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Spatial Reasoning With Multiple 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 and supporting many socio-spatial tasks. In a complex environment, people often need to utilize multiple reference systems that are intrinsic to different objects (intrinsic frame of reference, IFOR), but these IFORs may conflict with each other in one or more ways. Current spatial cognition theories do not adequately address how people handle multi-IFOR reasoning problems. Two experiments manipulated relative orientations of two task-relevant objects with intrinsic axes of orientation as well as their relative task salience. Response times (RTs) decreased with increasing salience of the targeted IFOR. In addition, RTs increased as a consequence of intrinsic orientation conflict, but not by amount of orientation difference. The results suggest that people encounter difficulties when they have to process two conflicting IFOR representations, and that they seem to prioritize processing of each IFOR by salience.

Keywords

spatial reasoning; spatial representation; intrinsic frame of reference

A large body of evidence suggests that people organize spatial representations and reason about spatial relationships using frames of reference (“FORs,” Grabowski, 1999; Levelt, 1996; Levinson, 1996; May & Klatzky, 2000; Shelton & McNamara, 2001; Wang, Johnson, & Zhang, 2001). FORs can be based on our own viewpoints, expressing spatial representations centered on ourselves including viewable scenes and reachable locations (the egocentric FOR, or EFOR). FORs based on navigable environments (the allocentric FOR, or AFOR), such as rooms, buildings, or cities, represent the layouts of those environments and what affordances they give to way finding (Klatzky, 1998; Mou & McNamara, 2002; Wang & Spelke, 2002). Recently a third type of FOR, which is generally called the intrinsic frame of reference (IFOR), has received much attention because of its unique properties (e.g., Kessler & Thomson, 2010; Li, Mou, & McNamara, 2009; Mou & McNamara, 2002; Mou, Zhang, & McNamara, 2009; Sun & Wang, 2010; Wang, Sun, Johnson, & Yuan, 2005).

What is unique about the IFOR is that its reference point and axes are not anchored on the observer self or the entire environment, but on an object or an object group that are *within*

the environment and *exogenous* to the observer, provided that the anchoring object(s) can afford distinctive orientation axes or boundaries (Li et al., 2009; Mou et al., 2009; Sun & Wang, 2010). Figure 1 highlights the distinction between the three reference systems. An observer is sitting in front of a computer screen that displays two cannons and a target. The target location can be represented relative to the observer self (EFOR) or relative to the frame of the computer screen which encompasses all displayed objects (AFOR). In addition, the target location can also be represented from the perspective of the cannon (IFOR), for example, the target bearing and distance can be defined in a polar coordinate system anchored to the cannon. In this case, the bearing and distance are defined as each cannon provides a distinctive intrinsic orientation axis (IOA). Psycholinguistic literature also points to other types of intrinsic perspectives depending on the spatial property of the anchoring object, for instance, inside versus outside, visible versus occluded (e.g., Grabowski, 1999; Levelt, 1996).

Note that the difference between AFOR and IFOR can be subtle. Whereas both systems use a reference point and axes that are exogenous to the observer's self, the IFOR is more flexible. First, the reference point and axes are usually fixed (i.e., absolute) for the AFOR but may vary at will for the IFOR. This is because the anchoring object in an IFOR can move, or there can be multiple anchoring objects each with a different IOA. Second, the AFOR representation of spatial relations is typically independent of the EFOR but the IFOR representation can *interact* with the EFOR, in which the observer can project his or her egocentric perspective onto the intrinsic axis of the exogenous anchoring object. As a consequence, the IFOR can possess spatial properties that are originally unique to the EFOR. For example in Figure 1, if the AFOR is used, the target location can be defined by Cartesian or polar coordinates relative to the bottom-left corner of the computer screen, which will remain constant regardless of the viewing angle of the observer. In contrast, if the IFOR is used, the observer can align his or her view with the intrinsic axis of the cannon by a mental self-rotation (SR), and refer the target location as on the "right" of Cannon 1, or, on the "left-front" of Cannon 2.

