

Spatial Representations with Conflicting Intrinsic Frames of Reference

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Abstract

Establishing and updating spatial relationships between objects in the environment is vital to maintaining situation awareness. Wang et al. (2005) found that updating of spatial representations in the intrinsic frame of reference (IFOR) can be prioritized based on salience of task demands. But their study used a task environment with only one IFOR. Often a task environment has several objects in it which may be task-relevant, and they may conflict with each other in one or more ways such as by being oriented in differing directions. Two experiments manipulated relative spatial orientation and task salience of two task-relevant objects such that the objects' orientations conflicted with each other and the task probabilistically demanded response based on the orientation of one or the other object. It was found that spatial updating in the IFOR was constrained by the limits of human attentional processes. Furthermore those constraints can be relaxed with practice.

Keywords: prioritized representation updating; conflicting spatial representations; spatial cognition; intrinsic frame of reference.

Introduction

Spatial cognition is crucial to our everyday interactions with our environment and other people including, for instance, maintaining awareness of one's task environment. A large body of evidence suggests that people organize spatial representations and reason about spatial relationships using frames of reference (FORs, (Levinson, 1996; Wang, Johnson & Zhang, 2001). FORs can be based on our own viewpoints, expressing spatial representations that are centered on ourselves (the egocentric FOR, "EFOR"). EFORs represent spatial affordances within our immediate vicinity, such as a pencil that is within reach. FORs based on navigable environments (the allocentric FOR, "AFOR"), such as rooms, buildings, or cities, represent the shapes of those environments and what affordances they give to wayfinding (Klatzky, 1998; Mou & McNamara, 2002; Wang & Spelke, 2002).

Most research in spatial cognition has focused on the EFOR and AFOR (May & Klatzky, 2000; Shelton & McNamara, 2001) though it is possible to distinguish a third type of FOR, the intrinsic (IFOR), so named because it is intrinsic to the person or object of focus (Mou & McNamara, 2002; Wang, Sun, Johnson & Yuan, 2005). The IFOR is a unique FOR that brings the spatial representation affordances of the EFOR outside the observer's body. The IFOR enables us to imagine spatial relationships from positions other than the one we currently occupy, including the positions of other people. This is important for action

planning, interpersonal communication of specific spatial representations, and even theory of mind. For instance, spatial relationships such as, "John is sitting to Mary's right." are represented in the IFOR. Here Mary is the reference anchor around which the framework for the spatial relationship of John's position is based (Levinson, 1996).

Given the importance of IFOR-based spatial representations in everyday tasks, one fundamental question is how easily IFOR representations can be updated within the context of a changing environment. It has been shown that egocentric representations can be updated fairly easily whereas updating allocentric representations other than self-locations often requires effort. Wang, Sun, Johnson, and Yuan (2005) studied IFOR spatial representations and how they may be updated to reflect changes in the task environment, particularly as a function of a target object's task salience. They found that updating of spatial representations in the IFOR can be prioritized based on salience to task demands and that IFOR updating is often, but not always, easy for those salient objects. However their study used a task environment with only one IFOR-supporting object. Often a task environment has several such objects in it which may be task-relevant and they may conflict with each other in one or more ways such as by being oriented in differing directions. In the above example regarding John and Mary, we may also notice that "John is sitting to Sam's left." In this case, John's spatial location is represented in an IFOR centered on Sam and that spatial relationship to John is not the same for Mary and Sam. When John moves, both Mary's and Sam's spatial representations should be updated.

Presumably increasing the number of task relevant IFOR-supporting objects would increase task complexity and consequently demand more attentional resources. At a certain point people will have to prioritize not only their updating of spatial representations of the targets of their actions but also the reference anchors of those spatial representations. In other words, if there are multiple IFOR-supporting objects that must be attended in a task environment then people will need to prioritize their updating not only of the action-target objects but also of the IFOR-supporting objects.

