Cogn Process (2004) 5: 175–188
DOI 10.1007/s10339-004-0022-2

RESEARCH REPORT

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Where is the donut? Factors influencing spatial reference frame use

Received: 13 October 2003 / Revised: 2 June 2004 / Accepted: 3 June 2004 / Published online: 29 July 2004

Abstract Because different reference frames can be used to describe a simple spatial situation such as the relationship between two objects, spatial descriptions can be confusing and/or ambiguous. To reduce this difficulty, do people assume a particular reference frame when interpreting spatial descriptions? If so, does the makeup of the spatial scene affect this assumption? Does cognitive load interact with this assumption? In three experiments, we examined reference frame use and how situational and cognitive factors interact with spatial description interpretation. The main cognitive factor involved memory load, i.e., whether responses were made from memory or not. From the features of the scene (object-facing direction, located object position) emerged two interactions of interest. First, since object-facing direction has implications for the cognitive strategies used to determine spatial relations, we assessed how object facing interacted with reference frame use. Second, we assessed how the descriptive axes associated with multiple reference frames influenced reference frame use. The results indicated that people predominantly use the intrinsic reference frame. Yet, despite this tendency, cognitive and situational variables also affected responses, both alone and in combination. These findings suggest that people maintain cognitive flexibility when interpreting spatial descriptions to reduce or inform potential ambiguities.

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Keywords Spatial cognition · Reference frames · Spatial language · Spatial location

Introduction

Imagine that a furniture store's delivery service has arrived with your new end table. They ask you where you want it and you reply, "Put it to the right of the recliner, please." They put the table next to the recliner, but in an inappropriate position (for example, on the side opposite to that you intended). Why might this have happened?

Comprehension of your description requires the use of a reference frame. Three different reference frames could have been used to interpret your instructions: the speaker's (yours), the listener's (delivery service's), or the object's (recliner's) point of view. Unless the speaker, listener, and object all occupy the same location with the same orientation, each reference frame can lead to a different interpretation. With different available reference frames, what determines the frame that will be used? We suggest that people adopt strategies for reference frame use that: (1) allow flexibility, (2) may not be the most cognitively economical, and (3) take into account the features of the spatial situation. The present work examines how cognitive processing interacts with features of the spatial scene during description interpretation.

According to Levinson (1996), three reference systems can be used to describe all spatial situations. Two of these, the relative and intrinsic, are relevant to the present work. A "relative frame" incorporates the speaker's coordinate system, involves a tertiary spatial relationship, and uses projective terms (left, right, front, back, above, below). An "intrinsic frame" uses an object's or another person's coordinate system, describes a binary relationship, and uses the same projective terms. When reference systems use the same terms, ambiguity may result. In these cases of ambiguity, how do processing demands interact with the details of a scene and the description in a final interpretation?

The present studies examined reference frame use in ambiguous situations. All scenes showed simple, two-object arrays; all descriptions used projective terminology. In each scene, one object had intrinsic sides (e.g., car, chair) and the other did not (always a donut-shaped object, herein referred to as the donut). Although simple in nature, these scenes allowed us to examine the interactions between cognitive processing and contextual factors of the scenes. By manipulating processing demands in the form of memory load, information source, and instruction specificity, we could assess cognitive flexibility and adherence to cognitive economy. For memory load, the scenario was either perceptually available or unavailable (experiments 1 and 2). The initial information source was either a picture (experiments 1 and 2) or a spatial description (experiment 3). Instructions either specified that different reference frames could provide plausible descriptions of the scenes (experiments 2 and 3) or did not mention such plausibility (experiment 1). Features of the spatial scene included the intrinsic object's orientation, and the donut's location relative to the intrinsic object. Although these features separately can affect reference frame use, the present work examined how these factors interact in spatial term interpretations.

