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ORIGINAL ARTICLE

Attentional control transfers beyond the reference frame

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Abstract
Much research has shown that humans can allocate attentional control differentially to multiple locations based on the amount of conflict historically associated with a given location. Additionally, once established, these control settings can transfer to nearby locations that themselves have no conflict bias. Here we examined if these control settings also extend to nearby locations that are presented outside of the original frame of reference of biased stimuli. During training, participants first responded to biased flanker stimuli that were likely high conflict in one location and low conflict in another location. Then they were exposed to two sets of unbiased stimuli presented in novel transfer locations outside of the established reference frame of biased stimuli. Across three experiments, attentional control settings transferred beyond the reference frame including when there was a visual border (Experiment 2) or meaningful categorical distinction (Experiment 3) delineating training and transfer locations. These novel findings further support the idea that stimulus-driven attention control can be flexibly allocated, perhaps in a categorical manner.

Introduction

To navigate daily life humans must be able to employ *attentional control* to attend to crucial stimuli in the environment, while ignoring irrelevant ones. Additionally important is the ability to learn about regularities in the environment and adjust attentional control accordingly. Broadly, the current study addresses the extent to which the learning that supports attentional control transfers outside of the context in which learning occurred. For example, imagine a daily commute from your job in the city to your home in the suburbs. From experience driving that route, you have likely learned to be more vigilant about attending to stimuli crucial for successful driving (e.g., traffic signals, pedestrians in crosswalks) in the busier areas closer to work than in the relatively calmer areas closer to home. However, one day construction forces you to approach your house from a different route. Will the learned experience with your route still affect how you attend to environmental signals in this new context? Specifically, if the route forces you to drive even farther into the suburbs will you still engage a relatively relaxed attentional state (similar to the one that worked well in the calmer areas near your home) or will this new context trigger a more unbiased attentional state reflecting the unknown of this new territory?

There is ample evidence from laboratory experiments that participants learn information about the environment and adjust cognitive control appropriately. However, it is an open question whether this learning extends beyond the frame in which it was learned (i.e., the reference frame), and this is the question the current research seeks to answer. One example of learning about the environment is the finding that different cognitive control settings can be adopted for different locations in space depending on the expected level of conflict (see Bugg & Crump, 2012, for a review). In this context-specific proportion compatibility paradigm, participants are asked to perform, for example, a flanker task in which they indicate the direction of the central arrow in a string of arrows, and the stimuli appear randomly in multiple locations in space. C*ompatible* trials—in which all the arrows face the same direction—are relatively easy compared to *incompatible trials*—in which the target arrow faces a different direction from the flanking arrows and cognitive control is needed to resolve the conflict (e.g., Eriksen & Eriksen, 1974). Level of conflict is manipulated by altering the proportion compatibility (PC), or ratio of compatible to incompatible trials, in different areas of space. The behavioral pattern indicating participants adjusted cognitive control based on PC is a reduced flanker compatibility

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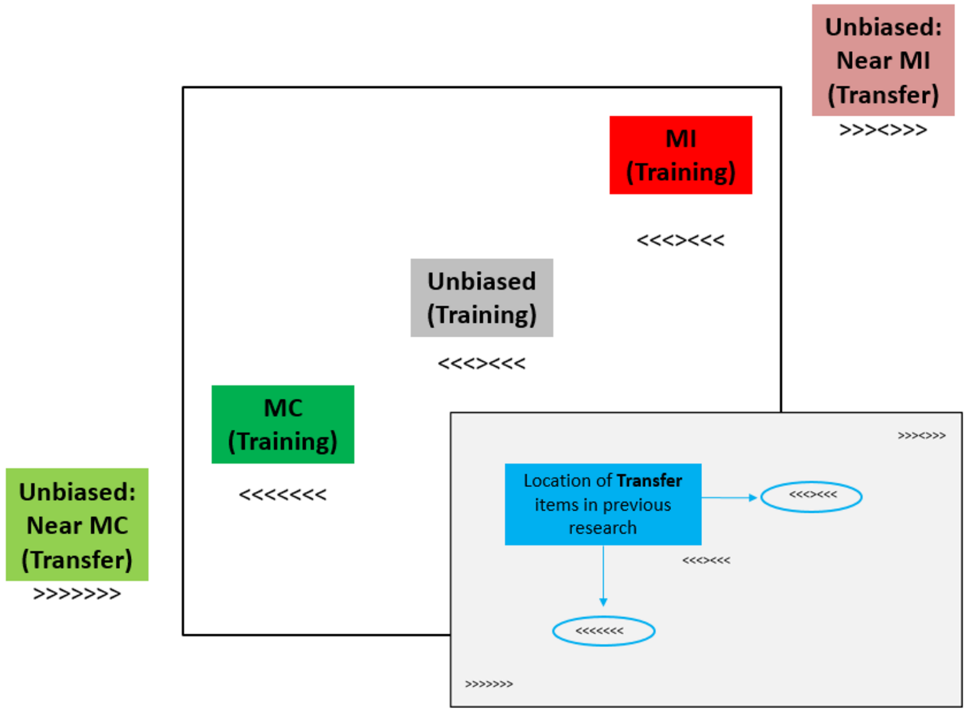

Fig. 1 Depiction of method. On each trial a single, black, flanker stimulus appeared on screen. The outside border depicts the border of the monitor. The "box" (inside border) around the training items only appeared in Experiment 2 (stimuli appeared on an entirely blank screen in Experiment 1). The insert depicts the location of transfer items in previous research (Weidler & Bugg, 2016) for comparison. Location of MC versus MI stimuli was counterbalanced across subjects. Stimuli not shown to scale

effect (i.e., heightened control) in the location associated with greater conflict (referred to as the *mostly incompatible* [MI] location) compared to the location associated with less conflict (referred to as the *mostly compatible* [MC] location; e.g., Corballis & Gratton, 2003; Crump, Gong, & Milliken, 2006). This *stimulus-driven* (i.e., triggered when the stimulus appears) effect is believed to occur because a relatively more relaxed and broad attentional state (i.e., one that allows in more information from the flankers) is triggered when a stimulus appears in the MC location compared to the relatively more stringent and narrow one (that allows less information from the flankers) when a stimulus appears in the MI location.

One finding supporting the idea that this location-specific proportion compatibility (LSPC) effect reflects flexible adjustments in cognitive control (versus for example, complex stimulus–response learning; e.g., Schmidt & Besner, 2008) is that these effects *transfer*—or extend—beyond the specific MC or MI biased stimuli to unbiased (i.e., equal proportion of compatible and incompatible) novel stimuli that appear in the same locations as biased items (Crump, Brosowsky, & Milliken, 2017; Crump & Milliken, 2009; see also Cañadas, Rodriguez-Bailon, & Milliken, 2013; but see Hutcheon & Spieler, 2017). In the present investigation, we focus on transfer of the LSPC effect to PC unbiased items in novel locations in space.

To our knowledge only one[1] prior study has demonstrated transfer of the LSPC effect to novel locations in the LSPC paradigm (Weidler & Bugg, 2016). In that study participants saw flanker stimuli appear in multiple locations in space along an invisible linear function (e.g., bottom left area of screen, central, and top right area of the screen). The stimuli at one endpoint of the function were MI (i.e., high conflict) biased whereas the stimuli at the other endpoint of the function were MC (i.e., low conflict) biased. Then, later in the experiment, these stimuli were presented in an unbiased (50% compatible) format in new locations along the invisible function either *closer* to the MC or *closer* to the MI endpoint of the function. Weidler and Bugg (2016) found reduced compatibility effects for the items appearing near the MI endpoint of the function than for the identical items appearing nearer the MC endpoint of the function, thus demonstrating that learned settings about conflict in certain locations can generalize to new locations in space elsewhere than the precise area of learning.