A "Two Cannons" pointing task was designed to test hypotheses regarding updating priority in a two-IFOR spatial task environment. In this task participants needed to determine which way a depicted cannon should turn to point at a designated target. Salience of the two cannons varied so as to make one or the other more important to the completion of the task. If people can attend to only one

IFOR at a time then in a an environment where multiple IFORs may exist updating those representations must be prioritized somehow. If priority of updating between IFORs goes according to salience, as Wang et al. (2005) found for updating target priority within one IFOR, then response time should vary with the targeted IFOR’s relative salience. That is, when two IFORs conflict the conflict should be resolved most easily in favor of the more salient IFOR. Furthermore, if people can only form one IFOR at a time they may wait to see which IFOR to use before they invest the time in forming it. Then we would expect an effect of conflict as they wait to see which IFOR to use but no effect of relative IFOR anchor angle since anchor angle would be irrelevant to IFOR selection. On the other hand if people can form and maintain multiple IFORs simultaneously then when the IFOR anchor objects conflict with each other on some dimension (e.g., orientation) there should be an effect of relative IFOR orientation angle such that at one angle the irrelevant IFOR may be easier to inhibit than at another angle.

Experiment 1

We designed a “two cannons” turning response task to investigate how people represent spatial information with multiple conflicting IFORs and how they resolve the conflicting attentional demands of updating spatial relationships involving multiple IFORs. The task required participants to determine the location of a designated target relative to a matching-color IFOR anchor, one of the two cannon stimuli. Orientation of the cannon stimuli varied so that turning direction responses dependent upon those orientations would conflict based on the orientations of the two IFOR anchors, the cannons, with respect to the indicated target. Task salience of the two anchors also varied so as to weight the conflict in favor of one IFOR or the other. If IFOR updating tends to be prioritized according to salience as Wang et al. (2005) found, then response time for each IFOR should be a function of that IFOR’s relative salience. That is, when two IFOR spatial relationships conflict, the conflict should be resolved most readily for the more salient IFOR.

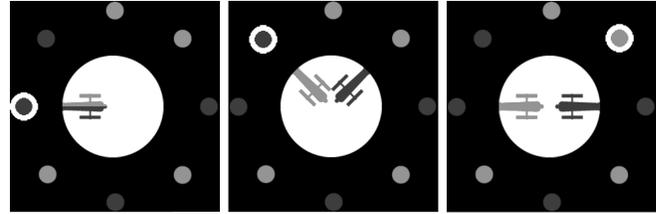


Figure 1. Experiment displays depicting 0° relative cannon angle (A, left), 90° cannon angle (B, center), and 180° cannon angle (C, right). Here blue is depicted as dark gray and red is light gray. In A both cannons (depicted as half red, half blue) are at 270° orientation. The highlighted blue dot indicates the target. In this case the correct response would be to punch the up arrow key to indicate that no turn is required. In B the correct response would be to punch the left arrow key, indicating that the blue cannon would have to turn to its left to face the target. In C the correct response would be to punch the right arrow key, indicating that the red cannon would have to turn to its right to face the target.

Method

Participants Ten graduate students and postdoctoral fellows were paid to participate in Experiment 1. Subjects had a mean age of 32.1 years (SD = 7.75) and five were female.

Design Table 1 enumerates the conditions for Experiment 1. We established conflict in the cannon IFORs by manipulating relative angle between the two cannons so that the two cannons either were on top of each other as in Figure 1A, at 90° to each other (Figure 1B), or 180° to each other (Figure 1C). We used 90° & 180° to compare degree of conflict. The ratio of blue dots to red dots varied sequentially within each trial block, always starting at 8 blue to 0 red and transitioning in increments of 2 dots to 0 blue to 8 red. Color ratio conditions occurred as sub-blocks of eight trials, each of which exhausted the set of eight possible target locations. Thus each block of 40 trials exhausted each of five color ratio conditions once and each of eight target location conditions five times for one combination of relative cannon angle and cannon orientations. Relative cannon angle and cannon orientations varied randomly by block.

Materials The experiments ran on a PC in E-Prime version 1.2. The two cannons subtended a viewing angle of

Table 1. Combinatorial table of conditions of Experiment 1. All factors varied within-subjects, except color ratio.