The interaction between an IFOR and an EFOR provides an important way to behaviorally differentiate people's usages of AFOR and IFOR, especially when a task can be performed by solely utilizing the AFOR. For example, Kozhevnikov, Motes, Rasch, and Blajenkova (2006) reported that some participants switched to a mental object rotation (OR) strategy instead of perspective taking when it fit the requirements of a spatial updating task. In our example (Figure 1), the updating task could be to respond to the target location relative to one of the cannons. Although the task has an intrinsic nature (i.e., using the cannon as an IFOR), it can also be achieved by mentally rotating the cannon according to the allocentric frame until it aligns with the target (i.e., only AFOR is involved). However, if the response time (RT) is dependent on the angular disparity between the EFOR and IFOR orientations, it will reflect the observer's effort of perspective taking (i.e., adopting an IFOR) (for a detailed discussion on perspective taking, see Kessler & Thomson, 2010).

Our example also highlights the fact that when people reason about spatial relationships in a complex environment, multiple relevant IFORs may coexist. In Figure 1, if the observer intends to report the target location from the perspective of the cannon, then one IFOR must

be processed for each cannon. Though it has been shown that representations of the EFOR, such as distance and bearing, are available to the observer quickly and effortlessly (Klatzky, 1998), those representations may not be so easily obtained for the IFOR (Kessler & Thomson, 2010; Wang et al., 2005). Evidence exists indicating that many imaginal transformations of spatial representations generally are not primitive, quick, nor effortless (Parsons, 2003; Shepard & Metzler, 1971). Prior work in the area of visuospatial perspective taking indicates that given the cognitive demands it is unlikely that people process more than perhaps a small number of these IFORs in parallel (Gunzelmann, Anderson, & Douglass, 2004; Parsons, 2003; Shepard & Metzler, 1971). In addition, when the same target can be referenced by multiple conflicting IFORs (e.g., with different IOAs), it may slow down people's response (Sun & Wang, 2010). Together, it is implied that a processing bottleneck may occur whenever a person attempts to simultaneously handle multiple IFORs. But then the issue arises whether such a bottleneck can be overcome by prioritizing individual IFOR representations.

We report a study regarding how people process multiple conflicting IFOR representations by prioritization. It has been shown that contextual factors may impact people's selection of reference systems. People accord the most salience to the reference system expected to involve an imminent action (Grabowski & Miller, 2000; Tversky & Hard, 2009). This means that when multiple IFORs coexist, people would likely resolve competition among conflicting IFORs in favor of the one that has the greatest salience, the one that is most likely to be required for some imminent action. To test this hypothesis, our study adopted a "Two Cannons" pointing task similar to that shown in Figure 1. In this task participants needed to determine which way one chosen cannon of the two shown should turn to point at a designated target. To do so they must have defined spatial representations of the target's location in terms of the orientation of the selected cannon in the task environment since the task centers on judgments regarding which way the cannon must turn to face the target. Salience of the two cannons was manipulated so as to make one or the other more likely to be the basis of response. If people can attend to only one IFOR at a time then in an environment where multiple IFORs exist those representations must be prioritized somehow. If priority of IFOR representations is determined by salience, as Wang et al. (2005) found for potential targets within a single-IFOR task environment, then RT should vary with the targeted IFOR's relative salience. That is, when there are two IFOR representations the more salient IFOR should take processing priority.

Experiment 1

Method

Participants—Fourteen graduate students and postdoctoral fellows participated. Participants volunteered and each received \$30 for approximately 45 min of their time. They had a mean age of 30.6 years ($SD = 6.93$) and six of them were female.