In the present study we investigate if the LSPC effect also transfers beyond the established frame of reference. More specifically, in the prior study investigating transfer of the LSPC effect to novel locations, the unbiased transfer items were presented in novel locations that fell between locations

[1] Note that Wendt, Kluwe, and Vietze (2008) presented PC-unbiased items in novel locations in space; however, they were equidistant from both MC and MI items so those authors did not examine transfer of differential control settings to new locations.

in which participants previously responded to biased items (see the insert in Fig. 1, Weidler & Bugg, 2016). Therefore, by reference frame, we (initially, but see Experiments 2 and 3) refer to the area of space defined by the biased items during the training blocks of the experiment. Will LSPC settings similarly transfer to unbiased items in novel locations that are presented outside of the trained frame of reference (i.e., to the unbiased "near MC" and "near MI" items in Fig. 1)? In terms of utility of cognition "in the wild" (e.g., driving a new route home from work) one could see how it would be advantageous for learning to generalize beyond its initial context. However, sometimes context change can serve as an important delineation for the suppression or elimination of old settings. For example, consider monitoring a radar screen for enemy threats. When a border indicates a change between countries (one of which is a bigger threat than the other) it may be important to quickly adopt a new setting based on that delineation despite their proximity.

To our knowledge only one study has examined whether cognitive control transfers beyond a reference frame and the findings from this study imply that transfer of cognitive control (i.e., LSPC settings) may not be expected in the present study. Kunde et al. (2003) asked participants to classify a *target* digit as greater or less than 5. Prior to that task, an additional *prime* number was presented briefly. This paradigm typically elicits compatibility effects—when the prime number falls on the same side of 5 as the target number, responses to the target are faster than when the prime falls on the other side of 5 (i.e., would necessitate the alternative response, as incompatible flanking arrows do on those trials in a flanker paradigm). In the paradigm of Kunde et al. primes that are never targets can cause compatibility effects. For example, when participants' targets were only ever the numbers 1, 4, 6, and 9, non-target prime numbers (i.e., 2, 3, 7, 8) additionally caused compatibility effects despite the fact they never occurred as targets. Importantly, however, for present purposes, compatibility effects did *not* occur when primes were outside of the target-established reference frame. More specifically, when targets included only the numbers 3, 4, 6, and 7 primes outside of that range (i.e., 1, 2, 8, 9) did not elicit compatibility effects (Kunde et al., 2003). If similar principles apply to the coding of space in the LSPC paradigm, then learned control settings may not be expected to transfer to stimuli in new locations presented beyond the frame of reference.

Overall, the goal of this research was to examine if attentional control can extend (transfer) beyond the frame of reference in which it is established. To investigate this, across three experiments we presented participants with flanker stimuli that appeared unpredictably in multiple locations along an imaginary linear function, as in prior research (Weidler & Bugg, 2016). However, unlike in prior research, the unbiased transfer items that appeared during the last blocks of the experiment near either the MC or MI items appeared in novel locations *outside* the trained frame of reference (i.e., further towards the end of the function than biased training items; see Fig. 1). If learning is restricted to the frame in which it is trained, then flanker compatibility effects should be equivalent for these two sets of transfer items appearing outside the frame of reference regardless of their location (because both transfer locations have the same 50% compatible and 50% incompatible proportion of trials). However, if learning of cognitive control settings can extend in a location-based manner outside of the frame of training, then flanker compatibility effects should be reduced for the set of unbiased items appearing near the high-conflict MI location than for items appearing near the low-conflict MC location.

Experiment 1

Experiment 1 was largely a replication of Experiment 1 from Weidler and Bugg (2016) with one important change. Although the transfer items still appeared nearer to the biased MC or nearer to the biased MI location, both sets of items appeared outside the area of training along the imaginary linear function.

Methods

Participants

Sixty undergraduates participated for course credit. Fifty-eight were right handed, 44 were female, and the average age was 19.40 years (SD = 1.07).

Stimuli and procedure

Participants viewed the display from approximately 60 cm. Stimuli were presented on a white background. Every trial began with a black fixation cross presented centrally for 1000 ms followed by a single flanker stimulus (seven black arrows presented in a row horizontally; 6.49° wide) that appeared until response. Participants' task was to indicate the direction of the central arrow by pressing the 2 (down), 4 (left), 6 (right), or 8 (up) key on the number pad. On compatible trials all arrows pointed in the same direction (there were four unique compatible trials) whereas on incompatible trials the six flanking arrows pointed a different direction than the central arrow (there were 12 unique incompatible trials).

Participants first completed a 12-trial practice block with four stimuli at each of the three training locations (PC bias of each location was maintained as in the training block, overall participants each saw the same set of randomly chosen six

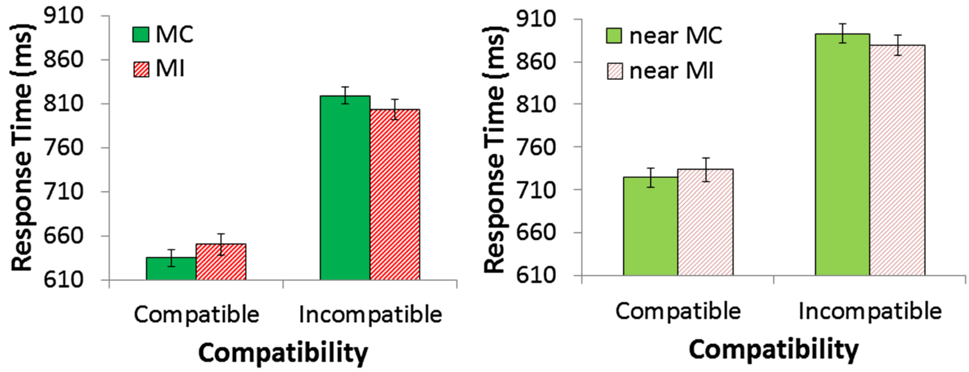

Fig. 2 Results from Experiment 1 biased locations (left panel) and unbiased transfer locations (right panel). Error bars represent *SEs*

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 three locations along a positively sloped invisible linear function (see Fig. 1). The stimuli presented centrally were 50% compatible (i.e., PC-unbiased; 6 repetitions of each compatible stimulus, 2 of each incompatible) whereas the other two locations (at 9.48 degrees away from the center of the screen 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). Location of MC versus MI location was counterbalanced across 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 18.27° away from fixation along the function *outside* of where training stimuli appeared (see Fig. 1). Both these sets of items—referred to subsequently as the *near MC* and *near MI* items—were 50% compatible.

Design

The training trials have a 2 proportion compatibility (PC: MC or MI) × 2 compatibility (compatible or incompatible) design whereas the transfer trials have a 2 location (near MC or near MI) × 2 compatibility (compatible or incompatible) design.

Results[2]

Only trials with RTs greater than 200 and less than 2000 ms were included in error rate analyses and RT analyses (trim removed < 1% of trials) and RT analyses additionally included only correct trials (cf. Bugg, 2015; Weidler & Bugg, 2016). Alpha was 0.05 for all analyses.

LSPC effects

RTs from the MC and MI[3] biased trials across all five blocks were analyzed with a 2 PC × 2 Compatibility repeated-measures ANOVA. The analysis revealed no effect of PC, $F < 1$, but a main effect of compatibility, $F(1, 59) = 1095.67$, $p < .001$, $\eta_p^2 = 0.95$ ($M_{compatible}$ = 642 ms, $M_{incompatible}$ = 811 ms). In addition, revealing the typical LSPC effect, PC and compatibility interacted, $F(1, 59) = 36.17$, $p < .001$, $\eta_p^2 = 0.38$, with the compatibility effect being larger for the MC (184 ms) than MI (153 ms) location (see Fig. 2).

[2] The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

[3] As in Weidler and Bugg (2016), RTs from central locations were not of interest or analyzed in the primary analyses because RTs were expected to be relatively fast (and compatibility effects were expected to be reduced) given that the stimuli were presented at fixation (see Corballis, & Gratton 2003 for a similar pattern). For the interested reader, it is noted that RTs for unbiased trials in the central location were faster in compatible (M = 567 ms) than incompatible trials (M = 668 ms), $t(59) = 20.41$, $p < .001$, and there were fewer errors in compatible ($M = 0.007$) than incompatible ($M = 0.028$) trials, $t(59) = 7.18$, $p < .001$. As can be seen from the means, overall RTs were faster and flanker compatibility effects (101 ms) were reduced in the central location (because the stimuli appeared at fixation) compared to either the MC (184 ms) or MI (153 ms) training locations. These observations were confirmed by reliable main effects – $F(1, 59) = 1166.04$, $p < .001$, $\eta_p^2 = 0.95$ for MC and $F(1, 59) = 1270.23$, $p < .001$, $\eta_p^2 = 0.96$ for MI – and interactions, $F(1, 59) = 240.32$, $p < .001$, $\eta_p^2 = 0.80$ for MC and $F(1, 59) = 147.98$, $p < .001$, $\eta_p^2 = 0.72$ for MI – from 2 Location × 2 Compatibility ANOVAs that compared the central unbiased trials to the MC and MI trials, respectively, across all five test blocks. Neither overall RTs, $F(1, 59) = 1.97$, $p = .166$ for the main effect of phase, nor the compatibility effect differed as a function of experiment phase; $F(1, 59) = 2.51$, $p = .119$, for the interaction from a 2 Phase (training or transfer) × 2 Compatibility repeated measures ANOVA; $M_{training}$ = 98 ms, $M_{transfer}$= 106 ms. Phase did produce a main effect in the same analysis on error rate, $F(1, 59) = 6.70$, $p = .012$, $\eta_p^2 = 0.10$ ($M_{training}$ = 0.013, $M_{transfer}$= 0.021), and marginally interacted with compatibility, $F(1, 59) = 3.06$, $p = .086$, $\eta_p^2 = 0.05$, as compatibility effects were larger in the transfer phase (0.024) than the training phase (0.017).

