Psychological Research (2022) 86:1615–1635
https://doi.org/10.1007/s00426-021-01580-9

ORIGINAL ARTICLE

Meaningful boundaries create boundary conditions for control

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Received: 15 February 2021 / Accepted: 9 August 2021 / Published online: 29 August 2021

Abstract

Recent research demonstrated that control states learned via experience in inducer locations were retrieved in novel, unbiased (i.e., diagnostic) locations positioned nearby. Such transfer has been observed even in the presence of a visual boundary (a line) separating inducer and diagnostic locations. One aim of the present study was to assess whether a meaningful boundary might disrupt retrieval of control states in diagnostic locations. Supporting this possibility, in Experiment 1 learned control states did not transfer from inducer locations superimposed on a university's quad to diagnostic locations superimposed on buildings outside the quad. Similarly, in Experiment 2 transfer was not observed for diagnostic locations positioned on a track outside of the field where inducer locations were positioned; however, transfer was also not observed for diagnostic locations on the field (inside the boundary). The latter finding helped motivate Experiments 3a and 3b, which tackled the second aim by examining whether a meaningful boundary might attenuate learning of control states for inducer locations within the boundary. Consistent with this hypothesis, a CSPC effect was observed only when a meaningful boundary was not present. Taken together, the findings provide evidence that meaningful boundaries influence how conflict experiences are organized during a task thereby impacting learning and transfer of context-specific control states.

Meaningful boundaries create boundary conditions for control Much research on cognitive control, or the processes that prioritize goal-relevant information over goal-irrelevant information, is interested in how humans flexibly engage a focused (i.e., filtering out distractors and/or enhancing goal relevant information) or relaxed (i.e., allowing processing of goal irrelevant information) scope of attention in a context-sensitive fashion and later apply (transfer) those learned control states to novel contexts. An important yet unresolved question regards the conditions under which such learning and transfer are observed. In the present study, we aim to examine the role of visual boundaries in both the learning of context-specific control states and the transfer of such states to novel contexts. We are especially interested in the role of meaningful boundaries, which we define as visual boundaries that separate two semantically distinct categories of space and not simply two categories of space (e.g., upper vs. lower; inside versus outside the visual boundary).

In the flanker task, participants respond to a central target stimulus (e.g., the direction of the central arrow) that is flanked by other stimuli (e.g., other arrows; Eriksen & Eriksen, 1974). Performance measures (reduced reaction time and error rate) indicate that this is easier when irrelevant information (flanking arrows) is compatible with the target information (e.g., < < < < <) than when it is incompatible (e.g., < < > < <). Context specific proportion congruence (CSPC) designs manipulate the proportion of compatible trials based on a contextual feature, such as the location on screen where stimuli are presented (Corballis & Gratton, 2003; Crump et al., 2006). For example, an upper location on a computer screen could be mostly compatible (MC) while a lower location could be mostly incompatible (MI). The CSPC effect is the reduction in the compatibility effect in the MI location compared to the MC location, which suggests that the irrelevant information has a smaller influence on performance in the MI location (see Bugg, 2015; Bugg & Gonthier, 2020; Crump et al., 2017; Wendt et al., 2012 for PC-dependent changes in compatibility effects in the flanker task; see Bugg & Crump, 2012 for a review of the effects of proportion congruence manipulations).

Portions of the data were reported at the 60th Annual Psychonomic Society meeting in New Orleans, LA.

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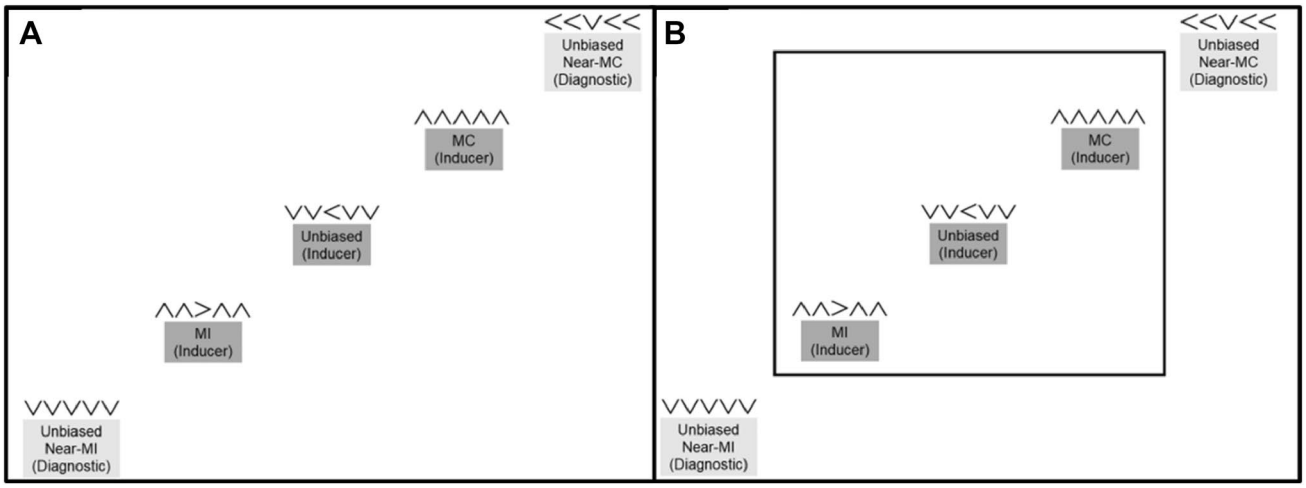

Fig. 1 An illustration depicting the design used in two prior experiments investigating transfer of the CSPC effect to novel locations. **a** Weidler et al. (2020, Experiment 1) A design where MI and MC inducer locations were presented in the lower-left and upper-right categories of the screen. The control state learned at each inducer location transferred to the closest diagnostic location (e.g., Near-MI location for the MI inducer location). **b** Weidler et al. (2020, Experiment 2) This is identical to **a** except a boundary (line) separated the inducer and diagnostic locations. Paralleling the previous experiment, transfer was observed at the diagnostic locations

A primary theoretical account of the CSPC effect is the episodic retrieval account (Crump & Milliken, 2009). According to this account, each trial during a task is stored in episodic memory (i.e., event files, instances; Hommel, 1998; Logan, 1988). Features that are task relevant (e.g., stimulus, response, congruency) and features that are task irrelevant (e.g., contextual features such as location) are included in the episodic representations. Critically, this account further posits that abstract features such as the control state that was used when responding on a given trial (e.g., relaxed or focused attention) are also bound in the episode (see also Dignath et al., 2019; Jiang et al. 2015). Accordingly, the CSPC effect is thought to emerge because the presentation of a stimulus in a MC or MI location triggers retrieval of the control state that historically has been associated with a given location (i.e., focused state for stimuli presented in MI location; see Crump & Milliken, 2009; Crump et al., 2017; for supportive evidence; but see Bugg et al., 2020; Crump et al., 2017; Hutcheon & Spieler, 2017; see also Schmidt & Lemercier, 2019 for an explanation excluding control).

For such triggering to occur, it must be assumed that episodes are organized based on the location in which stimuli have been presented, that is, participants "bin" their experiences in a location-specific fashion (or location is weighted relatively more strongly than other dimensions by which experiences could be binned; e.g., the response; Bugg et al., 2020; Diede & Bugg, 2019). In other words, the assumption is that experiences on trials occurring in the MC location are dumped into one bin, which is associated with a relaxed control state on average, and experiences on trials occurring in the MI location are dumped into another bin, which is associated with a focused control state on average. That is, associations are learned between locations and PC, which determine the control state that becomes bound to a location.

Transfer of CSPC effect to novel locations

An interesting pattern that has emerged in the CSPC literature is the finding that control states that are learned based on experience in inducer locations transfer to novel, diagnostic locations in the same category of space (Pickel et al., 2019; Weidler & Bugg, 2016; Weidler et al., 2020). In Weidler and Bugg (2020), stimuli appeared in inducer locations that were biased (MC or MI) providing the opportunity for participants to associate a unique control state with each location (see Fig. 1). Stimuli also appeared in nearby diagnostic locations that were different from the inducer locations (i.e., Near-MC and Near-MI locations; see Fig. 1). The same stimuli were presented in diagnostic locations as the inducer locations, but they were 50% congruent in diagnostic locations. The key finding was that a CSPC effect was found for the inducer locations and the diagnostic locations. The latter suggests participants retrieved a relaxed control state in the Near-MC location and a focused control state in the Near-MI location. From the perspective of the episodic retrieval account, this pattern implies that participants binned experiences not based on the specific coordinates associated with each location but rather based on the broader category of space in which the stimuli were presented (e.g., all stimuli in the upper right or upper category were dumped into one bin whereas all stimuli in the lower left or lower category were

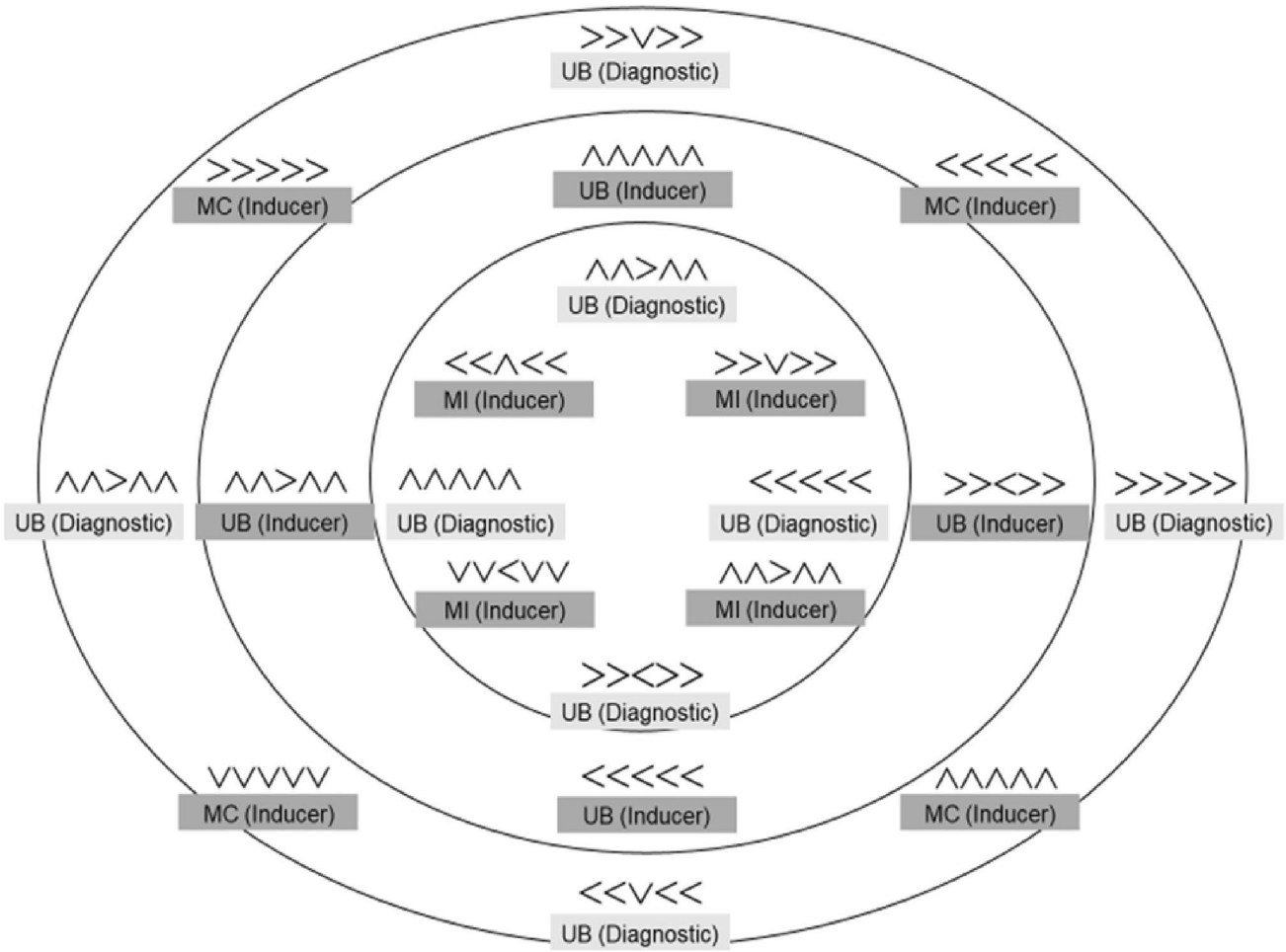

Fig. 2 An illustration depicting the design used by Weidler and Bugg (2016, Experiment 1). "UB" in this image refers to an unbiased location. Inducer locations occurred in three concentric circles. The outermost and innermost circles were MC and MI. Novel diagnostic locations were treated with the control state associated with the MC and MI circles. Locations that were MC and MI were counterbalanced across participants

dumped into a second bin), which corresponds with the categorical coding of space hypothesis (Weidler et al., 2020). If participants had binned based on specific coordinates, then a CSPC effect should have been found for the inducer but not the diagnostic locations since the diagnostic locations were matched in PC (both were 50% congruent).