Design and Materials—All experiment factors varied on a within-participants basis (Table 1). In each trial two cannon stimuli, one red and one blue, were presented in the center of a computer monitor (Figure 2). Each cannon had an obvious intrinsic orientation

and we established conflict between the cannon orientations by manipulating relative angle between the two cannons so that they were either on top of each other as in Figure 2 (top), at 90° to each other (Figure 2, center), or 180° to each other (Figure 2, bottom). Eight colored (red and blue) dots were also presented around the cannons. One of the eight dots (hence “target”) flashed 1 s after stimulus presentation. The participant's task was to indicate the direction the color-matching cannon (hence “targeted cannon”) should rotate in order to face the target. The eight dots presented in each trial could be in one of five different color ratios, from all-blue (8 blue:0 red) to all-red (0 blue:8 red), in increments of two dots. Thereafter we use a simple “x:y” form to represent the color ratio (e.g., 6:2 means 6 blue and 2 red, and 2:6 means 2 red and 6 blue). The purpose of color ratio manipulation was to give each cannon its relative salience since the target was randomly selected therefore the targeted cannon would be more likely in the “majority color.” Relative cannon angle and cannon orientations varied randomly by block, and in each block target could appear in any one of the eight possible locations. Each participant performed blocks of trials with a cannon orientation and cannon angle condition block twice to yield 480 trials total.

Procedure

At the beginning of a trial both cannons appeared, along with the eight color dots. One second later a yellow ring flashed around one dot to indicate that it was the target. Participants then responded as quickly and accurately as possible which way the targeted cannon (the cannon of the same color as the target) should turn to face the target: left, right, or no turn. Participants indicated their responses with the left, right, and up arrow keys, respectively, on the computer keyboard. Responses had the stipulation that the turn was to be the shortest way round. In the case of targets appearing 180° to the salient cannon's orientation participants could respond with either direction since the angular offset by either rotational direction was the same. The experiment played auditory feedback for both correct and incorrect responses. In the case of incorrect trials the experiment also paused for 2 s to discourage random guessing.

Results

Trials were filtered for response accuracy and outlier RTs before analysis. Response accuracy ranged from 90% to 99% with a mean of 95%. Outlier trials were filtered on a per-participant basis using the van der Loo (2009) method, which removed 218 observations, or 3.24% of the total. Trials with targets appearing at 0° and 180° bearing relative to the targeted cannon were filtered and excluded from analysis.

Dot Color Ratio, Target Color, and IFOR Conflict—Analyses of target color by color ratio, shown in Figure 3, left out two levels of the color ratio factor, 8:0 and 0:8, since there could only be one target color for each of those levels. RTs for blue targets got slower over the course of dot color ratio sequence (from more blue dots to more red dots) while RTs for red targets got faster. A repeated measures ANOVA revealed a significant interaction, $F(2, 26) = 17.891$, $p < .001$, indicating a type of salience effect. Presumably the blue cannon was salient (i.e., was paid more attention to) in the 6:2 condition and the red cannon was salient in the 2:6 condition. Therefore, when a red target appeared in the 6:2 condition participants might have to switch from the salient blue cannon-based IFOR currently being focused on to

the non-salient red cannon-IFOR, inducing a switch cost. As a result, a blue target would be faster in the case of the salient blue cannon (6:2 condition), and vice versa, resulting in an interaction between color ratio and target color. Further analyses show that the switch cost was different in different color ratio conditions. The switch cost was 139 ms in the 6:2 condition, $F(1, 13) = 23.032$, $p < .001$, and the switch cost was 59 ms in the 2:6 condition, $F(1, 13) = 3.44$, $p = .086$. The decrease of 80 ms probably indicates a practice effect. Overall, the significant interaction between color ratio and target color suggests that it is likely that participants could represent only one IFOR at any given time and that tasks involving multiple IFORs might have to incur additional switch cost.