Table 1 Mean error rates for Experiments 1, 2 and 3

Condition	PC	Trial type	Experiment 1	Experiment 2	Experiment 3
Training	MC	Compatible	0.007 (0.001)	0.005 (0.001)	0.003 (0.001)
		Incompatible	0.084 (0.009)	0.070 (0.008)	0.073 (0.008)
	MI	Compatible	0.006 (0.002)	0.003(0.001)	0.002 (0.001)
		Incompatible	0.063 (0.007)	0.056 (0.008)	0.048 (0.005)
Transfer	Near MC	Compatible	0.011 (0.003)	0.006 (0.002)	
		Incompatible	0.078 (0.009)	0.070 (0.010)	
	Near MI	Compatible	0.007 (0.002)	0.003 (0.001)	
		Incompatible	0.070 (0.009)	0.060 (0.008)	
Transfer in water	Near MC	Compatible			0.002 (0.001)
		Incompatible			0.068 (0.009)
	Near MI	Compatible			0.002 (0.001)
		Incompatible			0.059 (0.007)
Transfer on Island	Near MC	Compatible			0.002 (0.001)
		Incompatible			0.082 (0.008)
	Near MI	Compatible			0.003 (0.001)
		Incompatible			0.055 (0.007)

*SE*s are in parentheses

MC mostly compatible, *MI* mostly incompatible

The same analysis on error rate (all error rates are expressed as probabilities) revealed a main effect of PC, $F(1, 59) = 12.31$, $p = .001$, $\eta_p^2 = 0.17$ (M_{MC} = 0.045, M_{MI} = 0.034) as well as compatibility, $F(1, 59) = 91.55$, $p < .001$, $\eta_p^2 = 0.61$ ($M_{compatible}$ = 0.007, $M_{incompatible}$ = 0.073). In addition, mirroring the RT analysis, the two factors interacted, $F(1, 59) = 11.44$, $p = .001$, $\eta_p^2 = 0.16$, because the compatibility effects in error rate were larger in the MC location (0.076) than the MI location (0.056; see Table 1).

Additionally, we examined if the LSPC effect for biased items varied as a function of phase of the experiment (i.e., training blocks versus transfer blocks), given the inclusion of the PC-unbiased transfer items in the latter blocks. A 2 Phase (training or transfer) × 2 PC × 2 Compatibility repeated measures ANOVA was performed. Reporting only the unique results concerning the phase variable, phase influenced overall RTs, $F(1, 59) = 5.01$, $p = .029$, $\eta_p^2 = 0.08$, and interacted with compatibility, $F(1, 59) = 5.38$, $p = .024$, $\eta_p^2 = 0.08$: RTs were faster in the transfer phase in the latter half of the experiment ($M_{training}$ = 733 ms, $M_{transfer}$ = 718 ms) and the compatibility effect similarly was reduced ($M_{training}$ = 173 ms, $M_{transfer}$ = 162 ms). Phase did not interact with PC, $F(1, 59) = 1.72$, $p = .195$. Most importantly, there was no three-way interaction ($F < 1$), indicating that LSPC effects were equivalent in the training (34 ms) and the transfer (28 ms) phases. In the same analysis on error rate, phase produced no main effect or interactions (all Fs < 1).

Transfer effects

In order to examine if LSPC effects transfer outside an established reference frame RTs from the unbiased near MC and near MI locations from the two transfer blocks were analyzed with a 2 Location × 2 Compatibility repeated-measures ANOVA. As in the biased trials there was no effect of location, $F < 1$, but a main effect of compatibility, $F(1, 59) = 732.28$, $p < .001$, $\eta_p^2 = 0.93$ ($M_{compatible}$ = 729 ms, $M_{incompatible}$ = 886 ms). Importantly, location and compatibility interacted, $F(1, 59) = 18.96$, $p < .001$, $\eta_p^2 = 0.24$, because the compatibility effect was larger for stimuli appearing in the near MC location (169 ms) than for the identical set of items appearing in the near MI location (146 ms; see Fig. 2).

The same analysis on error rate revealed a marginal effect of location, $F(1, 59) = 3.69$, $p = .060$, $\eta_p^2 = 0.06$ (M_{MC} = 0.044, M_{MI} = 0.038) as well as an effect of compatibility, $F(1, 59) = 80.39$, $p < .001$, $\eta_p^2 = 0.58$ ($M_{compatible}$ = 0.009, $M_{incompatible}$ = 0.073). The factors did not interact, $F < 1$.

To examine whether the transfer effect waned across blocks as a function of learning the unbiased nature of the transfer locations, a 2 Block (transfer block 1 or transfer block 2) × 2 Location × 2 Compatibility repeated measures ANOVA was performed. Focusing only on unique effects of the block variable, the analysis revealed only a main effect of block, $F(1, 59) = 9.17$, $p = .004$, $\eta_p^2 = 0.14$, with faster RTs in the second transfer block (800 ms) than the first (815 ms). Block did not interact with PC, $F < 1$, or compatibility, $F(1, 59) = 2.67$, $p = .108$, nor did it modulate the two way location by compatibility interaction ($F < 1$; transfer effect was 23 ms in block 1 and 22 ms in block 2). Block did not produce a main effect, $F(1, 59) = 2.00$, $p = .163$, or interact with any of the factors (all Fs < 1) in the same analysis on error rate.

Discussion

This experiment was the first to assess if attentional control as assessed through an LSPC effect can transfer to novel locations in space that are outside of a trained reference frame. We found evidence for such transfer: there was a reduced compatibility effect for unbiased items appearing near the MI location compared to the same set of items appearing near the MC location, even though these transfer items appeared beyond the locations (outside of the reference frame) in which biased stimuli had previously appeared. However, it may be possible that in Experiment 1 participants were not aware that the transfer items appeared "outside" of the area where they had previously seen stimuli given that stimuli appeared one at a time on screen (i.e., participants never observed the entire linear function at once). This would not undermine the novelty or importance of these findings given that typically participants are not aware of location-specific manipulations, even when all items are biased and with more simple and noticeable location manipulations such as stimuli appearing above or below fixation (e.g., Crump, Vaquero, & Milliken, 2008). However, in Experiment 2 we made the distinction between training and transfer locations more salient to examine if LSPC effects still transfer beyond the trained frame of reference.

Experiment 2

The goal of Experiment 2 was to examine if the LSPC effect transfers beyond the reference frame when the physical distinction (i.e., a visual border) between training and transfer locations is more salient. We repeated Experiment 1 with one important change—a rectangle (box) was present on screen throughout the experiment. All of the training items (locations) appeared within that box, and only the unbiased transfer items (locations) appeared outside of it. Given that much research has indicated that space can be segmented by objects similar to the box presented in this experiment (e.g., Egly, Driver, & Rafal, 1994), separating the training and transfer items with a visual border provides a more stringent test of whether attentional control will transfer beyond an established reference frame.

Method

Participants

Sixty additional undergraduates participated. Four participated for cash (the rest for course credit), 58 were right handed, 38 were female, and the average age was 19.43 years (SD = .96).

Stimuli, procedure, and design

The stimuli, procedure, and design were identical to Experiment 1 except that a black box enclosing the area of space in which the training items appeared was on the screen continuously (see Fig. 1).

Results

Analyses were as in Experiment 1. The RT trim again removed < 1% of trials.