However, the transfer of the CSPC effect (i.e., finding that performance in the diagnostic locations mirrored that of the inducer locations even though only the latter were biased) could also be explained by the spatial proximity hypothesis. This hypothesis posits that transfer occurred in the previous studies (Weidler & Bugg, 2016; Weidler et al., 2020) because inducer and diagnostic locations were spatially proximal. That is, participants retrieved the control state associated with the closest biased location [see Pickel et al., 2019, for evidence that diagnostic locations trigger retrieval of the associated control state selectively when the task uses a spatial conflict (i.e., spatial Stroop) but not when the task uses an informational conflict (i.e., color-word Stroop)].

One prior study pitted these two hypotheses against each other (Weidler & Bugg, 2016). Flanker stimuli were presented at locations within separate concentric circles that formed a bullseye pattern (see Fig. 2). The outer circle, for example, was MC and the inner circle was MI. The key finding was that transfer of the CSPC effect was found for novel diagnostic locations within the MC and MI circles even though each diagnostic location was equivalently proximal to MC and MI locations. In addition to supporting the categorical coding of space hypothesis, this finding inspired consideration of the role visual boundaries may play in the learning and transfer of CSPC effects. More specifically, the presence of visual boundaries may encourage participants to bin experiences during the task according to categories created by these boundaries (e.g., a bin for each concentric circle in this case). On this view, transfer occurs because

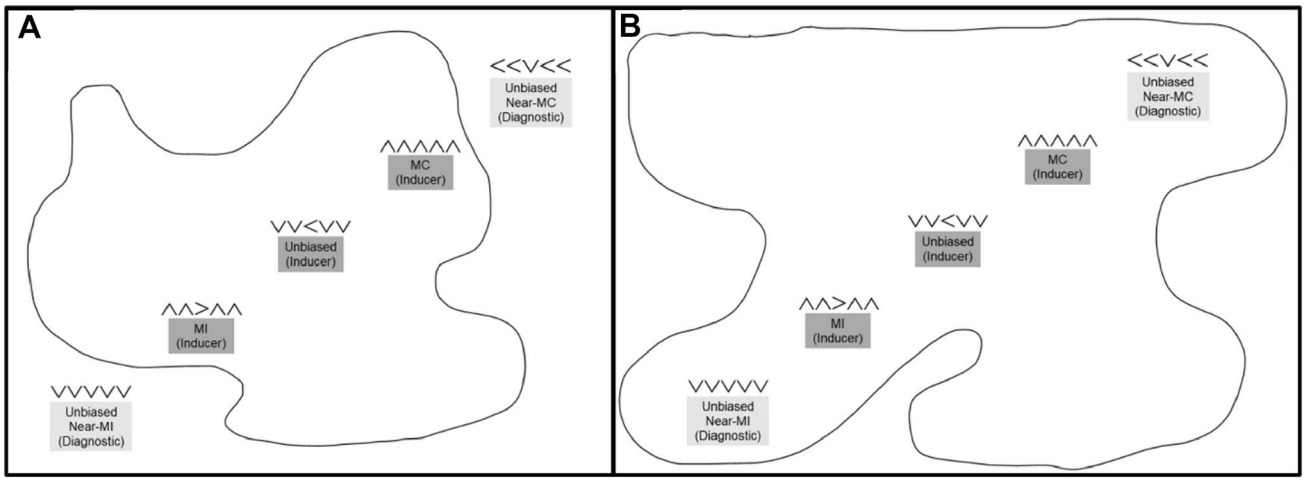

Fig. 3 An illustration depicting the design used in Weidler et al., (2020, Experiment 3). Participants were told that the boundary separated two meaningful categories of space. Inside the boundary represented the island, while outside the boundary represented water. In both designs, diagnostic locations were presented outside inducer locations on an invisible diagonal array. In **a**, the boundary encompassed the central three locations and separated the inducer locations from the diagnostic locations. In **b**, the boundary encompassed all five locations. Transfer was observed for reaction time in both designs, but for error rate it was observed only in the design used in **b**. The authors inferred that the difference between designs in error rate was because the locations were separated by the meaningful boundary in **a**. Locations that were MC and MI were counterbalanced across participants

the presentation of a stimulus in a diagnostic location (e.g., within the MI circle) triggers retrieval of a focused control state associated with the MI bin, and this category-driven control may override any effects of spatial proximity, as in the bullseye study.

However, not all experiments have demonstrated that visual boundaries affect transfer of control in this fashion. Consider an experiment from Weidler et al. (2020), the design of which is depicted in Fig. 1. As shown in Panel B, the visual boundary of a black line appeared on screen and formed a rectangle that surrounded the inducer locations and thus separated them from the diagnostic locations. Despite the presence of the visual boundary, transfer still occurred. That is, a CSPC effect was found for the diagnostic locations (in addition to the inducer locations) suggesting that participants still binned their experiences according to the broader categories of space (e.g., upper right versus lower left) and not according to the categories created by the boundaries (in the rectangle vs. outside of the rectangle). This led Weidler et al. (2020) to posit that perhaps a visual boundary is not sufficient and rather the boundary must be more meaningful to encourage distinct bins for the differing categories (and thus, for the inducer and diagnostic locations in this design).[1]

They provided an initial test of this *meaningful boundary hypothesis* using a novel display featuring an irregularly contoured shape that represented the border of an island (Weidler et al., 2020; see Fig. 3). The category of space inside the boundary represented land, and the category outside the boundary represented water. As illustrated in the figure, there were two types of transfer blocks. In one, the island border separated the inducer locations from the diagnostic locations. Note that this same display was used without the diagnostic locations during initial training blocks. In the second, the island border encompassed all locations (e.g., low tide revealed more shoreline). In both cases, the diagnostic locations were equivalently proximal to the inducer locations. On the view that meaningful boundaries affect binning and thereby retrieval of control states based on the bins, the prediction was that participants should bin experiences separately for the island and the water such that transfer to the diagnostic locations is observed for the Panel B display but not the Panel A display. For reaction time, inconsistent with this prediction (but consistent with the spatial proximity

[1] A similar assumption (that the boundary needs to be meaningful) could be inferred from a prior study that looked at transfer beyond a different type of reference frame using a prime-probe task. Kunde et al. (2003) found that compatibility effects (reflecting compatibility of responses corresponding to a prime number and a to-be-judged probe number) were found for a prime-only set (e.g., 2, 3, 7, and 8) that never appeared as targets when the target set included a larger range (e.g., 1, 4, 6, and 9) that "encompassed" numbers within the prime-only set. However, and most importantly for present purposes, when the target set (e.g., 3, 4, 6, and 7) had a smaller range such that the numbers from the prime-only set fell outside of that range (e.g., 1, 2, 8, and 9), compatibility effects were not observed. That is, transfer did not extend beyond the reference frame. The reference frame was arguably meaningful in that participants' knowledge of a mental number line, for example, distinguished numbers in and outside the frame.

hypothesis and categorical coding of space hypothesis) transfer to the diagnostic locations was observed in both displays as in the prior experiment that used a simple rectangle. In error rate, a significant CSPC effect was observed for the diagnostic locations selectively in Panel B; however, this provided only weak support for the meaningful boundary hypothesis.

To summarize, there is evidence that spatial proximity and the categorical coding of space play a role in explaining transfer of the CSPC effect to diagnostic locations. Visual boundaries, and perhaps especially meaningful boundaries, may also influence how participants bin their experiences and affect transfer to diagnostic locations. Additional research is needed, however, since thus far the evidence supporting a role for boundaries in affecting control in the CSPC paradigm is mixed.

Current study

While previous work suggests the possibility that meaningful boundaries affect the learning and transfer of control states, more research is needed to test the meaningful boundary hypothesis. In Weidler et al., (2020, Experiment 3), the boundary formed by the irregularly shaped black line may not have yielded a meaningful distinction between the island and the water. Looking at Fig. 3, there were no perceptual features that semantically distinguished the category within the boundary from the category outside the boundary—in essence, it was just a black line like the rectangle in Weidler et al., (2020, Experiment 2). Furthermore, the test of transfer depended on participants buying into the idea that water had receded or expanded in the display and updating their representations of the image used during training when encountering the transfer blocks in Panel B of Fig. 3. In the current study, we aimed to provide a stronger test of the meaningful boundary hypothesis using a display that clearly separates semantically distinct categories of space in a way that is immediately clear to a naïve participant.

We were interested in two distinct but interrelated ways that a meaningful boundary may affect how people bin their experiences and thereby modulate CSPC effects. First, a meaningful boundary might disrupt transfer of the CSPC effect from inducer locations to diagnostic locations that fall outside the boundary (cf. predictions from Weidler et al., 2020). Considering the episodic retrieval account, this may occur if retrieval of the learned control states does not occur when stimuli are presented in locations separated from the inducer locations by a meaningful boundary (i.e., in diagnostic locations). Hereafter we refer to this as the *meaningful boundaries dictate retrieval hypothesis,* or *boundaries for retrieval hypothesis* for short. According to this hypothesis, a CSPC effect should be observed for the inducer locations within the meaningful boundary (indicating learning of the control states for the MC and MI location) but there should not be a difference in compatibility effects between the near-MC and near-MI diagnostic locations (i.e., no transfer) outside the boundary.

Second, a meaningful boundary might interfere with or preclude learning of the control states for the inducer locations positioned within the boundary. Hereafter we refer to this as the *meaningful boundaries attenuate location-specific learning hypothesis,* or *attenuated learning hypothesis* for short. To our knowledge, this hypothesis has not yet been tested. According to this hypothesis, a CSPC effect should not be observed for the inducer locations, or it may be weaker in comparison to a condition in which the meaningful boundary is absent. Theoretically, the idea is that the meaningful boundary may encourage participants to bin *all* experiences within the boundary (i.e., those occurring in the MC, unbiased, and MI locations) together in a single bin representing the semantic category of space inside the boundary where the locations are positioned (similar to how experiences within a set of MC and MI locations that formed a group based on relative proximity were binned together resulting in a 50% bin overall and no CSPC effect in Diede & Bugg, 2019). This result would imply that participants learned the PC of the entire area within the meaningful boundary (i.e., 50% congruent) rather than the location-specific PCs of the inducer locations. If diagnostic locations were presented outside the boundary, compatibility effects should be equivalent for near-MC and near-MI locations (i.e., no CSPC effect since both locations were encoded as 50% congruent). The latter prediction is consistent with the prediction that follows from the boundaries for retrieval hypothesis above; however, the difference is that one would expect to observe a CSPC effect for the inducer locations according to that hypothesis but not according to the attenuated learning hypothesis.