Relative Cannon Angle	Cannon Orientation (specific to each cannon angle condition)	Target Position (all cannon angle conditions)	Target Color (all cannon angle conditions)	Dot Color Ratio (all cannon angle conditions)
0°	90°(blue & red)	0° – 315°, with 0° being up and incrementing clockwise in steps of 45°. 8 positions total. Varied randomly, without replacement, within each color ratio cycle.	red or blue, varied randomly within each color ratio cycle, constrained by color ratio condition.	8 blue : 0 red – 0 blue : 8 red, in increments of 2 dots. 5 color ratios total. Varied sequentially within each trial block.
	270°(blue & red)			
90°	45° (blue) & 315° (red)			
	135° (red) & 225° (blue)			
180°	90°(blue) & 270°(red)			
	90°(red) & 270°(blue)			

approximately 6° while the entire display of cannons and surrounding dots subtended a viewing angle of approximately 12°. The cannon stimuli were constructed such that they each had an obvious intrinsic orientation (Figure 1). They appeared as though viewed from above, with wheels at their rear and a barrel in the middle, extending far forward.

Procedure Upon onset of the stimulus display, the experiment paused for one second before it flashed a yellow ring around one dot to indicate that it was the target. The matching-color cannon thus became task-salient. Participants were to then respond as quickly and accurately as possible which way the salient cannon should turn to face the dot: left, right, or no turn. Responses had the stipulation that the turn was to be the shortest way round. Participants indicated their responses with the left, right, and up arrow keys, respectively. In the case wherein the target was directly behind the indicated cannon, participants could respond either left or right as turning either way would result in a change in cannon orientation of 180°. The experiment played a “zap” sound as feedback for a correct trial. In the case of incorrect trials the experiment paused for two seconds to discourage random guessing and it played a distinctive “uh oh” sound. Subjects erred on fewer than 5% of trials on average.

Results and Discussion

Data from both experiments were filtered for subject error and outliers, outliers being outside the subject’s mean ± 3 standard deviations. This removed approximately 5% of observations. Figure 2 depicts effects on response time of the interaction of target color and dot color ratio. Again, in Experiment 1 color ratio sequence began with all blue dots

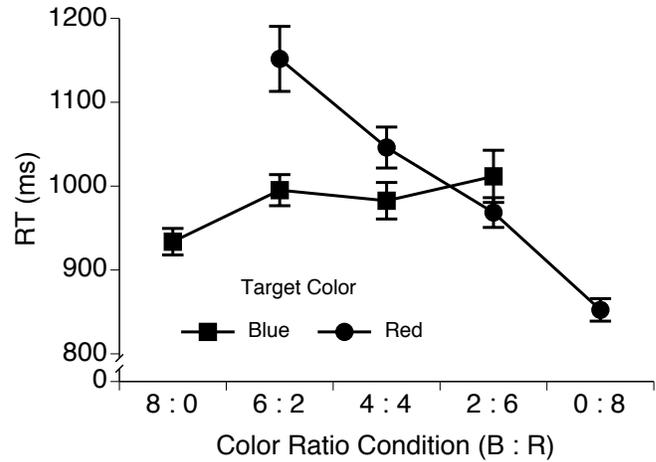


Figure 2. Experiment 1 response times as a function of the interaction of target color and dot color ratio. Within-block color ratio sequence progressed left-to-right along the x-axis. Error bars depict standard error of the mean.

and transitioned gradually to all red dots (i.e., from 8 blue : 0 red to 0 blue : 8 red, hereafter abbreviated #blue:#red for Experiment 1). Repeated measures ANOVA found that target color by color ratio linear by linear interaction contrast was reliable, $F(1, 9) = 39.25, p < .001$, meaning that the RT function of blue targets and red targets over color ratio differed. In addition, Color ratio’s main effect was reliable, $F(3, 27) = 8.38, p < .001$.

The results suggest that for the blue targets as the blue cannon became less salient as the number of dots transitioned from blue to red, the ability of subjects to respond to the blue cannon did not fall off, it stayed the