Information processing strategies and demands

Cognitive flexibility and cognitive economy appear to go hand-in-hand; in order to be flexible in the application of strategies, it helps to develop alternate interpretations of presented information. We assessed these aspects of spatial processing by examining two reference frames, the relative and the intrinsic, based on the spatial relationships and spatial terms used in a presented scene (Levinson, 1996). Neuropsychological and behavioral data supports the independence of these two reference frames (e.g., Arguin and Bub 1993; Woodin and Allport 1998). Between these reference frames, researchers have suggested that individuals rely on a default or dominant frame, but have not agreed which frame might serve this role. Some have argued for relative frame dominance since it corresponds with the perceptual view of the scene (Levelt 1982, 1989; Linde and Labov 1975). Because of this, the relative frame should be the most cognitively economical. Other frames must be computed through processes such as mental rotation. However, other researchers have found no evidence supporting relative frame dominance and instead support intrinsic frame dominance (Carlson-Radvansky and Irwin 1993; Carlson-Radvansky and Radvansky 1996; Taylor et al. 1999, 2001a). Still other research suggests a highly flexible, resource intensive approach wherein more than one reference frame may initially be activated (Carlson et al. 2002; Carlson-Radvansky and Jiang 1998). These conflicting findings have led some to contend that no default or dominant frame exists (Frank 1998; Tversky 1996), which in turn, suggests that individuals use reference frames flexibly (as a function of strategies, preferences, or spatial cues).

As stated earlier, flexibility may necessitate engaging in processes that require extended cognitive activity (which, in our terms, are not cognitively economical). Intuitively, the intrinsic frame seems to require additional cognitive processing, such as determining the object's principal axes. Despite this extra processing, recent neurophysiological studies using event-related potentials (ERPs) support dominant intrinsic frame use (Carlson et al. 2002; Taylor et al. 1999, 2001a). Results of Taylor et al. (1999, 2001a) indicated predominant use of the intrinsic frame by showing a larger N400 ERP component when the intrinsic reference frame was not used. The N400 is hypothesized to reflect greater need for semantic integration (Holcomb 1993). So, when participants could not rely on their preferred frame, they engaged in additional semantic processing, most likely reassessing whether the term could fit the spatial context.

By placing information processing demands on participants, we also assessed the use of processing strategies. Previous research suggests that memory load and initial information sources should impact the reference frame strategies that participants adopt. Bryant et al. (2001) suggest that spatial processing differs depending on whether the scene is readily available, i.e., whether information must be retrieved from memory or can be directly viewed. Using a sentence–picture verification paradigm, we manipulated the spatial scene's perceptual availability.

Early sentence–picture verification research evaluated how observers encode pictures and develop sentence-based descriptions from those depictions (Chase and Clark 1971, 1972; Clark and Chase 1972). Clark and Chase (1974) proposed three ordered rules for comparing pictures and descriptions. The first rule suggests that observers consciously select to encode object locations in a particular order, perhaps based on preferences, motivation, or prior knowledge. The second rule proposes that without this constraint, observers encode the picture with respect to a stable or prominent reference object. If no salient referent is available, according to rule three, observers rely on a default encoding of objects based on directional biases (e.g., verticality; Clark 1973).

How might these rules be applied with respect to task-driven memory loads? Clark and Chase (1972, 1974) tested whether the sequential order of comparisons influenced use of these ordered rules. In a verification task, participants compared an initial image-based depiction to a verbal description (e.g., star is above line, or line is not above star). Verification latencies supported use of the three rules. When instructed to pay attention to a particular object, participants tended to encode the depiction with respect to the object, supporting the first rule. Participants also encoded descriptions with respect to a reference object (e.g., a stable line, supporting the second rule), and usually encoded the top object with respect to the bottom object (supporting the third rule).

In more recent behavioral studies, sentence–picture verification tasks have been used to investigate complex spatial reference frames. Participants in these studies are asked to verify whether a spatial relation is correctly represented in a picture. Within this paradigm, Logan and Sadler (1996) identified a sequence of cognitive steps for using reference frames. First, the located and reference objects must be found. Second, directions are assigned around the reference object. Next, the spatial relation between the objects in the picture are computed and compared to the spatial term. Finally, the appropriate response is made. Carlson et al. (2002) showed ERP evidence supporting these steps. For steps two and three, the available reference frames need to be considered. Thus, for these steps, differences in processing the available reference frames may emerge and preferences for one frame over another may be revealed. This is a situation in which memory load should have the greatest impact.