In short, a meaningful boundary may disrupt retrieval of learned control states outside the boundary or attenuate learning of control states inside the boundary, or both, leading to no CSPC effect for diagnostic locations. The current study was developed to examine whether meaningful boundaries play some role in the learning and transfer of CSPC effects in line with an account that ascribes a role to meaningful boundaries (see Table 1 for a summary of the predictions for the different hypotheses considered above).

As a preview, Experiment 1 used a diagonal layout like Weidler et al., (2020; see Fig. 1). Inducer locations were presented within a rectangular campus quad and diagnostic locations were presented outside the quad on campus buildings, with the two categories separated by a sidewalk. Contrasting previous findings, but consistent with the boundaries for retrieval hypothesis, we found a CSPC effect for

Table 1 Predicted results based on relevant hypotheses for CSPC paradigms examining transfer from inducer locations to nearby diagnostic locations

Hypothesis type	Hypothesis	CSPC effect at inducer locations?	CSPC effect at diagnostic locations (within boundary)?	CSPC effect at diagnostic locations (outside boundary)?
Hypotheses assuming boundaries are irrelevant	Spatial proximity hypothesis	Yes*	Yes	Yes
	Categorical coding of space hypothesis	Yes*	Yes	Yes
Hypotheses assuming meaningful boundaries affect control	Boundaries for retrieval hypothesis	Yes	Yes	No
	Attenuated learning hypothesis	No	No	No

The spatial proximity hypothesis and categorical coding of space hypothesis cannot be disentangled using the current design. The designs in the current study were aimed at understanding whether a meaningful boundary affects control (i.e., determining whether data support the hypotheses in the bottom half of the table rather than those in the top half of the table). The boundaries for retrieval hypothesis and attenuated learning hypothesis make unique predictions about how the meaningful boundaries will affect control, as evidenced by patterns of CSPC effects for inducer and diagnostic locations

*These hypotheses were developed to explain transfer of CSPC effects to diagnostic locations and are predicated on the assumption that there will be a CSPC effect for inducer locations

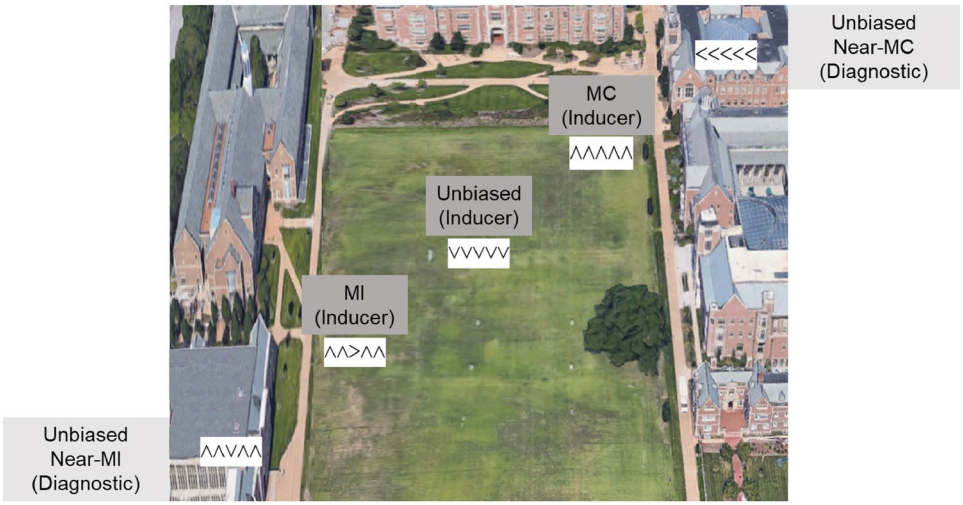

Fig. 4 A depiction of the display in Experiment 1. The background image remained on screen throughout the experiment. On each trial, a single flanker stimulus appeared on screen. Inducer locations appeared on the quad, while diagnostic locations appeared on buildings outside the quad. The inducer MC and MI locations were counterbalanced across subjects

inducer but not diagnostic locations. That is, transfer was not observed in the presence of a meaningful boundary. Experiment 2 aimed to conceptually replicate and extend this finding with a different meaningful boundary. In this case, a track-and field-display was used with some locations appearing within the track and others appearing within the field. Again, transfer to locations outside the boundary did not occur; however, neither did transfer to locations inside the boundary. Notably, the CSPC effect for the inducer locations was relatively weak, raising the possibility that the boundary attenuated learning of the location-specific PCs of the inducer locations within the boundary. Experiments 3a and 3b directly tested the attenuated learning hypothesis, and in particular the prediction that the CSPC effect for inducer locations would be reduced in the presence of a meaningful boundary. The inducer locations were presented in the same positions across Experiments 3a and 3b but only in Experiment 3b were the locations accompanied by a meaningful boundary (thus creating a distinct semantic category of space for the inducer locations). The CSPC effect for inducer locations was observed only when a meaningful boundary was not present supporting the attenuated learning hypothesis. Together, these experiments provide novel evidence showing two ways in which meaningful boundaries influence the binning of experiences for different locations, and accordingly CSPC effects for both inducer and diagnostic locations.

Experiment 1

Experiment 1 examined whether a meaningful boundary can disrupt transfer from inducer locations to diagnostic locations that fall outside the boundary. As shown in Fig. 4,

we superimposed the inducer and diagnostic locations on an aerial image of a campus quad. The inducer locations appeared on the grassy quad and the diagnostic locations appeared on buildings that surrounded the quad, and a sidewalk served as the boundary separating these locations. The positions of the locations used in Experiment 1 were identical to Weidler et al., (2020, Experiments 1 and 2, see Fig. 1), so the key difference was the use of an image with distinct categories of space inside and outside the meaningful boundary. If spatial proximity or the categorical coding of space drives transfer to novel locations, transfer should occur as in previous studies and a significant CSPC effect should be seen for the diagnostic locations. Alternatively, if meaningful boundaries play a role, transfer should not be found. That is, statistically, a non-significant CSPC effect should be observed for the diagnostic locations.

Method

Participants

Sixty Washington University undergraduates (36 female, Age $M = 19.70$, SD = 1.32) participated for cash or course credit. Two participants' data were removed for having an error rate above 15%, and one participant's data were removed due to a data collection error in ePrime. The data from the remaining 57 participants (34 female, Age $M = 19.67$, SD = 1.33) were included.

Design and stimuli

Flanker stimuli were five black arrows presented in a row horizontally 3.5 cm wide and 0.7 cm tall. On compatible trials, all arrows pointed in the same direction (there were four unique compatible trials; e.g., < < < < <) whereas on incompatible trials, the four flanking arrows pointed in a different direction than the central arrow (there were 12 unique incompatible trials; e.g., < < > < <). Arrows pointed up, down, left, or right. The background image was modified from a Google Maps satellite aerial image of Washington University's campus (Google, Maxar Technologies, U.S. Geological Survey, USDA Farm Service Agency, 2021). This image showed a quad surrounded by buildings. The image and the locations where stimuli were superimposed on the image can be seen in Fig. 4. This image was presented on a screen that was 30 cm tall and 37.5 cm tall. The five locations were superimposed on an invisible diagonal array that was 38.5 cm long. Each location was 7.7 cm apart from each other.

Procedure

First, a brief demographic survey was administered. Then participants began the task where they first saw the background image of Washington University's quad and were instructed to identify (on subsequent slides) what location was highlighted in each slide and to write an activity that could be performed in that location. For example, one could play with a Frisbee on the quad or buy lunch in the student center. The five highlighted locations were those in which flanker stimuli later appeared during the flanker task. This task was included to prime participants to delineate buildings from the quad.

Participants then began the flanker task. The experimental procedure hereafter was based on previous experiments, laid out specifically in Weidler et al. (2020). Participants used lab computers that were positioned approximately 60 cm away from them. Stimuli were presented on a background depicting Washington University's quad (see Fig. 4). Every trial began with a black fixation cross presented centrally for 1000 ms followed by a single flanker stimulus. The flanker stimulus appeared on screen until response. The flanker stimulus was superimposed over a white rectangle that appeared on the display concurrent with stimulus onset. Participants' task was to indicate the direction of the central arrow by pressing the 2 (down), 4 (left), 6 (right), or 8 (up) key with their right index finger on the number pad of a keyboard. Participants were instructed to respond as quickly as possible while maintaining a high level of accuracy.

Participants first completed a 12-trial practice block with four stimuli at each of the three inducer locations (The PC bias of each location was in keeping with the PC bias seen later in the induction blocks; overall, participants saw the same set of randomly chosen six compatible and six incompatible stimuli). Next, they completed three training blocks followed by two transfer blocks. During each 144-trial training block, 48 stimuli appeared in each of the three inducer locations along a positively sloped invisible diagonal (see Weidler & Bugg, 2016; Weidler et al., 2020). The stimuli presented in the center location were 50% compatible (i.e., PC-unbiased; 6 repetitions of each compatible stimulus, 2 of each incompatible), whereas the other two locations along the diagonal each had a different PC bias (in the 75% compatible [MC] location there were 9 repetitions of each compatible stimulus and 1 repetition of each incompatible stimulus, in the 25% compatible [MI] location there were 3 repetitions of each compatible and incompatible stimulus). The side that was MC or MI was counterbalanced between participants.

In each of the 240-trial transfer blocks, in addition to the 144 trials that appeared in each training block, two identical sets of 48 PC-unbiased stimuli appeared in two novel locations along the diagonal outside of where inducer stimuli

Table 2 Experiment 1 reaction time (ms) and error rate with standard deviations in parentheses

Location type	PC	Trial type	RT	CE (RT)	Error rate	CE (error rate)
Inducer (training blocks)	MC	Compatible	666 (72)	135 (41)	0.32 (0.57)	2.86 (3.87)
		Incompatible	801 (89)		3.18 (4.09)	
	MI	Compatible	679 (74)	120 (42)	0.16 (0.67)	2.16 (3.13)
		Incompatible	799 (86)		2.32 (3.18)	
Inducer (all blocks)	MC	Compatible	663 (70)	135 (37)	0.44 (0.66)	3.07 (3.75)
		Incompatible	798 (88)		3.51 (3.95)	
	MI	Compatible	670 (68)	120 (35)	0.28 (0.70)	2.47 (2.95)
		Incompatible	790 (80)		2.75 (2.98)	
Diagnostic	Near-MC	Compatible	742 (78)	141 (46)	0.39 (0.88)	4.30 (4.52)
		Incompatible	883 (88)		4.68 (4.82)	
	Near-MI	Compatible	747 (85)	134 (40)	0.32 (0.74)	3.86 (4.35)
		Incompatible	882 (90)		4.18 (4.58)	

CE compatibility effect, *MC* mostly compatible inducer location, *MI* mostly incompatible inducer location. *Near-MC* diagnostic trials near the MC inducer location; *Near-MI* diagnostic trials near the MI inducer location; *Inducer (training blocks)* inducer locations in the first three blocks of the experiment; *Inducer (all blocks)* inducer locations in all five blocks of the experiment; *Diagnostic* diagnostic locations in fourth and fifth blocks of the experiment

appeared (see Fig. 4). Both diagnostic locations, referred to subsequently as near-MC and near-MI locations, were 50% compatible.

Results

For this and all subsequent experiments, an alpha of 0.05 was used for all analyses. In addition, only trials with RTs greater than 200 and less than 2000 ms were included (0.72% of trials were removed in this trim) and error trials were excluded from the analysis of RT (cf. Bugg, 2015; Weidler & Bugg, 2016; Weidler et al., 2020). Error rates will subsequently be expressed as probabilities. All analyses use a 2 × 2 repeated measures ANOVA with factors of location (either MC and MI for the inducer location analyses or near-MC and near-MI for the diagnostic location analyses) and trial type (compatible or incompatible).