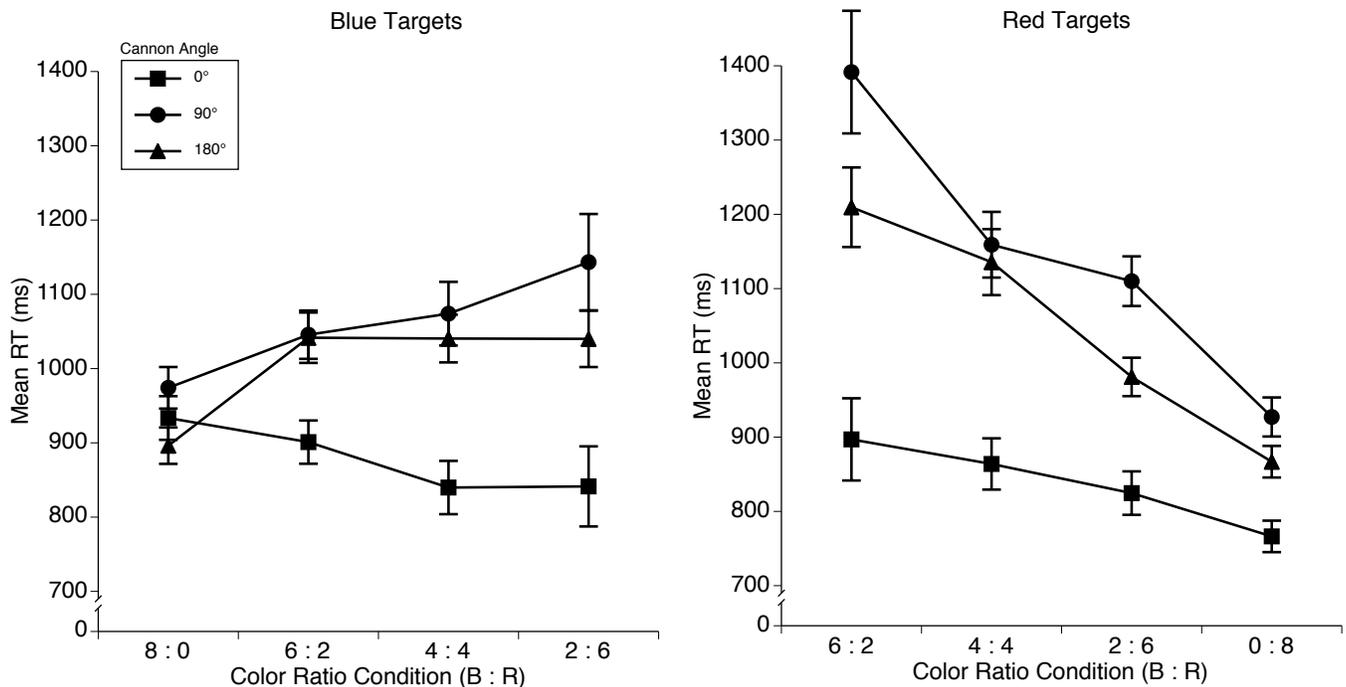


Figure 3. Experiment 1 RTs by target color, cannon angle, and color ratio condition. Error bars depict SEM.

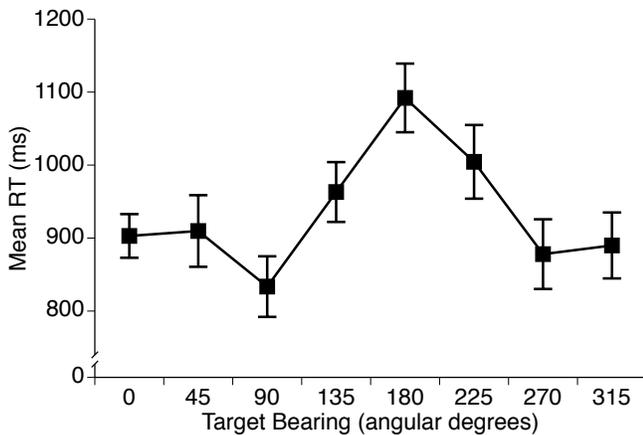


Figure 4. Experiment 1 RTs by target bearing at color ratio 8:0. Error bars depict SEM.

same. This is surprising given that as the blue cannon decreased in salience subjects should have paid less attention to it, thus taking longer to recognize and respond to a rare blue target trial. Additionally, the preservation of the ability to respond to blue did not come at the cost of responding to red, as red targets showed a dramatic decrease in response time across the color ratio condition progression. This indicates little or no strategic trade-off of prioritizing one IFOR over the other.