To examine the effect of IFOR conflict, we further separated trials based on relative cannon angle. Since the degree of conflict (i.e., relative cannon angles of 90° and 180°) did not differ significantly (1,001 ms vs. 961 ms, $F(1, 13) = 3.84$, $p = .072$), we collapsed those two relative cannon angle conditions and only distinguished those trials with an IFOR conflict (relative cannon angles $> 0^\circ$) and those without (relative cannon angle $= 0^\circ$). The results are shown in Figure 4, which shows that target color only mattered when cannon angles conflicted with each other: the target color by dot color ratio interaction was significant when conflict was present, $F(2, 26) = 26.908$, $p < .001$, and was not when conflict was absent, $F(2, 26) = .2794$, $p = .759$. This makes sense in that the target color indicated which IFOR participants should have selected and there was no selection to be made when the IFORs did not conflict. In addition, the presence of IFOR conflict slowed participant performance relative to not having IFOR conflict, $F(1, 13) = 30.355$, $p < .001$.

Targeted Cannon Orientation—As mentioned previously, it is possible that the participants had performed the task by rotating the cannon toward the target (OR) instead of rotating their egocentric perspective onto the cannon's orientation (SR). That is, it is possible that only the AFOR was used, and no perspective taking in IFOR had occurred. To rule out this alternative strategy, we plotted RT as a function of the targeted cannon orientations (relative to the observer's self-orientation, Figure 5). It appears that RT was significantly dependent on the angular disparity between the self and cannon orientations, $F(5, 65) = 15.634$, $p < .001$, suggesting that participants took longer to respond to trials where the targeted cannon misaligned with their own perspective with a larger angle. The increased RT at the greater misalignments indicates that participants might have used some type of mental self-rotation to adopt an IFOR representation from the perspective of the targeted cannons.

Target Bearing—Figure 6 depicts RT as a function of target bearing relative to targeted cannon. The main effect of target bearing was significant, $F(5, 65) = 10.710$, $p < .001$. Further analyses show that participants were slower when target bearing was 135° or 225° (135° and 225° target bearing versus 45°, 90°, 270°, and 315° target bearing, $F(1, 13) = 17.693$, $p < .001$). The target bearing results are consistent with earlier findings in spatial cognition literature (e.g., Hunt & Waller, 1999; Wang et al., 2005) and suggest that similar spatial processes were engaged in this task where IFOR operations were dominant.

Experiment 2

Experiment 1 revealed a subtle saliency effect in that the switch cost was not as big in the 2:6 condition as that in the 6:2 condition. We suspected that this was due to a practice effect because in Experiment 1 dot color ratio varied sequentially such that the 6:2 condition was always presented earlier than the 2:6 condition. To counterbalance the sequential practice effect, Experiment 2 was designed to vary dot color ratio sequentially in the opposite order, from all-red (0:8) to all-blue (8:0). In all other respects Experiment 2 was identical to Experiment 1.

Method

Fourteen graduate students and postdoctoral fellows participated in Experiment 2. Participants each received \$30 for approximately 45 min of their time. They had a mean age of 32.8 years ($SD=7.24$) and five 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. Otherwise Experiment 2 replicated Experiment 1's materials and procedures identically.

Results

As in Experiment 1, trials were filtered for response accuracy and outlier RTs before analysis. Response accuracy ranged from 94% to 99% with a mean of 96%. Outlier trials were filtered on a per-participant basis using the van der Loo (2009) method, which removed 211 observations, or 3.14% of the total number of trials. Trials with targets appearing at 0° and 180° bearing relative to the targeted cannon were filtered and excluded from analysis.

Dot Color Ratio, Target Color, and IFOR Conflict—In Experiment 2 saliency progressed from red to blue. As in Figure 3, Figure 7 depicts effects on RT of the interaction of target color and dot color ratio. A similar interaction was found, $F(2, 26) = 18.351$, $p < .001$, indicating that targets compatible with the salient IFOR were faster than those not compatible. As saliency progressed from red to blue, we again observed a decreased switch cost, only this time red targets were faster than blue targets in the earlier 2:6 condition (175 ms, $F(1, 13) = 23.323$, $p < .001$) and blue targets were faster than red targets in the later 6:2 condition (66 ms, $F(1, 13) = 5.728$, $p = .032$). The reduced RT again indicates a possible practice effect.