For null effects, we additionally present Bayes Factors. We report Bayesian evidence for the null hypothesis compared to evidence of the alternative hypothesis (BF_{01}). A value between 1 and 3 indicates anecdotal evidence for the null hypothesis and a value between 3 and 10 indicates substantial evidence for the null hypothesis (Wagenmakers et al., 2011). We calculated Bayes Factors using JASP (see Van Doorn et al., 2020), which assumes an effect size of 0.707.

Inducer trials were analyzed separately from diagnostic trials (cf. Weidler & Bugg, 2016; Weidler et al., 2020). The inducer trials have a 2 × 2 within-subject design with factors of proportion compatibility (MC or MI) and compatibility (congruent and incongruent). The diagnostic trials similarly have a 2 × 2 within-subject design with factors of location (near-MC or near-MI) and compatibility (compatible or incompatible). See Table 2 for descriptive statistics.

Reaction time

Inducer locations

In the first three training blocks, we found a non-significant effect of PC, F (1, 56) = 2.51, p = 0.119, η_p^2 = 0.04, BF_{01} = 6.41 and an effect of compatibility, F (1, 56) = 696.06, p < 0.001, η_p^2 = 0.93, such that compatible trials (M = 673, SE = 9) were responded to faster than incompatible trials (M = 800, SE = 11). Most importantly, revealing the CSPC effect, PC and compatibility interacted, F (1, 56) = 8.28, p = 0.006, η_p^2 = 0.13, with the compatibility effect being larger for the MC (M = 135, SE = 5) than MI (M = 120, SE = 6) location.

Across all five blocks we found a non-significant effect of PC, F(1, 56) = 0.00, p = 0.967, η_p^2 = 0.00, BF_{01} = 6.93, and an effect of compatibility, F(1, 56) = 879.91, p < 0.001, η_p^2 = 0.94, such that compatible trials (M = 666, SE = 9) were responded to faster than incompatible trials (M = 794, SE = 11). Most importantly, revealing the CSPC effect, PC and compatibility interacted, F (1, 56) = 13.60, p < 0.001, η_p^2 = 0.20, such that the compatibility effect was larger for the MC (M = 135, SE = 5) than MI (M = 120, SE = 5) location (see Fig. 5).

Diagnostic locations

For diagnostic locations in the transfer blocks, we found no effect of location, F(1, 56) = 0.29, p = 0.593, η_p^2 = 0.01,

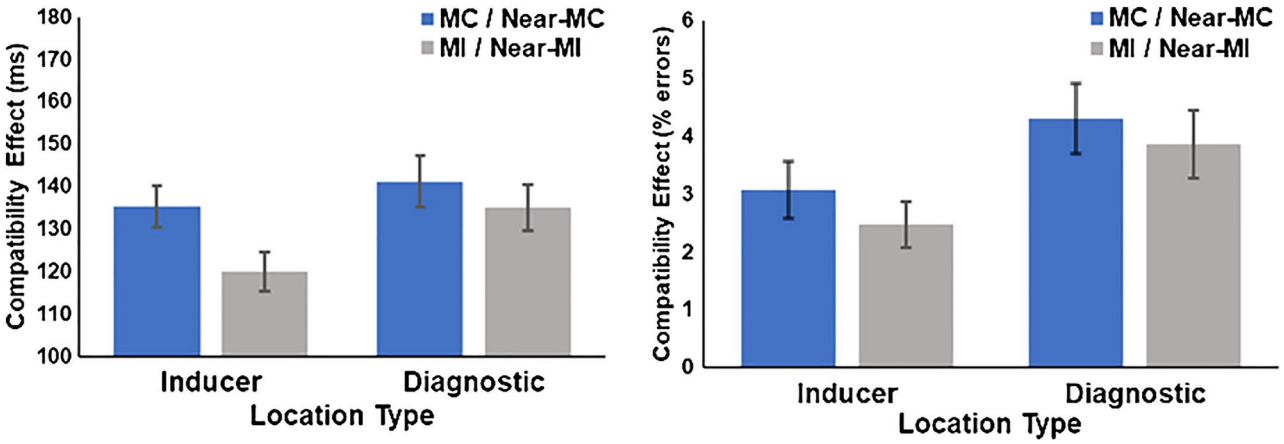

Fig. 5 Reaction time and error rate results for Experiment 1 as a function of PC and Location Type. The labels MC and MI correspond to the PC of the inducer locations while the labels Near-MC and Near-MI correspond to the diagnostic locations, which were 50% compatible each. A significant CSPC effect was observed in the inducer trials for reaction time, though it did not transfer to the diagnostic trials. We did not observe a CSPC effect in the inducer or diagnostic locations in error rate

$BF_{01} = 7.09$, but a significant effect of compatibility, $F(1, 56) = 901.13$, $p < 0.001$, $\eta_p^2 = 0.94$, such that compatible trials ($M = 745$, SE = 10) were responded to faster than incompatible trials ($M = 883$, SE = 12). Most importantly, location and compatibility did not interact, $F(1, 56) = 0.93$, $p = 0.338$, $\eta_p^2 = 0.02$, $BF_{01} = 3.45$, indicating the compatibility effect did not differ between stimuli appearing in the near-MC location ($M = 141$, SE = 6) and the near-MI location ($M = 134$, SE = 5; see Fig. 5).

Error rate

Inducer locations

The same analysis of inducer locations in the three training blocks for error rate revealed a significant effect of PC, $F(1, 56) = 7.33$, $p = 0.009$, $\eta_p^2 = 0.12$, such that trials in the MC condition ($M = 1.75\%$, SE = 0.43%) were responded to less accurately than trials in the MI condition ($M = 1.24\%$, SE = 0.34%), and a significant effect of compatibility, $F(1, 56) = 33.50$, $p < 0.001$, $\eta_p^2 = 0.37$, such that compatible trials ($M = 0.23\%$, SE = 0.08%) were responded to more accurately than incompatible trials ($M = 2.75\%$, SE = 0.49%). The two factors interacted, $F(1, 56) = 4.16$, $p = 0.046$, $\eta_p^2 = 0.07$, such that the compatibility effect in error rate was larger in the MC location ($M = 2.86\%$, SE = 0.51%) than the MI location ($M = 2.16\%$, SE = 0.41%).

In inducer locations across all five blocks, we found a significant effect of PC, $F(1, 56) = 5.57$, $p = 0.022$, $\eta_p^2 = 0.09$, such that trials in the MC condition ($M = 1.97\%$, SE = 0.43%) were responded to less accurately than trials in the MI condition ($M = 1.52\%$, SE = 0.32%) and a significant effect of compatibility, $F(1, 56) = 46.19$, $p < 0.001$, $\eta_p^2 = 0.45$, such that compatible trials ($M = 0.36\%$, SE = 0.09%) were responded to more accurately than incompatible trials ($M = 3.13\%$, SE = 0.46%). Although the two factors did not interact, $F(1, 56) = 2.68$, $p = 0.107$, $\eta_p^2 = 0.05$, $BF_{01} = 2.77$, the compatibility effects showed the same pattern seen in RT, such that the compatibility effect in error rate was larger in the MC location ($M = 3.07\%$, SE = 0.50%) than the MI location ($M = 2.47\%$, SE = 0.39%; see Fig. 5).

Diagnostic locations

For diagnostic locations in the transfer blocks, we found a non-significant effect of location $F(1, 56) = 1.18$, $p = 0.282$, $\eta_p^2 = 0.02$, $BF_{01} = 5.95$, but a significant effect of compatibility, $F(1, 56) = 59.85$, $p < 0.001$, $\eta_p^2 = 0.52$, such that compatible trials ($M = 0.24\%$, SE = 0.08%) were responded to more accurately than incompatible trials ($M = 2.75\%$, SE = 0.49%). As with the RT analyses, location and compatibility did not interact, $F(1, 56) = 0.71$, $p = 0.402$, $\eta_p^2 = 0.01$, $BF_{01} = 4.52$ (see Fig. 5).

Discussion

A significant CSPC effect was observed in reaction time for the inducer locations that were presented on the quad indicating that participants learned the control states associated with the inducer locations. However, the CSPC effect did not transfer to diagnostic locations that were on the buildings outside of the meaningful boundary. This means the presentation of a stimulus in a near-PC diagnostic location (near-MC or near-MI) did not trigger retrieval of the control state that was learned and retrieved in the nearby inducer

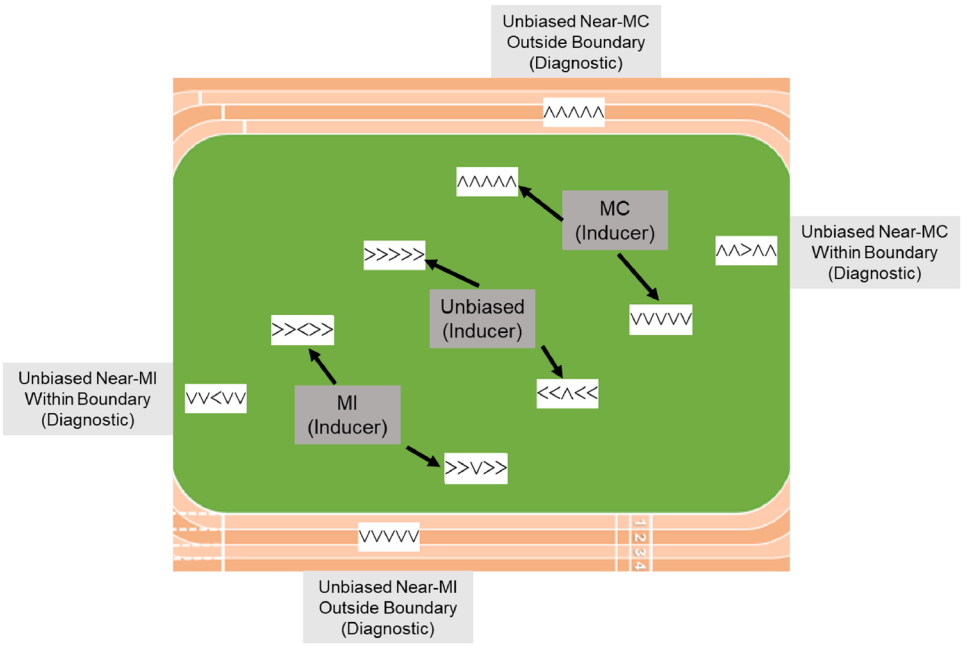

Fig. 6 A depiction of the display in Experiment 2. The background image remained on screen throughout the experiment. On each trial, a single flanker stimulus appeared on screen. Inducer locations appeared on the field. One set of diagnostic locations was on the field (within boundary), while another set of diagnostic locations was on the track (outside boundary). The inducer MC and MI locations were counterbalanced across subjects

location (MC or MI, respectively). The finding supports the boundaries for retrieval hypothesis and thereby supports a role for meaningful boundaries, but it is inconsistent with the spatial proximity and categorical coding of space hypothesis both of which anticipated transfer to diagnostic locations. Interestingly, the finding contrasts with Weidler et al. (2020) who found transfer of the CSPC effect from the inducer to diagnostic locations when the boundary comprised a rectangle or an island shape that created a line between the two location types. As anticipated, one reason for this may have been because the boundary that separated inducer and diagnostic locations in the present study was more meaningful. Consequently, the boundary may have disrupted retrieval of control states when stimuli appeared in diagnostic locations outside the boundary (in a separate semantic category).

Experiment 2

Experiment 1 found no transfer of control states across a meaningful boundary despite there being a CSPC effect for inducer locations, supporting the boundaries for retrieval hypothesis. We designed Experiment 2 to conceptually replicate and extend Experiment 1. The key question we addressed is whether meaningful boundaries are used flexibly. Specifically, will a significant CSPC effect be found for diagnostic locations if they are presented within the boundary (in the same semantic category of space as the inducer locations) but not outside the boundary? The boundaries for retrieval hypothesis predicts this pattern as control settings should be retrieved for locations inside the boundary but not outside the boundary. In contrast, the spatial proximity hypothesis and categorical coding of space hypothesis would predict an equal degree of transfer for both within boundary and outside boundary diagnostic locations (i.e., these locations are equidistant to, or are both in the same category of space [e.g., upper right] as, the inducer locations).