The present studies used elements from sentence–picture verification studies to compare processing with and without memory load. Experiments 1 and 2 presented the picture either prior to the description or simultaneous with it. Thus, participants either needed to build a memory representation from the picture, or did not because the picture was present. Consistent with Bryant et al. (2001) we predicted that memory load would influence reference frame processing. When responding from memory, participants should prefer using the intrinsic frame as demonstrated by Taylor et al. (2001a). Responses based on perceptually available comparisons should show less preference because people can perceptually access information about the relative frame. In experiment 3, the picture was presented prior to the description. With the initial information given as a description, we predicted a strong tendency to adhere to the steps suggested by Clark and Chase (1972, 1974) resulting in a single, intrinsic frame interpretation.

Contextual influences on reference frame use

Features of the spatial scene could impact reference frame use, either alone or in combination. We examined the following contextual variables: (1) the position of the donut relative to the intrinsic sides of the reference object and (2) the orientation of the reference object. These two contextual variables then, necessarily, interact with the spatial terms used for accurate descriptions. From these contextual variables arise two issues of interest: strategy differences based on object-facing direction and cognitive consequences of conflicting reference frames sharing a descriptive axis.

Object-facing directions and interactions

Object-facing direction drives the interaction between reference frames. When the object and observer are not aligned, ambiguity in using spatial terms can result due to a "competition effect", or stimulus–response incompatibility, in assigning directions to the spatial term (Carlson et al. 2002). The competition effect occurs when reference frames assign conflicting directions to the same spatial term. In these cases Carlson-Radvansky and Irwin (1994) proposed that multiple reference frames may initially be activated. Then, over time, the accessibility of unnecessary frames may be inhibited (Carlson-Radvansky and Jiang 1998). There are cognitive costs associated with a reference frame conflict. Carlson et al. (2002) showed ERP evidence of the competition effect, particularly when participants were either instructed to consider both possible reference frames or to use the less preferred frame.

If we only consider situations in which a competition effect exists, object-facing direction has implications for cognitive strategies, particularly for the intrinsic frame. Determining spatial locations from an object's intrinsic frame requires additional cognitive processing, such as mental rotation. However, different object orientations lend themselves to different cognitive processing strategies, as shown in mental rotation research. Mental rotation findings show increased response time and decreased accuracy as a function of the degree of necessary rotation (e.g., Shepard and Metzler 1971). A different strategy, one of flipping the object, is sometimes adopted for 180° rotations, eliminating the need for intermediate representations (Kanomori and Yagi 2002). Participants may use different strategies when the object faces to the right or to the left compared to when it faces toward or away from the participant. As such, we specifically examined object-facing direction when reference frames conflicted.

Strategy differences based on object-facing direction are likely to interact with donut location. Franklin and Tversky (1990) proposed the "spatial framework model" to explain response differences based on an object's location around a person. In their studies, participants read stories describing objects surrounding a protagonist. Then, the text reoriented the protagonist and participants verified locations relative to the protagonist's new orientation. Response times differed as a function of object location. Participants responded fastest to objects above and below the protagonist, next fastest to those in front and behind, and slowest to those to the right and left. This response time pattern was evident whether the information was learned from descriptions (Franklin and Tversky 1990) or models (Bryant and Tversky 1999), whether the objects were described as surrounding the person or in a scene in front of them (Bryant et al. 1992), whether the objects surrounded a person or another object (Bryant and Tversky 1992), and whether responses were elicited using directional terms or object names (Bryant and Tversky 1992). An exception to this pattern was seen when participants physically, rather than mentally rotated, to accomplish the verification (De Vega and Rodrigo 2001).

The spatial framework pattern reflects a mental model with the protagonist/object at the model's center. As such, the response pattern is driven by perceptual availability and symmetry, but is not based on an internalized perception (Bryant et al. 2001). For the horizontal plane, the front/back plane has greater perceptual availability since perceptual organs generally face forward (Clark 1973). Bryant et al. (1992) showed faster responses for objects in front of and behind the protagonist when objects were described as surrounding the protagonist and the protagonist was described as the viewer. When the objects were described as surrounding the protagonist, but the protagonist was separate from the viewer, this response pattern was not evident. In contrast, the right/left dimension has equal perceptual availability, but also has symmetry, making distinctions between right and left more difficult.

In the present experiments, we predicted that object-facing direction would show a main effect based on available strategy differences. The direction of this effect, however, was not clear. Because participants may adopt a switching strategy rather than a mental rotation strategy when the object faces toward (for right/left donut locations) or away from them (for front/back donut locations), responses to these facing directions may be faster and more accurate. However, when the object faces toward or away, some donut locations use the same descriptions for both reference frames and some require different descriptions. This confusion may be sufficient to result in slower responses and reduced accuracy.