As in Experiment 1, we separated trials based on relative cannon angle and distinguished those trials with an IFOR conflict (relative cannon angles $> 0^\circ$) and those without (relative cannon angle $= 0^\circ$). The results are shown in Figure 8. Again, the interaction of color ratio and target color depended on whether there was an IFOR conflict: When IFORs conflicted participants were faster for those targets that were compatible with the salient IFOR, $F(2, 26) = 13.681$, $p < .001$, and without IFOR conflict target color did not interact with color ratio, $F(2, 26) = 2.2121$, $p = .1297$. This replicates Experiment 1's pattern of results supporting our hypothesis that people might only be able to adequately process one IFOR at any given time when multiple conflicting IFORs are involved. It also rules out the possibility that the effects of color ratio were due to the presentation sequence of the color ratio.

Target Bearing—Again a similar main effect of target bearing was identified, $F(5, 65) = 11.707$, $p < .001$. Further analyses show that participants were slower for targets appearing at 135° and 225° bearing relative to the targeted cannon than those at 45° , 90° , 270° , or 315° , $F(1, 13) = 23.463$, $p < .001$ (Figure 9).

General Discussion

The main purpose of this paper was to examine how people can handle multiple conflicting IFORs. Results in the two experiments clearly show that participants experienced a switch cost in RT when there was a conflict of IFORs (i.e., conflict trials eliciting greater RTs than nonconflict trials). More importantly, our results show that RTs were longer when the target was in the non-salient IFOR relative to the salient IFOR. These results imply a limitation in people's processing of multiple conflicting IFORs and suggest that it is likely that only one IFOR could be actively represented at a time. We suspect that this limitation may be related to people's limited capacity of working memory and the nature of human attention. Imagining the spatial layout from the perspective of another object or agent can be a costly process. When multiple conflicting IFORs are potentially relevant people may have to prioritize the process based on various concerns such as salience and focus on one IFOR at a time. While this could lead to a switch cost when the currently focused IFOR turns out to be irrelevant, IFOR prioritization may afford a type of situation awareness and allows fast actions when the currently focused IFOR is more likely to be the targeted IFOR.

In addition, our results show that the time cost of generating an IFOR representation is at least partly due to subjects aligning themselves with the axes of the targeted cannon (i.e., adopting an IFOR). The result that RT increases as a function of observer to targeted cannon misalignment indicates that people perform some type of mental self-rotation and perspective taking to align themselves with the targeted cannon. Our results support this explanation even though other types of strategies such as mental object rotation or visibility judgment have also been suggested (Keehner, Lippa, Montello, Tendick, & Hegarty, 2006; Kessler & Rutherford, 2010; Kosslyn, Thompson, Gitelman, & Alpert, 1998; Kozhevnikov et al., 2006; Michelon & Zacks, 2006; Wohlschlagel & Wohlschlagel, 1998; Wraga, Shephard, Church, Inati, & Kosslyn, 2005; Wraga, Thompson, Alpert, & Kosslyn, 2003; Zacks & Michelon, 2005; Zacks & Tversky, 2005). If subjects had been performing the Two Cannons task by mental object rotation of the cannons then the RTs as a function of the targeted cannon orientations should have been flat, which was not what we found. Our results clearly indicate the relevance of self-rotation and perspective taking in IFOR-related operations, though further studies are necessary to examine the detailed mechanisms underlying the processes.

If people can only process one IFOR representation at a time, as our findings have suggested, then complex spatial reasoning involving multiple IFORs may have to occur in multiple steps rather than in parallel. For example, in a socio-spatial context, we may know that Bob stands to the left of Charlie in a room. If Bob walks around and after a while, we might be able to easily update Bob's position relative to Charlie by maintaining a “Charlie-based” IFOR. However, if the task at hand is suddenly changed to updating Charlie's position relative to Bob, it may not be as easy since the task now requires a new Bob-based

IFOR, which can cost additional resources. One way to reduce the cost of simultaneously maintaining multiple IFORs in complex environments is to prioritize. Our results suggest that task-relevant salience measures, which can be determined by top-down and bottom-up processes, serve as useful bases for prioritization in multi-IFOR spatial reasoning. In this manner a complex problem may be broken down into a few tractable problems. Then the most urgent spatial reasoning problem may be addressed while the others are queued.