To address whether people use meaningful boundaries flexibly, we used a new background image and a new design (see Fig. 6). The background image was an illustration of a field surrounded by a track. The background was an illustration rather than a photograph, and the distinction between field and track was plausibly cleaner in Experiment 2 than Experiment 1. In Experiment 1, the diagnostic locations were presented outside the meaningful boundary. In Experiment 2, there were two distinct types of diagnostic locations: one type was presented within the same boundary as the inducer locations (i.e., within the field) and the second type was presented outside the meaningful boundary (i.e., outside the field [on the track]). Critically, these two kinds of diagnostic locations were equidistant from the inducer location.

Method

Participants

Sixty Washington University undergraduates (38 female, Age $M = 19.77$, $SD = 1.28$) participated for course credit. One participant's data were removed because their error rate was above 15%, and one participant's data were removed due to a data collection error in ePrime. Data from the remaining

58 participants (37 female, Age $M = 19.74$, SD = 1.29) were analyzed in the results.

Design and stimuli

Design and stimuli were the same as Experiment 1, with a few notable exceptions. First, there were now ten locations on screen where a flanker stimulus (superimposed on the white rectangle) could appear. These locations were presented along two invisible diagonal arrays. Each of the two invisible diagonal arrays was 28 cm long, and each of the locations was 5.6 cm apart from each other. The two arrays were parallel to each other, and separated by 14 cm. Second, the background image displayed an athletic field surrounded by a running track. One of the diagnostic locations in each array was presented on the field (i.e., within the boundary along with the inducer locations) and one was presented on the track (i.e., separated by a meaningful boundary from the inducer locations).

Procedure

The procedure was equivalent to Experiment 1 with a few notable exceptions. The pre-task highlighted each of the ten locations that were used in the experiment. Participants responded on a piece of paper whether the highlighted location was on the track or on the field.

The experiment started with three training blocks of 144 trials and presented stimuli in the middle three inducer locations of each of the two parallel diagonal invisible arrays (i.e., the six inducer locations). In each of the two arrays, there were 24 trials in the MC, unbiased, and MI locations. The fourth block was a transfer block, there were 240 trials total across the six inducer locations and the four diagnostic locations. There were 24 trials in each of the inducer locations and 24 trials in each of the diagnostic locations. Two of the diagnostic locations were presented on the field (referred to hereafter as *within boundary*) and two of the locations were presented on the track (referred to hereafter as *outside boundary*). The fifth block served as a booster block and was identical to training Blocks 1–3, presenting trials only in the inducer locations. The purpose was to re-strengthen CSPC learning and maximize the possibility that a CSPC effect would be found for the inducer locations, and thus transfer to diagnostic locations. This cycling between transfer blocks with diagnostic locations and booster blocks without diagnostic locations continued across the course of the next three blocks (i.e., Block 6 and 8 included diagnostic locations whereas Block 7 did not).

Results

0.66% of trials were removed in the RT trim. Analyses used a 2 × 2 repeated measures ANOVA with factors of PC (or near-PC) and trial type unless otherwise specified. See Table 3 for descriptive statistics.

Reaction time

Inducer locations

For the inducer locations in the first three training blocks we found a non-significant effect of PC, F (1, 57) = 1.68, $p = 0.201$, $\eta_p^2 = 0.03$, $BF_{01} = 6.72$, and an effect of compatibility, F (1, 57) = 1026.09, $p < 0.001$, $\eta_p^2 = 0.947$, such that compatible trials ($M = 682$, SE = 11) were responded to faster than incompatible trials ($M = 815$, SE = 13). PC and compatibility had a marginally significant interaction, F (1, 57) = 3.92, $p = 0.053$, $\eta_p^2 = 0.06$, $BF_{01} = 1.93$, such that the compatibility effect was larger in the MC condition ($M = 138$, SE = 5) than MI condition ($M = 128$, SE = 5).

For inducer locations in all training blocks (i.e., the training and booster Blocks 1, 2, 3, 5, and 7) we found a non-significant effect of PC, F (1, 57) = 1.07, $p = 0.306$, $\eta_p^2 = 0.02$, $BF_{01} = 6.86$, and an effect of compatibility, F (1, 57) = 939.89, $p < 0.001$, $\eta_p^2 = 0.943$, such that compatible trials ($M = 674$, SE = 11) were responded to faster than incompatible trials ($M = 800$, SE = 12). There was a significant interaction between PC and compatibility, F(1, 57) = 4.70, $p = 0.034$, $\eta_p^2 = 0.08$, such that the compatibility effect was larger in the MC condition ($M = 130$, SE = 5) than the MI condition ($M = 121$, SE = 5).

For inducer locations across all eight blocks, we found a non-significant effect of PC, F (1, 57) = 1.10, $p = 0.299$, $\eta_p^2 = 0.02$, $BF_{01} = 7.02$ and an effect of compatibility, F (1, 57) = 1012.88, $p < 0.001$, $\eta_p^2 = 0.95$, such that compatible trials ($M = 668$, SE = 10) were responded to faster than incompatible trials ($M = 794$, SE = 12). There was an interaction between PC and compatibility, F (1, 57) = 7.92, $p = 0.007$, $\eta_p^2 = 0.12$, such that the compatibility effect was larger in MC conditions ($M = 130$, SE = 4) than MI conditions ($M = 122$, SE = 5; See Fig. 7).

Diagnostic locations

To examine if CSPC effects transfer within or outside an established meaningful boundary, RTs from the unbiased near-MC and near-MI locations from the two transfer blocks were analyzed with a 2 × 2 × 2 repeated measures ANOVA

Table 3 Experiment 2 reaction time (ms) and error rate with standard deviations in parentheses

Location type	PC	Category	Trial type	RT	CE (RT)	Error rate	CE (error rate)
Inducer (first three blocks)	MC	Within boundary	Compatible	678 (82)	138 (35)	0.45 (1.01)	2.00 (2.45)
			Incompatible	815 (101)		2.45 (2.91)	
	MI	Within boundary	Compatible	687 (89)	128 (39)	0.21 (0.95)	1.98 (1.67)
			Incompatible	814 (96)		2.19 (2.16)	
Inducer (training blocks)	MC	Within boundary	Compatible	670 (81)	130 (34)	0.53 (1.01)	2.74 (3.15)
			Incompatible	800 (98)		3.28 (3.54)	
	MI	Within boundary	Compatible	678 (83)	121 (36)	0.38 (1.52)	2.34 (1.96)
			Incompatible	799 (93)		2.72 (2.46)	
Inducer (all blocks)	MC	Within boundary	Compatible	664 (80)	130 (30)	0.41 (0.77)	2.63 (3.17)
			Incompatible	794 (98)		3.05 (3.51)	
	MI	Within boundary	Compatible	671 (80)	122 (35)	0.33 (1.32)	2.52 (2.51)
			Incompatible	792 (92)		2.84 (2.90)	
Diagnostic	Near-MC	Within boundary	Compatible	696 (83)	151 (60)	0.36 (1.32)	4.74 (5.26)
			Incompatible	847 (116)		5.10 (5.67)	
	Near-MI	Within boundary	Compatible	705 (90)	142 (54)	0.55 (1.51)	3.07 (4.27)
			Incompatible	847 (115)		3.62 (4.23)	
Diagnostic	Near-MC	Outside boundary	Compatible	705 (90)	150 (48)	0.55 (1.20)	4.86 (5.40)
			Incompatible	854 (106)		5.41 (5.48)	
	Near-MI	Outside boundary	Compatible	714 (81)	140 (56)	0.53 (1.66)	3.79 (4.64)
			Incompatible	854 (112)		4.33 (4.98)	

CE compatibility effect, *MC* mostly compatible inducer locations; *MI* mostly incompatible inducer locations. *Near-MC* diagnostic trials near the MC inducer locations; *Near-MI* diagnostic trials near the MI inducer locations; *Inducer (in first three blocks)* inducer locations in the first three blocks of the experiment; *Inducer (in just training blocks)* inducer locations in Blocks one, two, three, five, and seven; *Inducer (in all blocks)* inducer locations in all eight blocks of the experiment; *Diagnostic* diagnostic locations in the transfer blocks. *Within boundary* locations were presented on the field along with inducer locations; *Outside boundary* locations were presented on the track outside of the field where inducer locations were presented

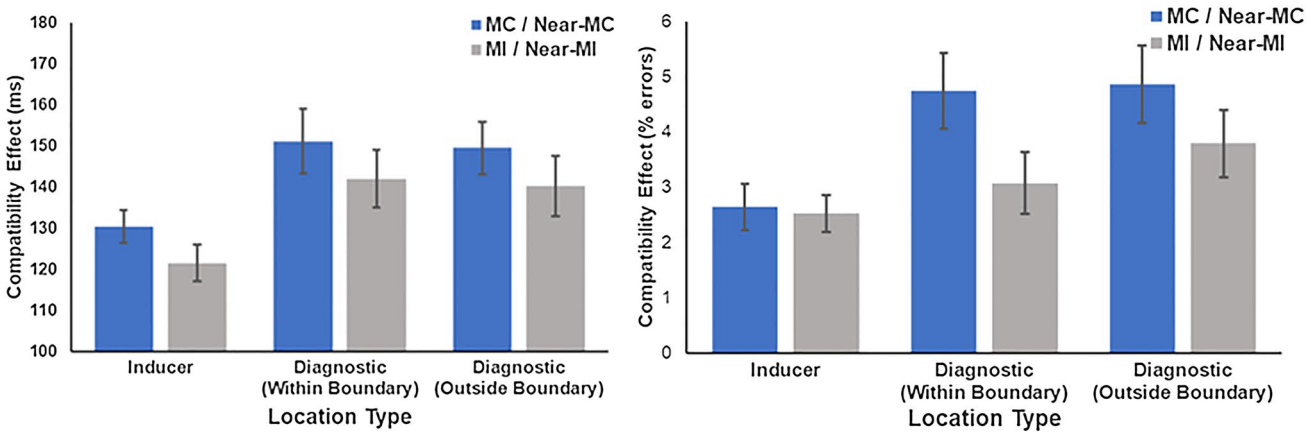

Fig. 7 Reaction time and error rate results for Experiment 2 as a function of PC and Location Type. The labels MC and MI correspond to the PC of the inducer locations. A significant CSPC effect was observed in the inducer locations in reaction time but not in error rate. The labels Near-MC and Near-MI correspond to the diagnostic locations, which were 50% compatible each. Within refers to the diagnostic locations that were presented on the field, within the same boundary as the inducer locations. Outside refers to locations that were presented on the track, separated by a boundary into a different category of space. In reaction time, we did not observe a significant CSPC effect within the boundary or outside the boundary. In error rate, we observed a significant CSPC effect within the boundary, but not outside the boundary

with factors of location, category (within or outside boundary) and trial type. There was not a significant effect of location, $F(1, 57) = 2.48$, $p = 0.121$, $\eta_p^2 = 0.04$. $BF_{01} = 8.18$. There was a significant effect of compatibility, $F(1, 57) = 708.20$, $p < 0.001$, $\eta_p^2 = 0.926$, such that compatible trials ($M = 705$, SE = 11) were responded to faster than incompatible trials ($M = 851$, SE = 14). There was a significant effect of category, $F(1, 57) = 6.44$, $p = 0.014$, $\eta_p^2 = 0.10$, such that trials inside the field ($M = 774$, $SE = 13$) were responded to faster than trials on the track ($M = 782$, SE = 12). There was not an interaction between compatibility and location, $F(1, 57) = 3.16$, $p = 0.081$, $\eta_p^2 = 0.05$, $BF_{01} = 3.57$. location and category, $F(1, 57) = 0.06$, $p = 0.808$, $\eta_p^2 = 0.00$, $BF_{01} = 6.71$. nor category and compatibility, $F(1, 57) = 0.12$, $p = 0.731$, $\eta_p^2 = 0.00$, $BF_{01} = 6.47$. There was also not a three-way interaction, $F(1, 57) = 0.00$, $p = 0.984$, $\eta_p^2 = 0.000$ $BF_{01} = 4.71$ (see Fig. 7).