Breaking the interaction down to more specific experimental conditions, it is clear that IFOR conflict mattered when interacting with color ratio (Figure 3). Collapsing across 90° and 180° cannon angles gives an abstracted conflict versus no conflict (0° cannon angle) contrast. With five post hoc comparisons for this family of tests of the target color by color ratio by conflict interaction, the Bonferroni-corrected $\alpha' = .01$. Conflict by target color was not reliably different for blue targets ($t(9) = 3.028, p = .014$), but was for red ($t(9) = 3.821, p = .004$). This means that conflict in IFORs was a product of task demands, which in turn was a combination of IFOR spatial properties and probabilistic IFOR selection properties. The 90° versus 180° cannon angle difference was not reliable (for red targets in the 2:6 color ratio condition, $t(9) = 3.095, p = .013$). Furthermore the slope of the conflict versus no conflict by color ratio interaction function was different for blue targets, but not for red targets: $t(9) = 3.903, p = .004$; and $t(9) = -1.779, p = .109$, for blue and red respectively. This means that for blue targets as the color ratio progressed from blue to red RTs got slightly faster for 0° cannon angle trials but slower for 90° and 180° cannon angle trials. This indicates that participants really saw the two overlapping cannons as one IFOR in the 0° cannon angle condition, whereas the 90° and 180° cannon angle conditions worked well as a manipulation to induce IFOR conflict. When the color ratio was 6:2 the cost to switch attention on the IFORs can be calculated as the difference between the RTs for the blue and red targets within the conflict condition. That switching cost was 257 ms.

The 8:0 condition might be taken as a base case of the two cannons task in that the color ratio of the dots perfectly

predicts target color, and therefore which cannon participants should attend. Here, then, we can get a sense for target bearing's RT function (Figure 4). It shows that targets at 135° and 225° bearing took longer to respond to than targets at other bearings (except 180°, which was subject to Hick's Law since participants could respond either direction to this target bearing), $t(9) = -3.848, p = .004$.

Kessler & Thomson (2010) used a similar response scheme in their perspective alignment task. They found a flat target bearing function except for longer RTs at 135° rotation in either direction. They speculated that visual comparisons could be made up to about 90° of rotation but that greater degrees of rotation required complex imaginal transformations that took longer. Presumably the same cognitive and perceptual-motor processes take place with the two cannons task since it also requires the alignment of perspectives with the IFOR of the designated cannon.

However, the target bearing function went flat for conditions where a switch of attended cannon was likely, namely when the target belonged to the non-salient IFOR. For instance, when the color ratio was 2:6, a red target was more likely to appear than a blue target. That probability difference made the red cannon more task-salient. Subjects could therefore save some response time by attending the red cannon during the SOA. But if the target turned out to be blue then subjects would have to move attention to the blue cannon and establish a new IFOR around it. When this happened RTs were not longer for 135° or 225° target bearing, contrast for blue targets at 2 blue to 6 red $t(7) = -.997, p = .352$; contrast for red targets at 6 blue to 2 red, $t(7) = -2.087, p = .075$. Note that $df = 7$ for these two analyses as two subjects were missing data for these cells, likely due to subject error or outlier RTs. The 135°/225° target bearing effect probably went away for these two conditions because target position would already have been known when it became clear that the non-salient cannon must form the basis of the response. Target bearing could then be integrated during the IFOR attention switch latency rather than, as in the 8:0 color ratio condition, having all other representations formed before target onset and being the last representation left to be formed before responding.

It could be that each piece of the spatial information is acquired and represented as it becomes available, and that pieces are retrofitted into the rest of the representation as needed. This could mean that in 6:2 with a red target, for example, the potential targets have their representations built first (maybe in association with the more likely IFOR), and after the target onset the targeted IFOR is built and retrofitted to the extant spatial environment representation.

Experiment 2

The asymmetry of the target color interaction with color ratio found in Experiment 1 was unexpected, and if real, could imply that people, with practice, may be able to maintain representation more than one IFOR at a time. As trial blocks progressed and blue became less salient then response times for blue targets should have become longer as the blue cannon reduced in updating priority relative to the red cannon. Instead a practice effect on the blue IFOR was apparently sufficient to cancel the expected probability

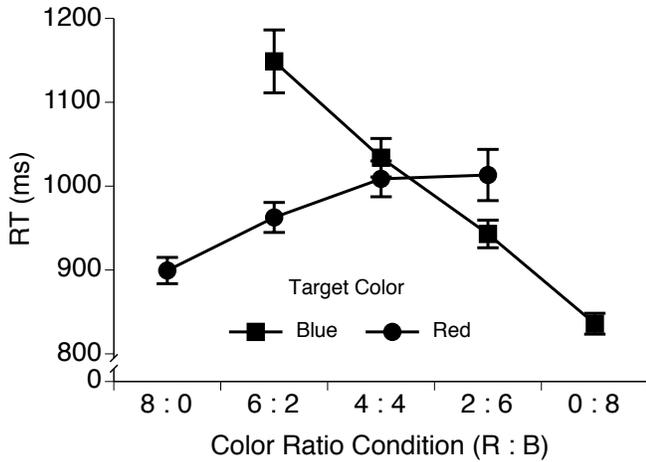


Figure 5. Experiment 2 RTs as a function of the interaction of target color and dot color ratio. Within-block color ratio sequence progressed left-to-right along the x-axis. Error bars depict SEM.