From another aspect, IFOR representations may simply be too complex to keep in mind more than one at a time since it requires a mental model of the spatial world from another agent's perspective. This mental model incorporates object recognition situated within a spatial reference frame similar to the egocentric – that is, with the same representational affordances – but involves transformations in terms of the recognized object's intrinsic axis of orientation (e.g., Kessler & Thomson, 2010; Li et al., 2009; Mou & McNamara, 2002; Mou et al., 2009). This rich representation certainly puts considerable demands on working memory and attention. Therefore it is plausible that people may adopt a “one at a time” strategy when facing multiple conflicting IFORs. One benefit of such a strategy is that it affords quick actions when the currently focused IFOR is indeed relevant.

In a broader theoretical sense our results are congruent with a multi-FOR account of human spatial cognition. According to the FORMS (Frame of Reference-based Maps of Salience) theory of human spatial cognition (see Sun & Wang, 2010; Wang et al., 2001, 2005), spatial representations are organized into multiple FORs and spatial relations are represented within each FOR as maps of salience. That is, some relations within a FOR are more salient and therefore have corresponding mental representations that are more readily accessible to the mind than others. Spatial performance is determined by the interactions among available FOR representations. IFOR representations are used by people together with the other FORs, egocentric and allocentric, to meet the spatial reasoning challenges of our environments and support situation awareness. The interaction between multiple conflicting IFORs – and the interaction between the IFOR and the EFOR – addressed in this study fit into this larger theoretical framework well.

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Figure 1.

Some spatial relationships in different frames of reference. An observer is sitting in front of a computer screen that displays two cannons and a target. The target location can be defined in one egocentric reference system (relative to the observer self), two intrinsic reference systems (relative to each cannon), and one allocentric reference system (relative to the computer screen).

Figure 2.

Experiment displays depicting 0° relative cannon angle (top), 90° relative cannon angle (center), and 180° relative cannon angle (bottom). Here blue is depicted as dark gray and red is depicted as light gray. In the top panel, 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 the center panel, 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 the bottom panel 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.

Figure 3.

Experiment 1 response times, target color by dot color ratio. Error bars depict standard error of the mean.

Figure 4.

Experiment 1 response times, target color by dot color ratio and conflict status. Error bars depict standard error of the mean.

Figure 5.

Experiment 1 response times by targeted cannon orientation. Orientations increment clockwise relative to vertical. Error bars depict the 95% confidence interval of the mean.

Figure 6. Experiment 1 response times by target bearing. Error bars depict standard error of the mean.

Figure 7. Experiment 2 response times, target color by dot color ratio. Error bars depict standard error of the mean.

Figure 8.

Experiment 2 response times, target color by dot color ratio and conflict status. Error bars depict standard error of the mean.

Figure 9. Experiment 2 response times by target bearing. Error bars depict standard error of the mean.

Table 1

Combinatorial table of conditions of Experiment 1. Absolute orientation 0° is up, incrementing clockwise. All factors varied within-participants

Relative cannon angle	Cannon orientation (specific to each cannon angle condition)	Target position (all cannon angle condition)	Target color (all cannon angle condition)	Dot color ratio (all cannon angle condition)
0°	90° (blue & red) 270° (blue & red)			
90°	45° (blue) & 315° (red) 135° (red) & 225° (blue)	0°–315°, in increments of 45° positions total. Varied randomly, without replacement, within each color ratio cycle.	Eight red or blue, varied randomly within each color ratio cycle, constrained by color ratio condition.	Eight blue: 0 red – 0 blue: 8 red, in increments of two dots. Five color ratios total. Varied sequentially within each trial block.
180°	90° (blue) & 270° (red) 90° (red) & 270° (blue)			