More interesting are the interactions between object-facing direction and both the donut location and reference frame. When the object faces to the right or to the left and the intrinsic frame is used, results should replicate the spatial framework pattern as all locations should be determined through mental rotation. The response pattern for the relative frame cannot be predicted as easily. When the object faces toward or away, participants should be able to determine correct descriptions between the reference frames by switching terms (e.g., front for back or right for left).

Descriptive term axis discrepancy and interactions

Projective spatial terms are paired along an axis. Some pairs have a marked member, while others do not. Front is considered as marked or positive relative to the back. Left/right, in contrast, is a symmetrical pair; each member is treated equally (Clark 1973). What are the cognitive consequences when different reference frames use the same descriptive axis? Using the same axis may facilitate processing if the directional pairings prime one another. In contrast, using the same axis may lead to confusion requiring additional checking of term accuracy.

These predictions about descriptive term axis discrepancy may interact with the axis used (i.e. front/back or right/left). Further, projective term interpretation sometimes requires assumptions about the spatial scene, particularly the relative frame interpretation of front and back. In English, the reference object is assumed to face the observer, or in the position of canonical encounter (Clark 1973; Hill 1982). Because of this, an object located in front of a reference object from the relative reference frame is located between the reference object and the observer, while an object located in back would be on the far side of the reference object. Other languages make different assumptions about reference object orientation (Hill 1982). While linguists have posited these assumptions, behavioral evidence suggests greater variance in interpreting these terms (Taylor et al. 2001b).

Interaction of information processing and context

While the information processing evidence provided above suggests cognitive flexibility, few studies have explicitly examined flexibility in spatial frame processing. Further, previous work has not examined how features of the spatial scene might interact with information processing demands.

Cognitive flexibility may be the direct result of differences in the spatial scene, i.e. contextual factors. Mounting evidence suggests that situational variables can draw attention toward one frame or the other, increasing its use. For example, making the intrinsic features of an object more salient increases the likelihood that the intrinsic frame will be engaged (Levelt 1984). Highlighting a physical or functional relationship between two objects (Carlson-Radvansky et al. 1999; Carlson-Radvansky and Irwin 1993) or taking advantage of gravitational relationships (Friederici and Levelt 1990) has a similar effect. All of these factors focus attention on specific aspects of the objects and scene.

Summary

The present research examined how cognitive processing demands and elements of spatial scenes interact in reference frame use. Cognitive processing demand was manipulated by increasing memory load. Scene elements included the reference object's orientation, the donut's location, and the spatial term used to describe the scene. With respect to the scene elements we were particularly interested in how these scene elements interacted. In particular, we were interested in the following questions: (1) Because different cognitive strategies can be adopted for different object-facing directions, how does facing direction interact with the donut location and (2) does processing differ if the conflicting reference frames share the same description axis? The interactivity of these elements would further support evidence suggesting cognitive flexibility in reference frame use.

Experiment 1

Participants

Thirty-one Tufts University undergraduates, 18 females and 13 males, participated for partial course credit. All participants were native English speakers.

Materials

Participants received 318 trials, each consisting of a picture and a spatial term. Pictures illustrated two objects; the reference object had intrinsic sides and the located object was always the donut. A total of six intrinsic objects were used, including two different chairs, a recliner, a couch, an airplane, and a car. The intrinsic object faced one of four directions (towards the participant, away from the participant, to the left, or to the right) and the donut was placed in one of four locations (intrinsically in front of, in back of, to the left, or to the right of the reference object). See Fig. 1 for an example picture. Four spatial terms were used (left, right, front, and back). A large asterisk separated each trial.

Procedure

Students participated in groups of four at separate Apple computers running Superlab software. The instructions first introduced participants to the intrinsic objects by presenting and naming each one, and to their four possible orientations, illustrating each using one of the intrinsic objects. Participants were told that they would see pictures of two objects (one of the intrinsic objects and the donut) as well as a spatial term. They were instructed to determine as quickly and accurately as possible whether the word could describe the donut's location. The instructions did not elaborate on the different interpretations based on reference frames to provide a baseline measure of reference frame use.