LSPC effects

The 2 PC[4] × 2 Compatibility analysis on RT from biased items again revealed no effect of PC, $F < 1$, a compatibility effect, $F(1, 59) = 1363.24$, $p < .001$, $\eta_p^2 = 0.96$ ($M_{compatible}$ = 604 ms, $M_{incompatible}$ = 766 ms) and the PC by compatibility interaction, $F(1, 59) = 56.77$, $p < .001$, $\eta_p^2 = 0.49$, with a larger compatibility effect in the MC (177 ms) than MI (147 ms) location (see Fig. 3). The same analysis on error rate revealed an effect of PC, $F(1, 59) = 7.34$, $p = .009$, $\eta_p^2 = 0.11$ (M_{MC} = 0.037, M_{MI} = 0.030) as well as an effect of compatibility, $F(1, 59) = 73.77$, $p < .001$, $\eta_p^2 = 0.56$ ($M_{compatible}$ = 0.004, $M_{incompatible}$ = 0.063). In addition, the interaction between the two factors approached significance, $F(1, 59) = 3.98$, $p = .051$, $\eta_p^2 = 0.06$, with the error rate compatibility effect being larger for the MC (0.065) than MI (0.053) location.

[4] As in Experiment 1, there was an effect of compatibility for the central location in both RT, $t(59) = 23.53$, $p < .001$($M_{compatible}$ = 532 ms, $M_{incompatible}$ = 630 ms) and error rate, $t(59) = 5.64$, $p < .001$($M_{compatible}$ = 0.004, $M_{incompatible}$ = 0.024). Also as in Experiment 1, RTs were faster in the central locations than in either the MC, $F(1, 59) = 1209.53$, $p < .001$, $\eta_p^2 = 0.95$, or MI location, $F(1, 59) = 1289.66$, $p < .001$, $\eta_p^2 = 0.96$, and the compatibility effect was reduced in the central location (98 ms) compared to either the MC (177 ms), $F(1, 59) = 317.26$, $p < .001$, $\eta_p^2 = 0.84$, or MI (147 ms), $F(1, 59) = 99.81$, $p < .001$, $\eta_p^2 = 0.63$, location. Furthermore, neither overall RTs nor the compatibility effect in the central location differed as a function of phase, $Fs < 1$ ($M_{training}$ = 98, $M_{transfer}$ = 100.) In the same analysis error rate phase produced a marginally reliable main effect, $F(1, 59) = 3.03$, $p = .087$, $\eta_p^2 = 0.049$, with more errors in the transfer phase (0.015) than training phase (0.012). Phase and compatibility did not interact in the error data in Experiment 2 ($F < 1$).

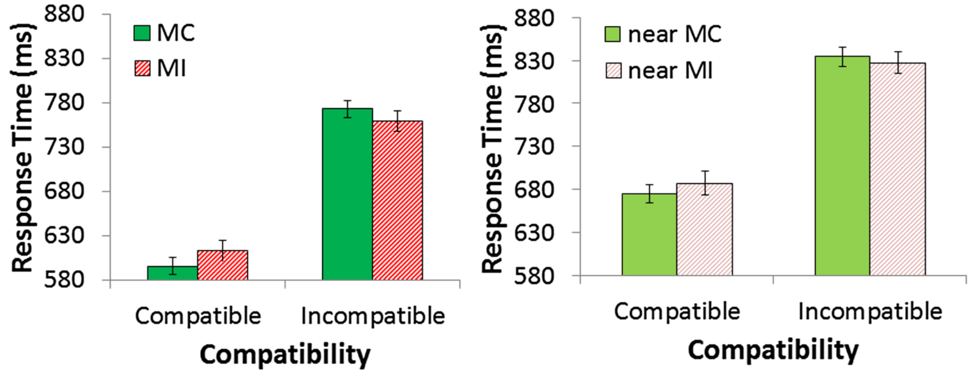

Fig. 3 Results from Experiment 2. Error bars represent *SE*s

Additionally, a 2 Phase × 2 PC × 2 Compatibly ANOVA on the RT from biased items revealed a main effect of phase, $F(1, 59) = 38.19$, $p < .001$, $\eta_p^2 = 0.39$ ($M_{training}$ = 694 ms, $M_{transfer}$ = 671 ms; we again only report unique effects of the phase variable). Unlike in Experiment 1, the compatibility effect was not reduced in the transfer phase compared to the training phase, $F < 1$, nor did phase interact with PC, $F(1, 59) = 2.66$, $p = .108$. Most critically, however, there was no three-way interaction as in Experiment 1, $F(1, 59) = 1.27$, $p = .265$. LSPC effects were equivalent in training (34 ms) and transfer (25 ms) phases. The same analysis on error rate revealed a marginal main effect of phase, $F(1, 59) = 3.21$, $p = .078$, $\eta_p^2 = 0.05$, with fewer errors in the training (0.031) than transfer phase (0.036). Phase did not interact with PC, $F(1, 59) = 1.35$, $p = .249$; however, it did marginally interact with compatibility, $F(1, 59) = 3.27$, $p = .076$, $\eta_p^2 = 0.05$, with a larger compatibility effect in the transfer (0.066) than training (0.055) phase. The three-way interaction was not reliable in the error rate data, $F(1, 59) = 1.98$, $p = .165$.

Transfer effects

To examine if LSPC effects transfer to novel locations outside the reference frame even when there is a visual boundary between training and transfer items, we again conducted a 2 Location × 2 Compatibility ANOVA on RTs from the unbiased trials presented outside of the box. The analysis revealed no effect of location, $F < 1$, but a main effect of compatibility, $F(1, 59) = 1147.38$, $p < .001$, $\eta_p^2 = 0.95$ ($M_{compatible}$ = 681 ms, $M_{incompatible}$ = 831 ms). Most importantly, as in Experiment 1, location and compatibility interacted, $F(1, 59) = 8.40$, $p = .005$, $\eta_p^2 = 0.13$, because the compatibility effect was larger for transfer items appearing outside the box near the MC location (160 ms) than for the identical items appearing outside the box near the MI location (141 ms).

The same analysis on error rate revealed an effect of location, $F(1, 59) = 4.59$, $p = .036$, $\eta_p^2 = 0.07$, with more errors near the MC (0.038) than near the MI (0.032) location, as well as an effect of compatibility, $F(1, 59) = 66.33$, $p < .001$, $\eta_p^2 = 0.53$ ($M_{compatible}$ = 0.005, $M_{incompatible}$ = 0.065). The two factors did not interact, $F(1, 59) = 1.72$, $p =. 195$, $\eta_p^2 = 0.028$.

Finally, we again examined if RTs for the unbiased transfer items differed as a function of transfer block, reporting here only unique effects of the block variable. The 2 Block × 2 Location × 2 Compatibility ANOVA revealed a main effect of block, $F(1, 59) = 17.05$, $p < .001$, $\eta_p^2 = 0.22$ (M_{block1} = 763 ms, M_{block2} = 748 ms), and a block by compatibility interaction, $F(1, 59) = 5.92$, $p = .018$, $\eta_p^2 = 0.09$ (156 ms compatibility effect in Block 1 compared to 143 ms effect in Block 2). As in Experiment 1, block did not interact with PC, $F(1, 59) = 2.05$, $p = .157$, nor was there a three-way interaction, $F(1, 59) = 1.03$, $p = .32$ (the transfer effect was 25 ms in Block 1 and 12 ms in Block 2). In the same analysis on error rate, block produced no reliable main effect, $F(1, 59) = 1.10$, $p = .298$, nor interactions with PC ($F < 1$), or compatibility, $F(1, 59) = 2.74$, $p = .103$. The three-way interaction was also not reliable, $F(1, 59) = 1.54$, $p = .219$.

Discussion

In the present experiment there was a visual border imposed between the training and transfer locations. Despite this addition the LSPC effect again transferred beyond the visual border, a type of boundary known to segregate space in other research (e.g., Egly, Driver, & Rafal, 1994), to unbiased items in new locations of space. Taken together with the results of Experiment 1, this implies that attentional adjustments that depend on the learning of the relationship between conflict and space are *not* restricted to the original reference frame.

Experiment 3

Experiments 1 and 2 showed that attentional control of conflict was insensitive to reference frames, either invisible or visible. One possible interpretation of these data is that control is unrestricted by reference frames, salient or otherwise, and transfers based on proximity within the visual field.