matching effect for the blue IFOR. However, it is also possible that the interaction effect could be due to sequence effects of color ratio presentation order. Experiment 2 was designed to test this possibility by replicating Experiment 1 except that dot color ratios were sequenced in the opposite order, this time going from red to blue within each block.

Method

Ten graduate students and postdoctoral fellows were paid to participate in Experiments 2. Subjects had a mean age of 32.1 years (SD = 6.03) and four of them were female.

Experiment 2's design duplicated Experiment 1's except that color ratios incremented from all red to all blue rather than blue to red as in Experiment 1. Experiment 2 replicated Experiment 1's materials and procedures identically.

Results and Discussion

The target color by conflict by color ratio interaction of Experiment 1 replicated in Experiment 2 (Figures 5 and 6), the different color ratio sequence notwithstanding (linear by linear interaction contrast of color ratio with target color $F(1, 9) = 96.6, p < .001$). With four post hoc comparisons for this family of tests, the Bonferroni-corrected $\alpha' = .0125$. Blue targets with conflicting IFORs took longer for subjects to respond to than blue targets with no conflict, contrast $t(9) = 4.629, p = .001$; and likewise for red targets $t(9) = 4.119, p = .003$. Also for red targets with conflict RTs got longer as the color ratio transitioned to more blue dots while the RTs became shorter for red targets with no conflict ($t(9) = -5.865, p < .001$), but the same was not true for blue targets ($t(9) = 3.035, p = .014$), all blue target RTs got shorter regardless of conflict status. This means that when subjects had to choose between IFORs (conflict), practice effects interacted with the time costs associated with switching attention between IFORs and the fact that target color was selected probabilistically from the set of dots. The time costs existed in turn because only one IFOR could be attended at any one time and moving attention from one to the other cost 215 ms.

As for target bearing, 135° and 255° were again slower than other target bearings, 180° excluded, in this experiment's color ratio and target color "base case," $t(9) = -2.706, p = .024$ (Figure 7). The two target bearings were not reliably different for blue targets at 2 blue to 6 red ($t(6)$