Error rate

Inducer locations

For inducer locations in the first three blocks, we found a non-significant effect of PC, $F(1, 57) = 1.36$, $p = 0.248$, $\eta_p^2 = 0.02$, $BF_{01} = 4.45$, and a significant effect of compatibility, $F(1, 57) = 90.89$, $p < 0.001$, $\eta_p^2 = 0.615$, such that compatible trials ($M = 0.32\%$, SE = 0.13%) were responded to more accurately than incompatible trials ($M = 2.32\%$, SE = 0.34%). PC and compatibility did not interact, $F(1, 57) = 0.00$, $p = 0.962$, $\eta_p^2 = 0.00$, $BF_{01} = 5.01$.

For inducer locations in all training blocks (i.e., Blocks 1, 2, 3, 5, and 7) we found a marginally significant effect of PC, $F(1, 57) = 3.86$, $p = 0.054$, $\eta_p^2 = 0.06$, $BF_{01} = 3.60$, such that trials in the MC condition ($M = 1.91\%$, SE = 0.39%) were responded to less accurately than in the MI condition ($M = 1.55\%$, SE = 0.31%). There was a significant effect of compatibility, $F(1, 57) = 74.20$, $p < 0.001$, $\eta_p^2 = 0.566$, such that compatible trials ($M = 0.46\%$, SE = 0.17%) were responded to more accurately than incompatible trials ($M = 3.00\%$, SE = 0.40%). PC and compatibility did not interact, $F(1, 57) = 1.25$, $p = 0.268$, $\eta_p^2 = 0.021$, $BF_{01} = 3.19$.

The same analysis of inducer locations across all eight blocks revealed a non-significant effect of PC, $F(1, 57) = 0.85$, $p = 0.362$, $\eta_p^2 = 0.02$, $BF_{01} = 6.41$, and a significant effect of compatibility, $F(1, 57) = 56.48$, $p < 0.001$, $\eta_p^2 = 0.50$, such that compatible trials ($M = 0.37\%$, SE = 0.14%) were responded to more accurately than incompatible trials ($M = 2.95\%$, SE = 0.42%). PC and compatibility did not interact, $F(1, 57) = 0.16$, $p = 0.694$, $\eta_p^2 = 0.00$, $BF_{01} = 4.79$ (see Fig. 7).

Diagnostic locations

To examine if CSPC effects transfer within or outside an established meaningful boundary, error rates from the unbiased near-MC and near-MI locations from the two transfer blocks were analyzed with a 2 × 2 × 2 repeated measures ANOVA with factors of location, category (within or outside boundary) and trial type. There was a significant effect of location, $F(1, 57) = 5.93$, $p = 0.018$, $\eta_p^2 = 0.09$, such that near-MC trials ($M = 2.73\%$, SE = 0.62%) were responded to less accurately than near-MI trials ($M = 2.09\%$, SE = 0.46%). There was a significant effect of compatibility, $F(1, 57) = 63.73$, $p < 0.001$, $\eta_p^2 = 0.53$, such that compatible trials ($M = 0.46\%$, SE = 0.19%) were responded to more accurately than incompatible trials ($M = 4.36\%$, SE = 0.66%). There was no effect of category, $F(1, 57) = 2.32$, $p = 0.133$, $\eta_p^2 = 0.04$, $BF_{01} = 6.88$. There was an interaction between compatibility and location, $F(1, 57) = 8.84$, $p = 0.004$, $\eta_p^2 = 0.134$, such that the compatibility effect was larger in near-MC conditions ($M = 4.80\%$, SE = 0.70%) than in near-MI conditions ($M = 3.43\%$, SE = 0.58%). There was not an interaction of location and category, $F(1, 57) = 0.04$, $p = 0.844$, $\eta_p^2 = 0.001$, $BF_{01} = 6.45$, nor an interaction of category and compatibility, $F(1, 57) = 1.09$, $p = 0.301$, $\eta_p^2 = 0.02$, $BF_{01} = 5.57$. There was also not a 3-way interaction, $F(1, 57) = 0.40$, $p = 0.529$, $\eta_p^2 = 0.01$, $BF_{01} = 4.32$ (see Fig. 7).

Discussion

Based on the boundaries for retrieval hypothesis, we predicted that transfer of the CSPC effect should occur for diagnostic locations within the meaningful boundary where the inducer locations were positioned (field) but not for diagnostic locations outside that boundary (track). In contrast, both the spatial proximity and categorical coding of space hypotheses predicted a significant CSPC effect for the inducer and the diagnostic locations, irrespective of whether those locations are within the boundary or outside the boundary. In reaction time, a CSPC effect was found for inducer locations, but it was not found for the diagnostic locations outside the boundary, consistent with the boundaries for retrieval hypothesis. However, a CSPC effect was also not found for the within boundary locations, which supports neither the boundaries for retrieval hypothesis nor either of the other hypotheses. In error rate, the compatibility effect was larger overall in the near-MC locations than near-MI locations, and this effect did not differ based on the type of diagnostic location. This suggests that for error

rate, diagnostic locations nearer the MC inducer locations appeared to trigger retrieval of the same control state as the MC inducer location (and conversely, diagnostic locations nearer the MI inducer location triggered retrieval of the same control state as the MI inducer location) irrespective of their location within or outside the boundary, which is consistent with the spatial proximity and categorical coding of space hypotheses. However, this effect was found only for error rate and thus the result does not provide strong evidence for these hypotheses.

It was surprising that a CSPC effect in RT was not found for the within boundary diagnostic locations, considering that the boundaries for retrieval hypothesis, spatial proximity hypothesis, and categorical coding of space hypothesis all anticipated this result. One potential reason this effect may not have been observed is because overall learning of the control states associated with the inducer locations was relatively weak. There was not a significant CSPC effect in the first three training blocks ($p = 0.053$; $\eta_p^2 = 0.06$ and the Bayesian analysis provided anecdotal support for the null), which means that upon presentation of the first transfer block (Block 4; i.e., the first occasion that stimuli were presented in diagnostic locations) participants had not robustly learned the PCs of the inducer locations. Without such learning, it can hardly be expected that transfer would occur even for within boundary diagnostic locations. Considering all five training blocks (first three plus booster training blocks 5 and 7), there was a significant CSPC effect ($p = 0.034$; $\eta_p^2 = 0.08$) for the inducer locations, but it was relatively weak in comparison to previous studies that *did observe transfer* using similar positioning of locations ($\eta_p^2 = 0.38$, 0.49, and 0.67 in Weidler et al., 2020, Experiments 1, 2, and 3, respectively). Only when all blocks were considered in the current experiment (including transfer blocks with diagnostic trials) was the CSPC effect for inducer locations highly significant ($p = 0.007$) and even then, it was smaller than previous studies ($\eta_p^2 = 0.12$).

The key point is that the non-significant (initially) and relatively weaker overall CSPC effect provides preliminary and indirect support for the second hypothesis discussed in the introduction section, the attenuated learning hypothesis. Namely, meaningful boundaries may have encouraged participants to organize experiences within the boundary into one (meaningful) bin rather than learn the PCs of each inducer location. The inducer locations within the field were 50% compatible on average, with four of the eight locations on the field being exactly 50% compatible. If participants binned all experiences together from locations on the field rather than separately binning experiences for each location on the field, then a CSPC effect should not be found. Rather, the control state that would be episodically retrieved for a new trial in *any* inducer location would be one based on learning that the entire field is 50% congruent (i.e., an intermediate/PC 50 state). The fact that the CSPC effect for the inducer locations was small but nonetheless reached significance when considering all blocks of the task suggests that learning of the location-specific control states occurred (e.g., at least some participants learned location-specific control states within the field and did not group all locations together); however, the resulting control states, though different, were perhaps more similar across MC and MI locations than in prior work that did not include meaningful boundaries.

Experiments 3a and 3b

The preceding findings provide suggestive evidence that a meaningful boundary may weaken the CSPC effect for locations within the boundary consistent with the attenuated learning hypothesis. We aimed to test this claim more directly in Experiment 3. In previous experiments, we used the training blocks (presentation of stimuli in inducer locations only) to facilitate learning of location-specific control states and then later assessed transfer of these states to diagnostic locations in the transfer blocks. In Experiments 3a and 3b, we fully removed the diagnostic locations and transfer blocks, and we compared the CSPC effect for inducer locations (training blocks) in two distinct learning environments. As we reasoned earlier, a meaningful boundary might interfere with or preclude learning of the control states for the inducer locations positioned within the boundary because the boundary may encourage participants to group all inducer locations within the boundary into one bin (rather than learning the unique PCs and associated control states for each location). To directly examine this possibility, we manipulated the background on which the locations were superimposed. In Experiment 3a, there was a white background on screen. In Experiment 3b, all locations appeared within the meaningful boundary of the track that was presented in Experiment 2. Across Experiments 3a and 3b, the locations were otherwise identical.

If use of a meaningful boundary that creates two distinct semantic categories of space promotes the dumping of inducer locations into a single bin (representing the field in this case), a significant CSPC effect should be observed in Experiment 3a (white background) but not in Experiment 3b (meaningful boundary) consistent with the attenuated learning hypothesis. Additionally, comparing the results between Experiments 3a and 3b, we should observe a three-way interaction of Experiment, PC, and Trial Type, such that the difference between compatibility effects in MC and MI locations (i.e., the CSPC effect) will be larger in Experiment 3a than in Experiment 3b.

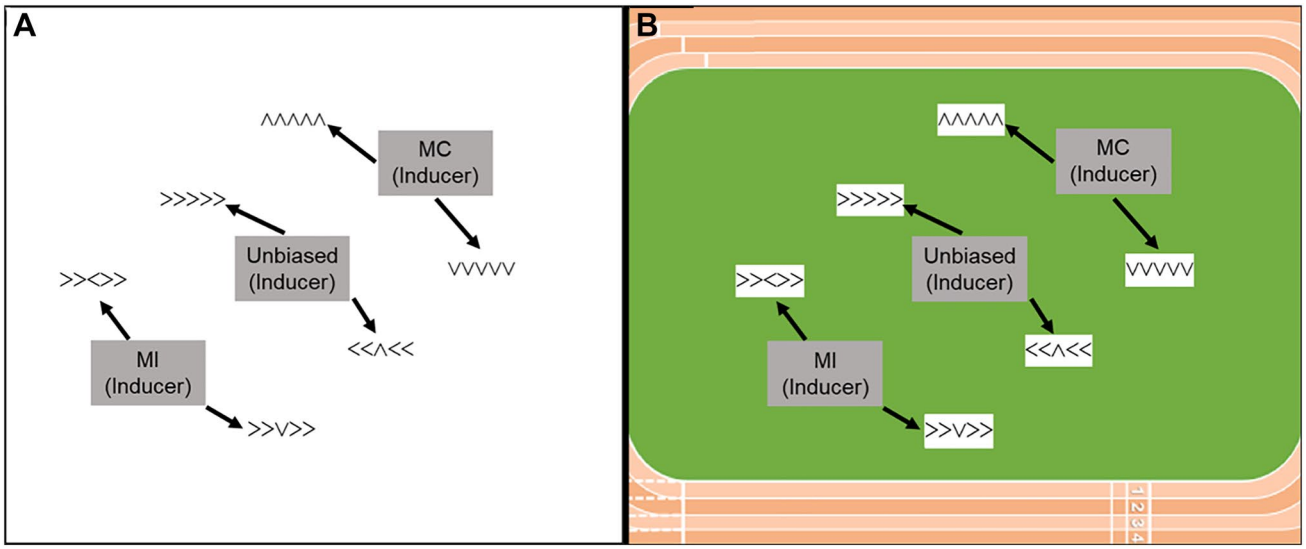

Fig. 8 A depiction of the displays used in Experiments 3a and 3b. In Experiment 3a (see Panel A), a white background was presented on screen. In Experiment 3b (see Panel B), the background image of a track and field from Experiment 2 was presented on screen. The background image remained on screen throughout the experiment. On each trial, a single flanker stimulus appeared on screen. The inducer locations were presented in the same locations in Experiments 3a and 3b. The inducer MC and MI locations were counterbalanced across subjects

Method

Participants

In Experiment 3a, 73 Washington University undergraduates (45 female, Age $M = 19.48$, SD = 1.17) participated for course credit. One participants' data were removed because their error rate was above 15%, and three participants were excluded for not using their right index finger to respond. Data from the remaining 69 participants (42 female, Age $M = 19.49$, SD = 1.17) were analyzed.