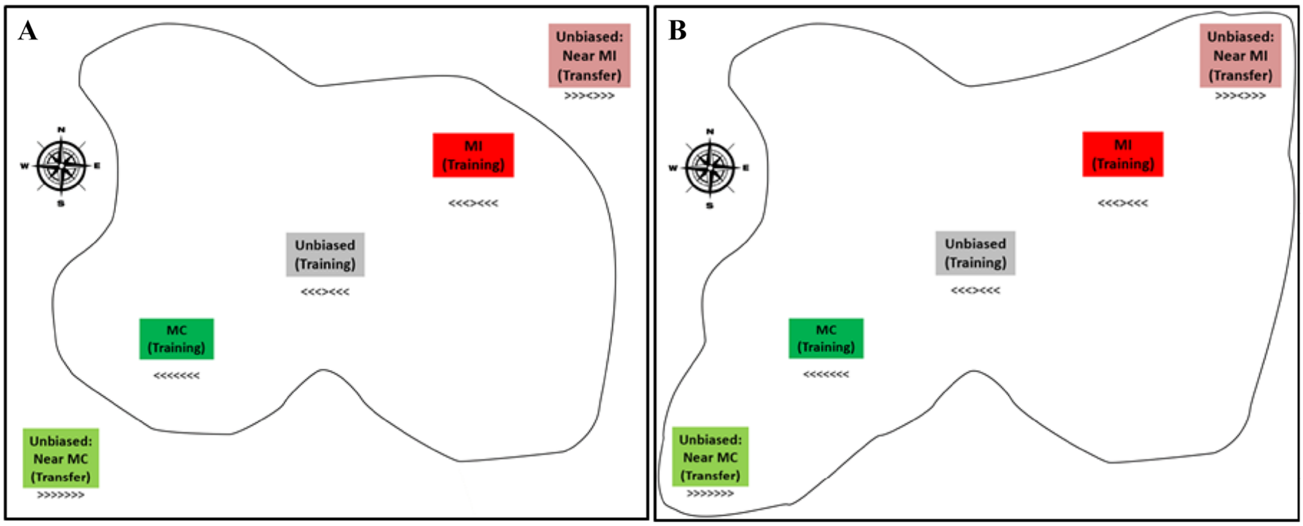

Fig. 4 Depiction of method for Experiment 3. During the training blocks, on each trial a single, black, flanker stimulus appeared on screen at one of the training locations featuring the small island in Panel a. During the transfer blocks, on each trial a flanker stimulus appeared at any of the training or transfer locations. Half of the transfer blocks displayed the small island reference frame (transfer locations were in the water) and the other half displayed the large island reference frame (transfer locations were on the island) shown in Panel b with order of presentation counterbalanced across participants

Alternatively, control may be bounded by reference frames that are salient and meaningful. In Experiment 2, although the reference frame was visible, participants were not alerted to the box or the boundaries created by it. Furthermore, the boundary did not hold any discernable meaning to the task making it potentially easy to ignore. In Experiment 3, our goal was to preserve the location of the training and transfer items while simultaneously increasing the salience/meaningfulness of the reference frame. The reference frame was a line drawing of a generic island (see Panel a, Fig. 4). The line drawing incorporated features of an island (a free form shape with rough edges as opposed to a geometric shape with straight edges) and an image of the cardinal directions appeared continuously on screen to give the drawing a "map-like" feel. We also made the reference frame salient using instructions that called participants' attention to the qualitative boundary between the space within the reference frame (referred to as the "island") and the space outside of the reference frame (referred to as the "water"). Finally, the instructions related these areas to the flanker task. On the view that control is unrestricted by reference frames, transfer was anticipated despite these changes. However, on the view that control may be bounded by reference frames that are salient and meaningful, it was predicted that these changes would deter generalization of control settings (i.e., transfer of the LSPC effect) to nearby novel locations outside of the reference frame (i.e., in the water). Given this prediction, we also included transfer blocks where the transfer locations were within the island (see Panel b, Fig. 4 and Method section for more detail about how this manipulation was employed). If control is indeed prevented from generalizing "off the island", then these blocks allow a comparison condition in which transfer is expected if participants can update the reference frame.

Method

Participants

Sixty additional undergraduates participated for course credit. All 60 participants were right handed, 52 were female, and the average age was 19.55 years (SD = 1.12).

Stimuli and procedure

Other than the exceptions noted below, the stimuli and procedure were identical to Experiments 1 and 2. The box was replaced with a line drawing of a freeform shape with an irregular contour, which is referred to hereafter as the "island". As shown in Fig. 4, there were two displays—one with a small island that separated the transfer locations from the training locations (Panel a), and one with a large island that encompassed all locations (Panel b). The shapes of the islands were designed to be irregular because we assumed that participants would be more likely to form a semantic association between the shapes and 'island' if shapes were used that resembled actual islands rather than simple rectangular boxes.

At the start of the task, participants were presented with instruction slides that read as follows:

> In this experiment, pretend that you have crash-landed on an island. Some unknown body of water surrounds the island. You will now be provided a simple outline of the island. Let the experimenter know when you are ready to view this outline.

After indicating that they were ready, participants were presented with the small island to view. On the top left corner of the screen cardinal points were presented to indicate which portions of the island were north, south, east, or west. The cardinal points were presented as an additional means of encouraging participants to encode the reference frame in a meaningful way. As in Experiments 1 and 2, participants were presented with flanker stimuli and told to respond to the central arrow; however, here, they were additionally instructed as follows:

> At different locations within the island you will be presented with a series of arrows on screen. Sometimes all of the arrows will point in the SAME direction. Sometimes the center arrow will point in a DIFFERENT direction from the rest of the arrows. The CENTER arrow is particularly important as that indicates the direction you must turn to avoid dangerous elements in the area. Your task is to press the response key that matches the direction the CENTER arrow is pointing.

Again, these instructions were added to encourage participants to represent the island/reference frame in a meaningful way. Following the presentation of the small island outline, participants completed the three training blocks exactly as in Experiments 1 and 2 (with the small island on screen throughout).

Unlike Experiments 1 and 2, there were four transfer blocks. In all four transfer blocks flanker stimuli were presented in both training and transfer locations. In two of the transfer blocks, the small island was displayed, so that the transfer items appeared in the water (i.e., outside of the reference frame) whereas the training items were contained within the island's boundary. In the other two transfer blocks, the larger island was displayed, and all locations were contained within the island's boundary (i.e., all within the reference frame). The order of presentation of the two types of transfer blocks was counterbalanced across participants. That is, all participants were presented with three training blocks and all four transfer blocks. However, after the training blocks, some participants were presented with two blocks with the transfer items in the water first and the other participants received two blocks with the transfer items on the island first. When the island shape changed from one block to the next, participants were told that it was the same island as the one they imagined crash landing on, but the shape had changed, either because the water tides receded (when shifting from the small island to the large island where the transfer items were on the island) or because the water tides rose (when shifting from the large island to the small island where the transfer items were in the water). All other aspects of the stimuli and procedure were the same, including the number of trials and the proportion of conflicting stimuli at each of the locations per block.

Design

The training trials represented a 2 proportion compatibility (PC: MC or MI) × 2 compatibility (compatible or incompatible) design whereas the transfer trials represented a 2 transfer item frame (in water or on island) × 2 location (near MC or near MI) × 2 compatibility (compatible or incompatible) design.

Results

The RT trim removed < 1% of trials.

LSPC effects

RTs from the MC and MI biased locations across all seven blocks were analyzed with a 2 PC[5] × 2 Compatibility repeated-measures ANOVA. The analysis revealed no main effect of PC, $F(1, 59) = 1.34$, $p = .25$, but did reveal a compatibility effect, $F(1, 59) = 1196.43$, $p < .001$, $\eta_p^2 = 0.95$ ($M_{\text{compatible}}$ = 596 ms, $M_{\text{incompatible}}$ = 749 ms). Importantly, the two factors interacted, $F(1, 59) = 118.25$, $p < .001$, $\eta_p^2 = 0.67$, with larger compatibility effects for the MC (170 ms) than MI (136 ms) location (see Fig. 5).

