereas in the between-task transfer paradigm used in Experiment 3, only the first trial of the transfer phase (Flanker task) represented a switch (there was no task switching after the first trial). To the extent that the need to switch tasks interferes with or masks the transfer of control, one might expect that transfer of learning- guided control is easier to observe in the present paradigm.

5.2. Potential neural mechanisms underlying learning and transfer of control

Classic memory paradigms show that prefrontal cortex (PFC) and medial temporal lobes (MTL), specifically the hippocampus, are critical in the formation and retrieval of episodic memories (for a review, see Simons & Spiers, 2003). Studies investigating the contributions of episodic memory processes to cognitive control have observed similar neural patterns. Jiang, Brashier, and Egner (2015) used fMRI to explore the neural mechanisms underlying the integration of concrete event features with abstract control states. They found that the hippocampus (left), putamen, MTL, and dorsal striatum were involved in the binding of event features and control settings, and they speculated that retrieval of event files is also supported by the hippocampus. Using a different paradigm, Jiang et al. (2020a) used fMRI to investigate the retrieval of goal-relevant task-sets associated with different contexts. After creating associations between contexts and task demands, they found that the hippocampus retrieves the associated task demand cued by the contexts, and the PFC implements goal-directed behavior by using retrieved task demands. Specifically, the right dorsolateral PFC (dlPFC) was active in the reinstatement of task demands.

Of course, learning-guided control involves not only episodic memory processes but additionally learning processes. In an elegant fMRI study, Chiu et al. (2017) distinguished the neural mechanisms underlying ISPC effects reflecting learning-guided control (using a confound-minimized design like that in the present study) from those underlying ISPC effects reflecting contingency learning (using an alternative design). The main finding was that the caudate nucleus of the dorsal striatum was the key neural structure uniquely supporting the acquisition and updating of learning-guided control settings. Alongside the findings of Jiang et al. (2015), this further reinforced the importance of the dorsal striatum in the binding of event features and control settings.

None of these studies examined transfer of learning-guided control to novel contexts so it is uncertain whether brain activity in the aforementioned areas would differentiate between predictive cues signaling different control demands when these cues appear in a novel context. In addition to examining the neural mechanisms supporting transfer via such a comparison, it would also be informative to see if brain activity changes depending on the similarity between training and transfer episodes and if the similarity in brain activity can predict the magnitude of the transfer effect (i.e., Ezzyat & Davachi, 2011; Polyn, Norman, & Kahana, 2009).

There is one prior EEG study we can draw upon to formulate predictions regarding the transfer of learning-guided control. Jiang et al. (2020b) examined transfer of control demands from learned stimuli to associated novel stimuli (see also Bejjani, Zhang, & Egner, 2018) and found that transfer was related to a decrease in alpha oscillation in medial frontal channels. A similar prediction might be formulated for between-task transfer triggered by a predictive cue (colored shape in Stroop to colored circle in Flanker as in Experiment 3); however, it remains to be seen whether the same pattern would be found considering that Jiang et al. investigated transfer via associative memory (two types of stimuli were associated with each other in an earlier phase of the experiment) and we investigated transfer based on the occurrence of a perceptually similar predictive cue. Jiang et al. (2020b) speculated that the decrease in alpha oscillation may reflect a shift away from the processing of current inputs to the processing of memories, which may or may not accompany the transfer in Experiment 3.

5.3. Limitations

A few limitations of the present study merit mention. First, as aforementioned, the effect size for between-task transfer (Experiment 3, $d = 0.22$) was small compared with the within-task transfer effects (Experiment 1, $d = 0.81$; Experiment 2, $d = 0.60$). The between-task transfer effect corresponded to a difference in RT of 5 to 9 ms. Although the reduction in the effect size compared to Experiments 1 and 2 was expected, this might raise the question of whether this effect is theoretically meaningful. We believe it is for several reasons. One reason is that it is not an effect in isolation, but rather it is an effect that was observed against the backdrop of two additional transfer effects (in Experiments 1 and 2). Importantly, these within-task transfer effects were also predicted a priori based on the same theoretical analysis of item-specific control and the role of predictive cues that led us to anticipate between-task transfer. A second reason is that our finding of far transfer in Experiment 3 (like our findings of near transfer in Experiments 1 and 2) was tested via a pre-registered design and confirmed through multiple pre-registered analyses that provided converging evidence for transfer (i.e., *t*-test analogous to Experiments 1 & 2, and analysis of the ISPC effect including within the first vs. second half, which was theoretically guided based on the assumption that the ISPC effect is a learned phenomenon and thus participants could also unlearn the predictive nature of the cue in the new task context as described above). Nonetheless, replication and/or extension of this finding would be valuable, including examination of new designs to enhance the magnitude of the transfer effect that address features of the present design (e.g., training and transfer trials were not intermixed) that likely contributed to the relatively small effect size.

A second limitation is that we selectively examined transfer based on the relevant dimension of the stimulus and we only examined one possible relevant dimension, color. While evidence from the picture-word Stroop task indicates that transfer also occurs when the relevant dimension is an animal picture, this form of transfer is more categorical in nature, and it is not yet clear whether transfer would be observed if the animal pictures were to be presented in a different task (far, between-task transfer). A third limitation relates to our pre-registered decision to examine transfer selectively in participants who showed a positive ISPC effect during the training phase (see also Bugg & Hutchison, 2013), on the assumption that we would not expect participants to show transfer in the presence of predictive cues if they had not learned the association between predictive cues and their history of conflict. Defining learners based on this criterion, however, means that a participant with a -1 ISPC effect was grouped differently from a participant having a $+ 1$ ISPC effect (non-learner vs. learner, respectively). There is a need to develop alternative indices that would allow us to categorize learners and non-learners. One possibility is to use representational similarity analysis (RSA). Freund, Bugg, and Braver (2021) applied RSA to fMRI data from a MI list in a Stroop task and examined several coding models (target, distractor, and incongruency coding). For present purposes a key finding was that subject-level target coding estimates predicted congruency effects such that individuals with greater target coding showed less interference. Possibly, subject-level coding of the target or differences between coding of the target for MC as compared to MI items, could be used as an indicator of learning. A fourth limitation is that, although we discussed potential neural mechanisms supporting learning and transfer of learning-guided control, we did not examine these mechanisms in the current study.

5.4. Conclusion

The purpose of the current study was to investigate the transfer of learning-guided control, namely item-specific control. After participants learned the associations between predictive cues (i.e., color) and the probability of conflict in the training phase, they encountered novel stimuli involving the predictive cues in the same task (Experiments 1 and 2) or a novel task (Experiment 3) in the transfer phase. We observed both within-task and between-task transfer evidenced by faster responses to incongruent transfer stimuli involving the MI predictive cue compared with the MC predictive cue, and a significant ISPC effect with the transfer stimuli in the first half of the transfer phase in Experiment 3. These findings converge in supporting the flexibility of learned item-specific control settings. The findings can be understood within the framework of the episodic retrieval account, such that encountering a predictive cue automatically retrieves the event file bound to the cue including the learned control settings. Turning back to the example from the introduction, the findings imply that you may indeed retrieve the learned control settings associated with the red and blue colors when driving a new road while using online navigation (as in near transfer), and you might similarly retrieve the learned control settings if you encountered the colors red and blue while performing a different task (e.g., a game involving these colors) on your phone (as in far transfer).

CRediT authorship contribution statement

Merve Ileri-Tayar: Conceptualization, Software, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing. **Caroline Moss:** Conceptualization, Investigation. **Julie M. Bugg:** Conceptualization, Writing – original draft, Writing – review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data are publicly available via the osf links provided in the manuscript.

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