In Experiment 3b, 64 Washington University undergraduates (43 female, Age $M = 19.64$, SD = 1.12) participated for cash or course credit. One participant's data were excluded for not using their right index finger to respond. Data from the remaining 63 participants (42 female, Age $M = 19.61$, SD = 1.11) were analyzed.

Design and stimuli

The design and stimuli were similar to Experiments 1 and 2 with a few notable exceptions. There were six locations used in the study, equivalent to the six inducer locations in Experiment 2. The computer monitor had different dimensions than the one used in Experiments 1 and 2. The monitor was 25 cm tall and 44.3 cm long. The locations were presented on two 15.5 cm diagonal arrays where the inducer locations were 7.75 cm away from the center location. The two diagonal arrays were parallel to each other, but separated by 14.5 cm. In Experiment 3a, the background image was a white background that covered the whole screen. In Experiment 3b, the background image was the track and field image that was used in Experiment 2. See Fig. 8 for a depiction.

Procedure

The procedure was the same as in Experiment 2 with a few notable exceptions. While Experiments 1 and 2 had participants participate in the room with the experimenter, participants were alone in individual rooms within a group testing room in Experiments 3a and 3b. As in previous experiments, participants were instructed to respond with just their right index finger. After the experiment, participants were asked whether they only used their right index finger throughout the experiment. Data from the three participants in Experiment 3a and one participant in Experiment 3b who responded "no" to this question were removed from the analysis. Second, there was no pre-task before the flanker task. Also, since Experiments 3a and 3b were interested in only the learning of the CSPC signal and not the transfer of those learned control states, the experiment comprised only training blocks (i.e., first three blocks of Experiments 1 and 2). The three blocks were 144 trials each. In each block, in each of the two arrays, there were 24 trials in the MC, unbiased, and MI locations. There were no diagnostic locations used in this design.

Table 4 Experiments 3a and 3b reaction time (ms) and error rate with standard deviations in parentheses

Experiment	PC	Trial type	RT	CE (RT)	Error rate	CE (Error rate)
Experiment 3a	MC	Compatible	634 (74)	166 (50)	0.42 (1.08)	3.72 (5.89)
		Incompatible	801 (96)		4.14 (6.52)	
	MI	Compatible	650 (79)	143 (42)	0.78 (1.76)	3.17 (4.48)
		Incompatible	794 (92)		3.96 (5.24)	
Experiment 3b	MC	Compatible	673 (91)	133 (39)	0.41 (0.82)	2.78 (3.49)
		Incompatible	806 (99)		3.19 (3.62)	
	MI	Compatible	672 (90)	126 (44)	0.38 (1.26)	2.79 (3.27)
		Incompatible	798 (102)		3.17 (3.26)	

CE compatibility effect; *Experiment 3a* locations were presented with a white background image; *Experiment 3b* locations were presented on the background image of the track and field from Experiment 2. All locations in Experiment 3b were presented on the field and surrounded by the track; *MC* mostly compatible inducer location; *MI* mostly incompatible inducer location

Results

Only trials with RTs greater than 200 and less than 2000 ms were included. 0.49% of trials were removed in Experiment 3a, and 0.63% of trials were removed in Experiment 3b. See Table 4 for descriptive statistics.

Experiment 3a (white background)

In reaction time, we analyzed the inducer locations across the three training blocks. The analysis revealed a non-significant effect of PC, $F(1, 68) = 3.22$, $p = 0.077$, $\eta_p^2 = 0.05$, $BF_{01} = 7.14$, and an effect of compatibility, $F(1, 68) = 946.40$, $p < 0.001$, $\eta_p^2 = 0.93$, such that compatible trials ($M = 643$, SE = 9) were responded to faster than incompatible trials ($M = 797$, SE = 11). Most importantly, revealing the typical CSPC effect, PC and compatibility interacted, $F(1, 68) = 22.19$, $p < 0.001$, $\eta_p^2 = 0.25$, with the compatibility effect being larger for the MC ($M = 166$, SE = 6) than the MI location ($M = 143$, SE = 5; see Fig. 9).

In error rate, we analyzed the inducer locations across the three training blocks. We found a non-significant effect of PC, $F(1, 68) = 0.15$, $p = 0.697$, $\eta_p^2 = 0.00$, $BF_{01} = 7.76$, and a significant effect of compatibility, $F(1, 68) = 34.61$, $p < 0.001$, $\eta_p^2 = 0.36$, such that compatible trials ($M = 0.60\%$, SE = 0.18%) were responded to more accurately than incompatible trials ($M = 4.05\%$, SE = 0.71%). The two factors did not interact, $F(1, 68) = 1.42$, $p = 0.237$, $\eta_p^2 = 0.02$, $BF_{01} = 3.35$ (see Fig. 9).

Experiment 3b (track and field background)

In reaction time, we analyzed the inducer locations across the three training blocks. The analysis revealed a non-significant effect of PC, $F(1, 62) = 2.47$, $p = 0.122$,

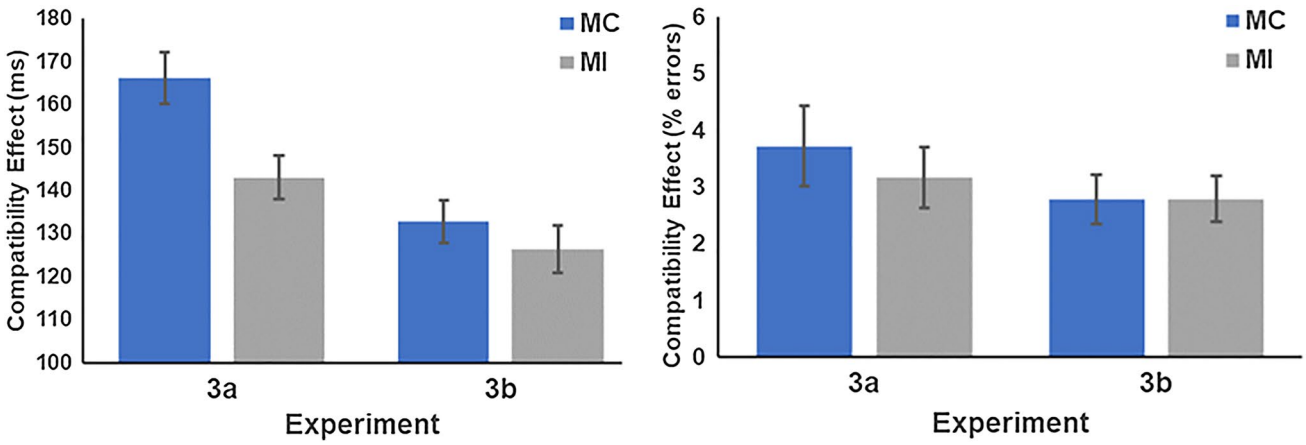

Fig. 9 Reaction time and error rate results for the MC and MI inducer locations in Experiments 3a and 3b. A significant CSPC effect was observed in Experiment 3a for reaction time, but not for Experiment 3b. We did not observe a CSPC effect in error rate for Experiments 3a and 3b

$\eta_p^2 = 0.04$, $BF_{01} = 6.75$, and an effect of compatibility, $F(1, 62) = 830.55$, $p < 0.001$, $\eta_p^2 = 0.93$, such that compatible trials ($M = 672$, SE = 11) were responded to faster than incompatible trials ($M = 802$, SE = 12). Most importantly, PC and compatibility did not interact, $F(1, 62) = 1.43$, $p = 0.236$, $\eta_p^2 = 0.02$, $BF_{01} = 3.36$, with the compatibility effect being similar for the MC location ($M = 133$, SE = 5) and the MI location ($M = 126$, SE = 6; see Fig. 9).

In error rate, we analyzed the inducer locations across the three training blocks. We found a non-significant effect of PC, $F(1, 62) = 0.01$, $p = 0.921$, $\eta_p^2 = 0.00$, $BF_{01} = 7.37$, and a significant effect of compatibility, $F(1, 62) = 59.74$, $p < 0.001$, $\eta_p^2 = 0.49$, such that compatible trials ($M = 0.40\%$, SE = 0.13%) were responded to more accurately than incompatible trials ($M = 3.18\%$, SE = 0.43%). There was no interaction between PC and compatibility, $F(1, 62) = 0.00$, $p = 0.972$, $\eta_p^2 = 0.00$, $BF_{01} = 5.44$ (see Fig. 9).

Combined analysis

Experiments 3a and 3b differed only in having different sets of participants and in the presence or absence of a meaningful boundary (as created by the background image). We ran a combined analysis to see if the CSPC effect differed between Experiments 3a and 3b. We ran a 2 × 2 × 2 mixed-effects ANOVA with within-subjects factors of PC and compatibility, and a between-subjects factor of Experiment.

In reaction time, there was not a main effect of experiment, $F(1, 130) = 1.28$, $p = 0.261$, $\eta_p^2 = 0.01$, $BF_{01} = 3.07$. There was a significant interaction of PC and experiment, $F(1, 130) = 5.64$, $p = 0.019$, $\eta_p^2 = 0.04$, such that the difference in average RT between MC and MI locations was smaller in Experiment 3a ($M = -4.96$, SE = 2.76) than in Experiment 3b ($M = 4.40$, SE = 2.80). There was a significant interaction of compatibility and experiment, $F(1, 130) = 13.489$, $p < 0.001$, $\eta_p^2 = 0.09$, such that the compatibility effect was larger in Experiment 3a ($M = 155$, SE = 5) than in Experiment 3b ($M = 130$, SE = 5). There was a significant interaction of compatibility, PC, and experiment, $F(1, 130) = 5.35$, $p = 0.022$, $\eta_p^2 = 0.04$, such that the interaction between compatibility and PC was significant in Experiment 3a but not in Experiment 3b.

In error rate, there was not a main effect of experiment, $F(1, 130) = 1.36$, $p = 0.246$, $\eta_p^2 = 0.01$, $BF_{01} = 3.53$. There was a non-significant interaction of PC and experiment, $F(1, 130) = 0.12$, $p = 0.735$, $\eta_p^2 = 0.00$, $BF_{01} = 7.19$. There was a non-significant interaction of compatibility and experiment, $F(1, 130) = 0.89$, $p = 0.348$, $\eta_p^2 = 0.01$, $BF_{01} = 3.05$. There was a non-significant interaction of compatibility, PC, and experiment, $F(1, 130) = 0.76$, $p = 0.385$, $\eta_p^2 = 0.01$, $BF_{01} = 4.71$.