The same analysis on error rate revealed a main effect of PC, $F(1, 59) = 21.26$, $p < .001$, $\eta_p^2 = 0.27$ (M_{MC} = 0.038, M_{MI} = 0.025) as well as an effect of compatibility, $F(1, 59) = 88.58$, $p < .001$, $\eta_p^2 = 0.60$ ($M_{\text{compatible}}$ = 0.002,

[5] As in Experiments 1 and 2 there was an effect of compatibility for the central location in both RT, $t(59) = 28.55$, $p < .001$($M_{\text{compatible}}$ = 528 ms, $M_{\text{incompatible}}$ = 627 ms) and error rate, $t(59) = 7.33$, $p < .001$($M_{\text{compatible}}$ = 0.003, $M_{\text{incompatible}}$ = 0.035). Also as in Experiments 1 and 2, RTs were faster in the central locations than in either the MC, $F(1, 59) = 1756.36$, $p < .001$, $\eta_p^2 = 0.97$, or MI location, $F(1, 59) = 1281.16$, $p < .001$, $\eta_p^2 = 0.96$, and the compatibility effect was reduced in the central location (99 ms) compared to either the MC (170 ms), $F(1, 59) = 355.41$, $p < .001$, $\eta_p^2 = 0.86$, or MI (136 ms), $F(1, 59) = 93.41$, $p < .001$, $\eta_p^2 = 0.61$, location. In addition, an analysis examining the compatibility effect as a function of phase revealed a significant Phase × Compatibility interaction, $F(1, 59) = 6.85$, $p = .011$, such that the compatibility effect was larger during the training phase (105 ms) compared to the transfer phase (94 ms). This may reflect practice. The same analysis on error rate phase produced a significant main effect of phase, $F(1, 59) = 5.99$, $p = .017$, $\eta_p^2 = 0.09$, with more errors in the transfer phase (0.014) than training phase (0.010). Phase and compatibility did not interact in the error data in Experiment 3 ($F < 1$).

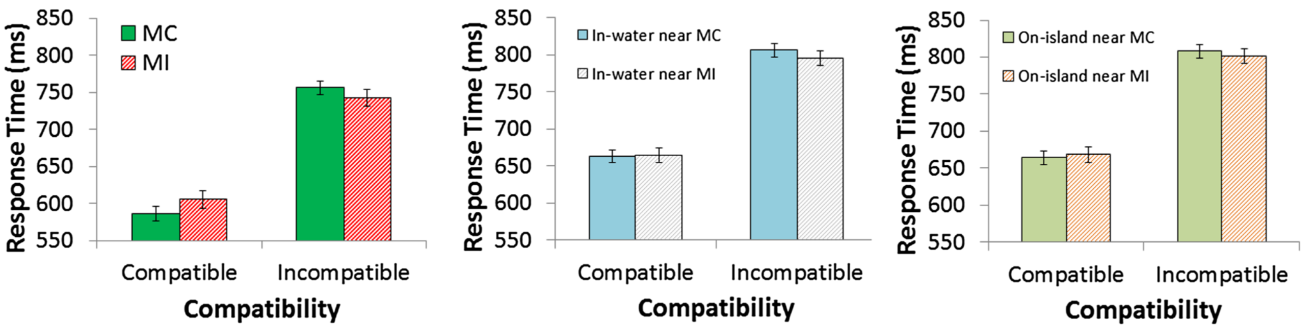

Fig. 5 Results from Experiment 3. Left panel: biased locations across all seven blocks. Middle panel: unbiased transfer locations in the water. Right panel: unbiased transfer locations on the island. Error bars represent *SE*s

$M_{\text{incompatible}} = 0.060$). This was qualified by a PC × Compatibility interaction, $F(1, 59) = 20.49$ $p < .001$, $\eta_p^2 = 0.26$, with the error rate compatibility effect being larger for the MC (0.071) than MI (0.046) location.

As in Experiments 1 and 2, we also examined if the LSPC effect for biased items varied as a function of phase (training vs. transfer) of the experiment. We ran a 2 Phase × 2 PC × 2 Compatibility repeated measures ANOVA and report only the unique results concerning the phase variable. The analysis revealed a main effect of phase, $F(1, 59) = 24.11$, $p < .001$, $\eta_p^2 = 0.29$ (M_{training} = 687 ms, M_{transfer} = 661 ms). The Phase × Compatibility interaction was also significant, $F(1, 59) = 18.29$, $p < .001$, $\eta_p^2 = 0.24$, with the compatibility effect being larger for the training phase (162 ms) than for the transfer phase (146 ms). This was qualified by a Phase × PC × Compatibility interaction $F(1, 59) = 16.12$, $p < .001$, $\eta_p^2 = 0.22$, with the LSPC effect being larger for the training phase (46 ms) than for the transfer phase (24 ms).

The latter pattern differs from that of Experiments 1 and 2 wherein the LSPC effect for biased items was equivalent during the training and transfer phases. This raises the question if perhaps changing the shape of the reference frame (i.e., from the small to large island) disrupted the LSPC effect in training locations. Recall that the order of the transfer island frame was counterbalanced so that following training blocks with the "in water" frame, half the participants continued to see the "in water" frame (in the first two transfer blocks) and were then switched to the "on island" frame (in the final two transfer blocks). The other half was presented with the opposite order of frames during the transfer phase (i.e., their frame switched twice during the experiment from "in water" during training to "on island" during the first two transfer blocks to "in water" during the last two transfer blocks). To examine whether these changes in frame affected the LSPC effect for the biased items in training locations, we ran a three-Phase (training phase, transfer phase 1, transfer phase 2) × 2 PC × 2 Compatibility repeated measures ANOVA separately for each counterbalance. We report only the unique effects of phase for this analysis.

For the first counterbalance (same transfer frame first), there was a Phase × PC × Compatibility interaction, $F(2, 58) = 3.24$, $p = .046$, $\eta_p^2 = 0.10$. The LSPC effects for the "in water" training blocks and the first "in water" transfer blocks were 42 and 35 ms, respectively. However, when the frame shifted to the "on island" frame in the final two transfer blocks, the effect dropped to 14 ms.[6]

For the second counterbalance (different transfer frame first), there was again a reliable Phase × PC × Compatibility interaction, $F(2, 58) = 5.32$ $p < .001$, $\eta_p^2 = 0.16$. The LSPC effect for the "in water" training blocks was 49 ms. Then, in the first "on island" transfer blocks, the LSPC dropped to 24 ms, mirroring the drop in magnitude when the frame shifted between phases 2 and 3 in the other counterbalance. When the reference frame changed back to the "in water" frame in the final two transfer blocks (i.e., returning to the original training frame), the LSPC effect remained at 21 ms.[7]

The same analyses were conducted on error rates. For the first counterbalance, the Phase × PC × Compatibility

[6] For thoroughness, in this first counterbalance there was also a reliable main effect of phase, $F(2, 58) = 12.35$, $p < .001$, $\eta_p^2 = 0.30$ ($M_{\text{Training phase}}$ = 702 ms, $M_{\text{Transfer phase 1}}$ = 679 ms, $M_{\text{Transfer phase 2}}$ = 669 ms). This was qualified by a marginally significant Phase × PC interaction, $F(2, 58) = 3.06$, $p = .055$, $\eta_p^2 = 0.10$ ($M_{\text{Training phase MI–MC}}$ = 5 ms, $M_{\text{Transfer phase 1 MI–MC}}$ = -1 ms, $M_{\text{Transfer phase 2 MI–MC}}$ = 11 ms), as well as a Phase × Compatibility interaction, $F(2, 58) = 5.39$, $p = .007$, $\eta_p^2 = 0.16$ ($M_{\text{Training phase I–C}}$ = 162 ms, $M_{\text{Transfer phase 1 I–C}}$ = 156 ms, $M_{\text{Transfer phase 2 I–C}}$ = 138 ms).

[7] Also, in the second counterbalance, there was a reliable main effect of phase, $F(2, 58) = 8.20$, $p = .001$, $\eta_p^2 = 0.22$ ($M_{\text{Training phase}}$ = 673 ms, $M_{\text{Transfer phase 1}}$ = 651 ms, $M_{\text{Transfer phase 2}}$ = 645 ms). This was qualified by a marginally significant Phase × PC interaction, $F(2, 58) = 2.71$, $p = .075$, $\eta_p^2 = 0.09$ ($M_{\text{Training phase MI–MC}}$ = -6 ms, $M_{\text{Transfer phase 1 MI–MC}}$ = 6 ms, $M_{\text{Transfer phase 2 MI–MC}}$ = 1 ms), as well as a Phase × Compatibility interaction, $F(2, 58) = 8.78$ $p < .001$, $\eta_p^2 = 0.23$ ($M_{\text{Training phase I–C}}$ = 162 ms, $M_{\text{Transfer phase 1 I–C}}$ = 152 ms, $M_{\text{Transfer phase 2 I–C}}$ = 136 ms).