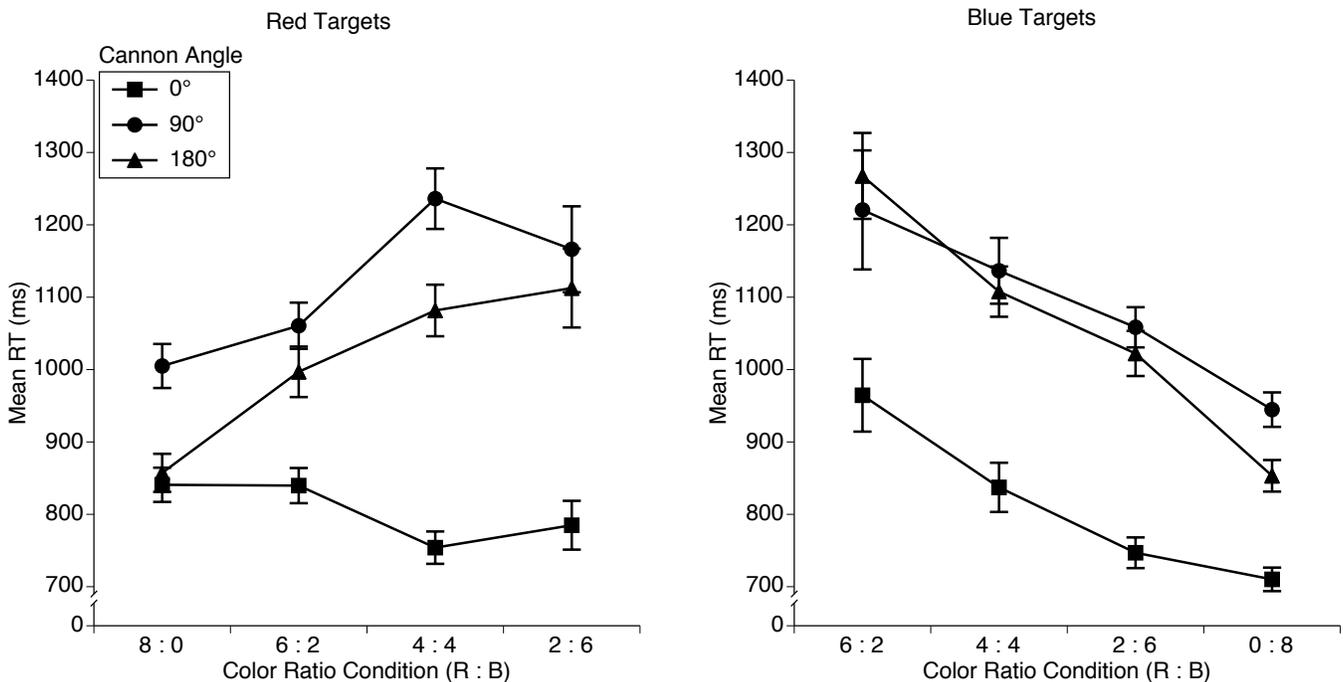


Figure 6. Experiment 2 RTs by target color, cannon angle, and color ratio condition. Error bars depict SEM.

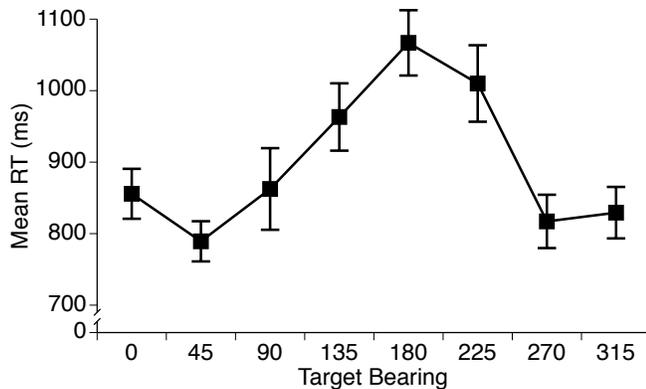


Figure 7. Experiment 2 RTs by target bearing at color ratio 0:8. Error bars depict SEM.

= -1.193, $p = .278$), nor for red targets at 6 blue to 2 red ($t(9) = -1.721$, $p = .119$). So again, having to switch IFORs precludes the kind of processing that yields the Kessler and Thomson (2010) type of target bearing effect.

General Discussion

People use IFORs every day. In social contexts, for example, we often infer various inter-personal relationships based on the spatial relations (such as position and distance) among people. Humans must know how to prioritize updating of IFORs so that the most relevant IFORs are represented sufficiently richly to support the task at hand. The present study extends the findings of Wang et al. (2005) to study prioritization and updating among multiple IFORs. Spatial updating was found to be significantly constrained by the limits of human attentional processes as evidenced by a switching cost of approximately 236 ms (averaged across the two experiments). But those constraints can be relaxed somewhat with practice, as our interaction effect of target color with color ratio showed. The results indicated that subjects engaged in little strategic trade-off of prioritizing one IFOR over the other, as apparently the cost of attending one IFOR-supporting object or the other, and engaging the target bearing representation based on that IFOR, decreased somewhat with practice. In a larger sense this suggests that since the cognitive mechanisms supporting IFOR-type representation are apparently susceptible to practice effects, that reasoning comes relatively late in the human attentional stream.

Meanwhile the conspicuous absence of a target bearing effect for the conditions in which a switch of attended IFOR was likely hints that the establishment of an IFOR is able to take advantage of spatial representations already in working memory. IFORs, therefore, may be limited to one instantiation at a time as a function of human working memory capacity, but they may be disbanded and instantiated dynamically, taking advantage of whatever spatial representation may be available at the time to be incorporated into the IFOR to support task performance as necessary

It is clear that attention plays a central role in mediating IFOR representational conflicts and in modulating salience.

Future work should clarify the computational mechanisms underlying spatial salience and people's capacity to effectively process spatial relationships in multi-IFOR task environments.

Acknowledgments

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