Discussion

Design-wise, Experiments 3a and 3b differed only in terms of the background image on the screen. A significant CSPC effect for inducer locations was observed when the background was white (Experiment 3a) but there was not a CSPC effect when the locations were encompassed within a meaningful boundary (Experiment 3b). The Bayesian analyses provided substantial support for the null in Experiment 3b, and the difference in CSPC effects across experiments was confirmed by the cross-experimental analysis.[2] These findings support the attenuated learning hypothesis, and more generally a role for meaningful boundaries in the CSPC effect. The findings suggest that a meaningful boundary encourages people to group their experiences with the inducer locations in a single 50% congruent bin (i.e., representing the field) rather than distinct bins for the MC and MI locations. Accordingly, regardless of whether a stimulus is presented in the MC or MI location, in the presence of a meaningful boundary the same 50% congruent (intermediate) control setting is retrieved resulting in no CSPC effect. Said differently, learning about the location-specific proportion congruencies within the field (i.e., the fact that one location was MC, and one was MI) is attenuated in the presence of a meaningful boundary and instead, participants learn about the proportion congruence of the field overall.

[2] As a reviewer pointed out, the reduction in the CSPC effect in Experiment 3b was driven primarily by faster RTs to congruent trials in both MC and MI locations in Experiment 3a compared to 3b. The faster RT for congruent trials in the MC location in 3a compared to 3b is consistent with the interpretation that participants in 3a learned a relaxed control state for the MC location resulting in greater processing of the flanker arrows (and thus greater facilitation in the form of faster RT) compared to 3b (where overall an intermediate, 50% congruent control state was learned). It is surprising that the same speed up was observed for congruent trials in the MI location in Experiment 3a compared to 3b (again indicating greater facilitation from the flankers in 3a) considering that a more focused control state was presumably retrieved in 3a than 3b (where, again, an intermediate control state was learned) resulting in greater filtering of the flankers in 3a. However, it is important to note that theorizing in the CSPC literature has tended to focus on differences in the overall CSPC effect (reflecting differences in compatibility effects between locations) and not differences in select trial types, unlike for example the item-specific proportion congruence (ISPC) literature which has observed fairly consistent patterns of ISPC effects and theorizing exists that anticipates specific patterns of ISPC effects based on differences in select trial types (see, e.g., Bugg & Dey, 2018; Bugg et al., 2011a, 2011b; Suh & Bugg, 2021). Here, the difference in the overall CSPC effect is in the direction consistent with the interpretation that CSPC effects are weaker when a meaningful boundary is present (i.e., in Exp 3b compared to 3a).

General discussion

In the current study, we examined whether a meaningful boundary affects how people bin their experiences during a task and thereby modulates CSPC effects at inducer and diagnostic locations. Our findings provided support for the boundaries for retrieval hypothesis and the attenuated learning hypothesis, both of which ascribe a role to meaningful boundaries in affecting the CSPC effect. The clearest support for the boundaries for retrieval hypothesis came from Experiment 1 where a CSPC effect was observed for inducer locations on a campus quad, but the effect did not transfer from these locations to diagnostic locations on buildings outside of the quad. While this contrasts with Weidler et al. (2020) who found transfer regardless of the type of boundary they used (rectangle, island formation), it is consistent with our proposition that a meaningful boundary may be more likely than a non-meaningful boundary to disrupt retrieval of control states for stimuli presented outside the boundary.

The results of Experiment 2 were less clear. In RT, we did not find transfer of the CSPC effect from inducer locations in a field to diagnostic locations in a surrounding track, consistent with the boundaries for retrieval hypothesis. However, we also did not observe transfer for diagnostic locations within the boundary (the field), which is inconsistent with this hypothesis as well as the spatial proximity hypothesis and categorical coding of space hypothesis (i.e., participants bin based on general categories of space like upper right and lower left, for example). We did find larger compatibility effects in error rate for near-MC diagnostic locations within *and* outside the boundary compared to near-MI diagnostic locations, which is consistent with the spatial proximity and categorical coding of space hypotheses.

Regarding the attenuated learning hypothesis, which posits that a meaningful boundary may encourage participants to bin all experiences within the boundary into a single bin such that learning of the location-specific PCs for inducer locations is attenuated, Experiments 2 and 3 provided suggestive and direct evidence, respectively. In Experiment 2, the CSPC effect for inducer locations within the meaningful boundary was initially (i.e., following training and prior to the first transfer block) non-significant, with the Bayes factor suggesting anecdotal support for the null. The CSPC effect became significant with additional experience, though the effect was relatively weak in comparison to prior studies that used a similar design and found transfer to diagnostic locations (Weidler et al., 2020). In Experiment 3, we directly tested the attenuated learning hypothesis by comparing the CSPC effect for inducer locations in a version of the task that included a meaningful boundary (Experiment 3b) and a version that did not (Experiment 3a). Consistent with the hypothesis, we found that a significant CSPC effect was observed selectively in the absence of a meaningful boundary, and the effect differed significantly across the two experiments. This finding provides the first direct evidence that the presence of a meaningful boundary in a CSPC design may limit learning about the PC of inducer locations.

In sum, the findings suggest that meaningful boundaries affect CSPC effects in at least two ways: the boundaries can disrupt retrieval of associated control states when stimuli appear in nearby locations outside the boundary, and the boundaries can attenuate learning of location-specific PCs for locations within the boundary. It is possible that disrupted retrieval and attenuated learning can simultaneously contribute to patterns of CSPC effects such as those observed in Experiments 1 and 2. For example, while we interpreted the lack of transfer of the CSPC effect to locations outside the boundary in Experiment 1 as supporting the boundaries for retrieval hypothesis because there was clear evidence for learning of the location-specific PCs (i.e., a highly significant CSPC effect for inducer locations), it remains possible that some attenuation of learning of the CSPC effect for the inducer locations occurred due to the presence of the boundary and that this too may have contributed to the lack of transfer. Future research might adapt the current method to address this possibility. For example, one might withhold the meaningful boundary during inducer blocks such that it cannot attenuate learning, and then present the image with the meaningful boundary in subsequent diagnostic blocks.[3] If there is still a null difference at diagnostic locations in this design (i.e., no CSPC effect), one would have stronger grounds to conclude that the meaningful boundary uniquely disrupted transfer consistent with the boundaries for retrieval hypothesis.

Another opportunity for learning in a CSPC paradigm

A novel conclusion from the present study is that presenting inducer locations that vary in PC within a meaningful boundary reduces the CSPC effect for these locations. An important question is why a meaningful boundary has this effect. There are multiple opportunities for learning within a CSPC paradigm (see Bugg et al., 2020, for a discussion of location, item, and location-item conjunctive learning), that is, multiple ways in which participants can organize their experiences during a task. For a CSPC effect to be found for inducer locations, participants must learn the association between specific inducer locations and their unique PCs (i.e., bin according to the inducer's location). In Experiment 3a, where flanker stimuli appeared on a white background, the significant CSPC effect indicates that participants

[3] We thank an anonymous reviewer for this suggestion.

learned this association. In Experiment 3b where flanker stimuli appeared on the field inside a track, there was not a CSPC effect indicating that participants did not learn this association.

We attribute the difference in the CSPC effect between Experiments 3a and 3b to the availability of another opportunity for learning (another way to bin) in Experiment 3b. Specifically, participants could learn the association between the overall field and PC (i.e., bin their experiences by the meaningful category of space in which the inducer locations were positioned) such that a stimulus presented in any inducer location retrieves the same intermediate control setting associated with the field as a whole (resulting in no CSPC effect). The difference in how participants binned their experiences in Experiments 3a and 3b may stem from the relative salience of the available bins (see Bugg & Dey, 2018, for a discussion of relative salience). Location may have been the most salient cue in Experiment 3a, while the salience of the meaningful category may have superseded location in Experiment 3b. Another possibility is that it may simply be more efficient to bin according to a single category of space (the quad or field) than according to multiple distinct locations.

Limitations and future directions

There are a few notable limitations. One is that in Experiment 1 we used a background image that was meaningful both in the sense of our definition and in the sense that participants had pre-existing knowledge of the space prior to the experiment. Experiments 2 and 3, however, which used an illustrated track-and-field, were not limited in this fashion. Accordingly, it does not appear that pre-existing knowledge of the space is necessary to observe effects of meaningful boundaries on the CSPC effect.

Second, our conclusions center on the role of meaningful boundaries but we cannot fully disentangle meaning from perceptual elements of the display such as color and other features that contributed to the meaningfulness of the boundaries. For example, consider that in Experiment 1 the inducer locations were superimposed on grass and the diagnostic locations were superimposed on buildings. Similarly, in Experiment 2 the inducer locations were superimposed on a green space representing grass and the diagnostic locations were superimposed on an orange space with shaded lines and numbers representing track lanes. Possibly these perceptual differences alone may have delineated the two spaces and disrupted retrieval of control states in the diagnostic locations outside the boundary. It is important to examine this possibility in future research. For example, one could create spaces within and outside the boundary that differ perceptually but not in a meaningful way (e.g., using scrambled features from current images). Alternatively, one could color the background inside the boundary one color and that outside the boundary another color (i.e., approximating the track-and-field image without the specific colors or details that establish the outside as the track, for example). If the meaningfulness of the boundaries is the critical element, then transfer of the CSPC effect to diagnostic locations outside the boundary should occur in these cases.

Third, we cannot rule out that contingency learning (learning of complex stimulus–response associations) could be making some contribution to the CSPC effects observed in our experiments since we did not use novel items (stimuli) in the inducer locations (see Braem et al., 2019, for a discussion of confound-minimized designs). However, this possibility does not undermine our conclusions about how meaningful boundaries affect the binning of experiences during the task, the magnitude of the CSPC effect in inducer locations, or transfer of the effect from inducer to diagnostic locations.

The results of the current study imply that participants may bin their experiences within meaningful boundaries into a single bin, thereby diluting or eliminating the distinction between MC and MI locations within the boundary. Subsequent work should harness this finding to investigate whether it could lead to approaches that can be used to boost (rather than attenuate) CSPC effects. If inducer MC locations were presented in one meaningful category (e.g., a park), and inducer MI locations were presented in a separate and distinct meaningful category (e.g., a pond), this grouping might facilitate the learning of the relevant control states for each category. In this case, the inducer locations *and* the meaningful categories of space are uniquely associated with a control state. Diagnostic locations could be presented within those meaningful categories to test whether transfer occurs within the meaningful boundaries. Transfer to diagnostic locations may be more likely in this kind of design compared to the design of Experiment 2 of the current study. In Experiment 2, inducer locations were uniquely associated with a control state but were encompassed within a shared meaningful category of space.

Conclusion

The present findings suggest that meaningful boundaries do play a role in the learning and transfer of CSPC effects. We found evidence of two ways in which meaningful boundaries affect control in a CSPC paradigm: the boundaries can disrupt retrieval of associated control states when stimuli appear in nearby locations outside the boundary as most clearly evidenced in Experiment 1, and the boundaries can

attenuate learning of location-specific PCs for locations within the boundary as Experiment 3 demonstrated. Considered in the context of the broader CSPC literature, the findings suggest that accounts of CSPC effects, including accounts of transfer of control states to novel locations in CSPC paradigms, should consider not just spatial proximity or how space is categorically coded (e.g., upper right) but additionally boundaries, and perhaps especially meaningful boundaries. Furthermore, the findings demonstrate that while CSPC effects can be reliably observed when location is the cue for control, they can also be disrupted by competing learning opportunities such as that created by the meaningful boundary in the current experiments. Continued investigation of various other design choices could yield important understanding of when and how people use location-specific information to guide control and when they do not, as well as a pragmatic guide for researchers aiming to use CSPC manipulations in their research.

Acknowledgements Special thanks to Natasha Frontera, Eva Jeliazkova, Lindsay Nobles, and Janelli Rodriguez for their time and effort on this project and their assistance with data collection. Thanks to the Cognitive Control and Aging lab for their helpful feedback on the project, and special thanks to Blaire Weidler for her insights. Data are available on OSF at https://osf.io/y7xa6/files/.

Funding Julie M. Bugg was supported by NIH AG057937.

Declarations

Conflict of interest Jackson S. Colvett declares that he has no conflict of interest. Julie M. Bugg declares that she has no conflict of interest.

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

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

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