[8] There was also a main effect of phase, $F(2, 58) = 5.38$ $p = .007$, $\eta_p^2 = 0.16$ ($M_{\text{Training phase}}$ = 0.025, $M_{\text{Transfer phase 1}}$ = 0.033, $M_{\text{Transfer phase 2}}$ = 0.038). The phase × compatibility interaction was significant, $F(2, 58) = 4.50$ $p = .015$, $\eta_p^2 = 0.13$ ($M_{\text{Training phase I–C}}$ = 0.046, $M_{\text{Transfer phase 1 I–C}}$ = 0.060, $M_{\text{Transfer phase 2 I–C}}$ = 0.067).

interaction was not significant ($F < 1$). The error rate LSPC for the three phases in order were: 0.019, 0.018, 0.017.[8] For the second counterbalance, the analysis revealed a Phase × PC × Compatibility interaction, $F(2, 58) = 4.33$, $p = .028$, $\eta_p^2 = 0.13$. Mirroring the pattern found for RTs, the error rate LSPC for the "in water" training blocks was 0.049. Then, in the first "on island" transfer block the error rate LSPC dropped to 0.011. Finally, when the reference frame changed back, the error rate LSPC remained at 0.017.[9]

Transfer effects

We conducted a 2 Transfer item frame × 2 Location × 2 Compatibility repeated measures ANOVA on RTs from transfer locations. The analyses revealed no main effect of transfer item frame ($F < 1$), and no main effect of location, $F(1, 59) = 1.66$, $p = .20$, but did reveal a main effect of compatibility, $F(1, 59) = 1240.18$, $p < .001$, $\eta_p^2 = 0.96$ ($M_{compatible}$ = 664 ms, $M_{incompatible}$ = 802 ms). The two-way interactions between transfer item frame and both location and compatibility were not significant (both Fs < 1). Importantly, there was a significant Location × Compatibility interaction (i.e., transfer), $F(1, 59) = 9.55$, $p = .003$, $\eta_p^2 = 0.14$, with the compatibility effect being larger for near MC locations (144 ms) than for near MI locations (132 ms). However, there was not a significant three-way Transfer item frame × Location × Compatibility interaction ($F < 1$), indicating that the LSPC effect did not change as a function of whether the transfer locations were on the island with the training locations or in the water outside of the reference frame.

We conducted the same analysis on error rates which revealed no main effect of transfer item frame, $F(1, 59) = 1.52$, $p = .22$, but did reveal a main effect of location, $F(1, 59) = 10.21$, $p < .01$, $\eta_p^2 = 0.15$ ($M_{nearMC} = 0.039$, M_{nearMI} = 0.030) and compatibility $F(1, 59) = 100.30$, $p < .001$, $\eta_p^2 = 0.63$ ($M_{compatible}$ = 0.002, $M_{incompatible}$ = 0.066). The two-way Transfer item Frame × Compatibility interaction was not significant, $F(1, 59) = 1.16$, $p = .29$. The analysis did reveal a significant Transfer item frame × Location interaction, $F(1, 59) = 4.30$, $p = .042$, $\eta_p^2 = 0.07$, with a smaller difference between near MC and near MI error rates in the small island condition (0.005) compared to the large island condition (0.013). Most importantly, the Location × Compatibility interaction was significant, $F(1, 59) = 11.43$, $p = .001$, $\eta_p^2 = 0.16$, with the error rate compatibility effect being larger for near MC locations (0.073) than for near MI locations (0.054), and transfer item frame modulated this interaction, $F(1, 59) = 4.98$, $p = .030$, $\eta_p^2 = 0.08$. We decomposed this interaction by running separate 2 Location × 2 Compatibility repeated measures ANOVAs for the "in water" (small island) and "on island" (large island) transfer frames. For the "in water" frame, the location × compatibility interaction was not reliable, $F(1, 59) = 2.11$, $p = .15$. However, there was a Location × Compatibility interaction for the "on island" frame, $F(1, 59) = 15.87$, $p < .001$, $\eta_p^2 = 0.21$, with the error rate compatibility effect being larger for near MC locations (0.080) than for near MI locations (0.052).

We again examined the magnitude of the transfer effect over time, here using a 4 Transfer block (first block, second block, third block, or fourth block) × 2 Location × 2 Compatibility repeated measures ANOVA for RTs from transfer locations. We focus only on unique effects of the block variable. The analysis revealed a main effect of block, $F(3, 177) = 3.72$, $p = .013$, $\eta_p^2 = 0.06$ ($M_{TransferBlock1}$ = 740 ms, $M_{TransferBlock2}$ = 736 ms, $M_{TransferBlock3}$ = 727 ms, $M_{TransferBlock4}$ = 730 ms), and a Block × Compatibility interaction, $F(3, 177) = 4.61$, $p = .004$, $\eta_p^2 = 0.07$ ($M_{TransferBlock1\ I-C}$ = 149 ms, $M_{TransferBlock2\ I-C}$ = 136 ms, $M_{TransferBlock3\ I-C}$ = 131 ms, $M_{TransferBlock4\ I-C}$ = 135 ms). Block did not interact with location ($F < 1$), nor did it modulate the two-way location by compatibility interaction, $F(3, 177) = 1.42$, $p = .24$. This indicates that the LSPC effect did not wane as a function of learning the unbiased nature of transfer locations. The same analysis on error rate revealed a marginally reliable main effect of block, $F(3, 177) = 2.53$, $p = .06$, $\eta_p^2 = 0.04$ ($M_{TransferBlock1}$ = 0.031, $M_{TransferBlock2}$ = 0.032, $M_{TransferBlock3}$ = 0.034, $M_{TransferBlock4}$ = 0.039). Importantly, block did not modulate any other effects or interactions including the three-way Block × Location × Compatibility interaction (Fs < 1).

Discussion

This experiment used a more salient and meaningful border (i.e., between land and water) as a reference frame to potentially deter transfer of the LSPC effect to novel locations outside its boundary. The evidence was mixed. For reaction time, contrary to this prediction, there was still evidence for transfer of the LSPC effect to unbiased items falling in novel locations outside the boundary of the island. This pattern was observed regardless of the transfer item frame, that is, whether the unbiased locations were presented in the water or on the island. In conjunction with Experiments 1 and 2, these data imply that learned associations between conflict and space may be unbounded by visual reference frames. However, the analysis of error rates revealed a different pattern. Transfer of the LSPC effect was observed selectively when the items were on the island; there was no transfer of the LSPC effect for error rate when the items were in

[9] The analysis revealed no main effect of phase ($F < 1$), but a Phase × PC interaction, $F(2, 58) = 4.84$, $p = .011$, $\eta_p^2 = 0.14$ ($M_{Training\ phase\ MI-MC} = -0.024$, $M_{Transfer\ phase\ 1\ MI-MC} = -0.002$, $M_{Transfer\ phase\ 2\ MI-MC} = -0.008$).

the water. This provides preliminary support for the notion that a more salient and meaningful reference frame (the delineation of transfer from training locations via a boundary between water and land) may deter transfer of control beyond the reference frame.

One additional finding merits comment. Converging with the view that the reference frame did play a meaningful role in this experiment, the LSPC effect for the biased training items decreased in magnitude when the reference frame changed. This, too, may suggest that the mechanisms underlying the LSPC effect are sensitive to changes in context even when the precise locations of the biased items within the frame do not change (training items were always inside the frame). Collectively, the findings of Experiment 3 suggest that the frames were salient and/or meaningful enough to impact some of the processes underlying the LSPC effect, while not deterring transfer of the LSPC effect beyond the reference frame for reaction time.

General discussion

Humans' flexible cognitive control systems allow us to adapt to a changing environment. One well-documented example comes from demonstrations of enhanced cognitive control in an area of space associated with greater conflict compared to one with less (e.g., Corballis & Gratton, 2003). Prior research has shown that these control settings can transfer, or extend beyond, PC biased items to the same items presented in novel areas of space that contain no conflict bias (Weidler, & Bugg, 2016). However, in all prior research investigating this question, the unbiased (transfer) items were presented within the reference frame of the PC biased items. Here we examined if LSPC effects can transfer beyond the context in which they are initially learned (acquired). Across three studies we indeed found evidence of transfer of LSPC effects beyond the trained area of space, including when there was a visual border ("box", Experiment 2) and a more qualitative visual border ("island", Experiment 3) between training and transfer locations. Thus, returning to our earlier example of driving home from work in the city to your home in the suburbs, if construction forced a detour near your home, these results suggest you would likely apply the appropriate relatively relaxed attentional state, despite the novel environment.

These findings have implications for understanding the mechanisms supporting location-specific cognitive control processes. Previous researchers have argued that location-specific control may be represented by a *categorical* coding of space (e.g., left vs. right, up vs. down; Weidler, & Bugg, 2016) as opposed to a coordinate coding. The present results support that idea: if the relationship between conflict and space is coded, for example, based on a "left" or "right" side of space, then any location falling into the category—regardless of whether it is within the established reference frame—may be subject to those rules and thereby trigger retrieval of the control settings associated with that category of space.

An alternative account is the proximity account which posits that, when encountering stimuli in new locations, participants adopt the control setting that corresponds to the closest neighboring location (i.e., "near MC" transfer items take on the control setting associated with the MC location because it is closer than the MI location and vice versa). However, this account has trouble explaining all extant findings using this paradigm. Specifically, Weidler and Bugg (2016; Experiment 2) biased one ring of a bull's eye with MC items and another with MI items and found that control transferred to unbiased items additionally presented in each ring. Relevant to the current point, this transfer occurred despite the fact that the unbiased items in the outer ring were almost as close in physical proximity to the biased items in the inner ring (that had the opposite PC bias) as the biased items presented within the same outer ring. Still, a variant of this account might posit that in the present research participants did not realize there were two distinct locations in the right side of space (biased and novel unbiased) given their proximity and the fact that participants only ever saw one stimulus at a time; thus, a stimulus appearing in either location triggered retrieval of the control setting associated with the biased location. Countering this idea, however, was the finding that transfer occurred even in Experiments 2 and 3 where a visual border was always present and clearly delineated the biased and novel unbiased location.

On the surface, the present results seem at odds with those from another conflict paradigm. Recall that Kunde et al. (2003) found that novel, non-target primes could produce compatibility effects, but only when those primes were within the established reference frame of the targets. More specifically, the authors asked participants to identify whether a target number was greater or larger than 5. Prior to that either a compatible (i.e., on the same side as 5 as the target) or incompatible (i.e., on the opposite side of 5) prime number was presented briefly. The primes were always 1–9 (excluding 5) whereas in one experiment the targets were the digits 1, 2, 8 and 9 and in the other they were 3, 4, 6, and 7. The key relevant finding is that novel non-target primes (e.g., 3 in the former experiment or 2 in the latter) produced compatibility effects selectively in the first experiment—when they were in the established reference frame of the targets. Contrary to that, in the present research the established compatibility effects extended to stimuli that occurred outside of the established reference frame.

Kunde et al. (2003) explained their results in terms of *action-triggers*, which create associations between expected stimuli and responses. According to this theory, novel primes will "trigger" compatibility effects only when they fall within the range of the expected responses. Framing our results in this context, we found that novel locations "triggered" the relevant control settings (and produced compatibility effects), even when outside the range in which participants had previously experienced stimuli. There are many differences between the current paradigm and that of Kunde et al. that may explain the discrepant results. One obvious possibility is that the differing findings reflect that non-target primes were not only outside of the reference frame in the research of Kunde et al. but additionally were unique stimuli. In the present experiments, although the transfer locations fell outside of the reference frame, the stimuli were the same arrow arrays participants had encountered inside the reference frame. In the terms of the Kunde et al. framework, our stimuli may have fallen within the range of expected responses, thereby promoting transfer. Another intriguing possibility is that these findings highlight a difference between how conflict is learned and represented in mental compared to physical space—with novel locations in *physical* space that fall outside of the established frame selectively being able to trigger learned settings. Clearly, further research is needed to better understand the conditions under which control does and does not transfer beyond a reference frame.

There are two limitations worth noting. First, it is possible that the reference frame could not deter the LSPC effect because it never was attended in the context of the flanker task. In fact, despite the salience of the on-screen border (island/water) manipulation in Experiment 3, one might argue that the border of the computer screen may have functioned as the more salient of the two borders in this study, thereby explaining why transfer was observed for reaction time (i.e., because transfer trials were within the reference frame established by the screen). Future research could tackle this question by presenting training and transfer stimuli on different monitors or by making the reference frame relevant to the ongoing task. However, countering the idea that the reference frame was completely ignored, in Experiment 3 transfer was deterred for error rate when the transfer items appeared in the water outside the island frame, and there were differences in the LSPC effect for training items as a function of changes in the frame across the training and transfer phases.

Second, we have been interpreting our findings as demonstrating that attentional control settings are flexible enough to extend to new contexts outside of a trained frame of reference. However, an alternative account of LSPC effects posited that these effects instead reflect a form of stimulus response learning (e.g., location cue and distractor compounds; e.g., Schmidt, & Besner, 2008, see also Schmidt, 2016). We think this explanation is unlikely to account for the present set of results because the same exact set of unbiased stimuli (i.e., with the same stimulus–response predictability) produced different flanker compatibility effects based on their location (see also Crump & Milliken, 2009; Surrey, Dreisbach, & Fischer, 2016 for examples of transfer in LSPC paradigms that cannot be explained by stimulus response learning). However, given the use of the same overall set of stimuli throughout the experiment (i.e., the same 16 flanker stimuli were used in the training and transfer locations), we cannot unequivocally rule out that some form of stimulus–response learning contributes to the demonstrated effect. Our goal, however, was not to distinguish between these two accounts and the novel demonstration of transfer of the LSPC effect beyond a frame of reference is informative regardless of the mechanism supporting the learning underlying the LSPC effect.

Furthermore, we favor an account of LSPC effects in which a stimulus appearing in a certain location serves to cue the relevant control setting based on past experience with conflict (i.e., loosen control and attend to all the symbols in MC location; cf. e.g., Crump, & Milliken, 2009). However, it is also known that in the context of visual search people can learn about regularities in the environment (e.g., Geng, & Behrman, 2005). Additionally, pertinent to the present research, learned biases in search can transfer in a categorical manner. Chua and Gauthier (2016) asked participants to perform a visual search task for targets superimposed on two different categories of objects (categories of Greebles, cf., e.g., Gauthier, & Tarr, 1997). They biased one category of Greebles to be target-rich in a certain region (e.g., the top of the Greeble) and the other category to be target sparse in that area (and target rich in the bottom of the Greeble). Then, in later blocks of the experiment novel exemplars from the two learned categories were presented with targets equally likely in both regions for all exemplars. Importantly, participants' learning about search biases transferred: search RTs in the novel exemplars were faster in the area that had previously been target rich for that exemplar's category. Given the similarity in general methods and findings, it seems plausible that some learning about search regularities may also be influencing our findings. Because there are relatively more arrow strings with many "targets" (i.e., compatible trials when all seven of the symbols are the same) in the MC location perhaps participants learn to execute a relatively broad search in MC that extracts information from both the target and the flankers (compared to a relatively narrow search in MI that focuses selectively on the target). Then these search settings could potentially transfer to novel nearby locations that do not contain that target bias, thereby contributing to the current effects.

To conclude, here we demonstrated for the first time that attentional control settings can transfer to novel locations beyond a reference frame. We posited that control was applied differentially based on learned categories of space (e.g., left vs. right; lower left vs. upper right) comprising relatively more (MI) or less (MC) conflict and these categories served as effective cues for control even for transfer locations that fell outside the frame of reference in which the categories were initially acquired. This was true even when a visual border separated the space inside and outside of the reference frame (Experiment 2), and when the border was salient and meaningful, differentiating the space on an island (inside the reference frame) from the space in the water (outside the reference frame; Experiment 3; with one exception in the lack of transfer of the LSPC effect in error rate from the island to the water). The findings support the idea that location-specific control settings can be flexibly applied to stimuli in new locations based on learned categorical representations, and may imply that it is difficult to disrupt the use of such spatial categories as cues for control.

Compliance with ethical standards

Conflict of interest Blaire Weidler declares that she has no conflict of interest. Abhishek Dey declares that he has no conflict of interest. Julie 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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