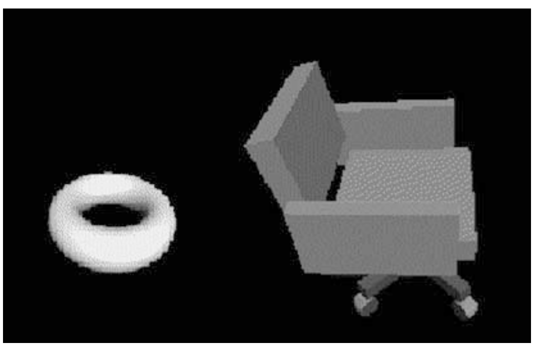

Fig. 1 Example of stimulus picture. The donut location here would be defined as left using the relative frame and back using the intrinsic frame

Participants were randomly assigned to one of three experimental conditions defined by the memory-load variable. Memory load was manipulated by changing the timing between the presentation of the picture and spatial term (delay, simultaneous, and simultaneous-delay). The conditions are described fully below. Trials were divided into three approximately equal experimental blocks to provide participants with short breaks and to circumvent computer memory constraints. The same instructions preceded each block so that blocks could be counterbalanced.

Each trial began with an asterisk, centered on the screen, followed by the stimulus picture and spatial term. Participants pressed the space bar to begin each trial. In the delay condition the picture appeared for 1,000 ms and was then replaced by the spatial term. In the simultaneous condition, the spatial term appeared simultaneously below the picture. In the simultaneous-delay condition, the picture appeared for 1,000 ms, and then remained while the spatial term appeared below it. When the term appeared, participants responded "yes" (i.e., "this term describes the donut's location") or "no" (i.e., "this term does not describe the donut's location") using designated keys.

In approximately half of the trials, the spatial term correctly described the donut location, either using the intrinsic frame, the relative frame, or both (approximately one-third for each). For the other half of the trials, the spatial term did not correctly describe the donut's location.

Design

The experiment involved a between-factor of presentation condition with three levels (delay, simultaneous, simultaneous-delay) and within-factors of reference frame (relative, intrinsic, both, neither), object-facing direction (right, left, toward, away), donut location (intrinsically right, left, front, back) and spatial term (right, left, front, back). These between-factors are combined to examine interactions of interest that will be described more fully below.

Results

Analyses examined trials in which the spatial term correctly described the donut location. Trials in which reaction time (RT) exceeded participant means by more than three standard deviations or in which participants did not use a designated response key were trimmed. Trimming resulted in loss of 2.5% of trials.

RT analyses first examined effects of presentation condition using two of the three conditions, delay and simultaneous-delay. In these two conditions, participants viewed the picture for 1,000 ms prior to seeing the description. Recall that participants in the simultaneous condition saw the picture and term at the same time;

thus, RTs for the simultaneous condition reflect picture-processing time and were uniformly longer. This analysis showed no effect of presentation condition ($P > 0.80$). The remaining analyses included all data.

Reference frame and presentation condition

Analyses of reference frame examined the relative, intrinsic, and both frame conditions and for the accuracy analysis how they interacted with the presentation conditions (delay, simultaneous, simultaneous-delay). Accuracy results showed a reference frame main effect, $F_{(2,\ 56)} = 71.607$, $P < 0.001$, MSE = 0.229, but RT did not ($P > 0.40$). Participants were least accurate using the relative frame ($M = 0.17$), compared to the intrinsic frame ($M = 0.76$) or both frames ($M = 0.83$). Follow-up contrasts indicated that relative frame use differed from the other two reference frame conditions ($P < 0.001$), which did not differ from one another ($P > 0.15$). Presentation condition interacted with reference frame, ($F_{(4,\ 56)} = 3.146$, $P < 0.05$, MSE = 0.229). Although the reference frame main effect was evident for all three presentation conditions ($P < 0.05$), the delay condition had increased relative frame accuracy and decreased intrinsic frame accuracy compared to the other presentation conditions (see Fig. 2).

Object-facing direction and interactions

Analyses of object-facing direction examined trials for which the reference frames were in conflict, i.e. the intrinsic and relative frame conditions only. This included trials in which the object faced right or left and a subset of trials in which the object faced toward or away (toward with the donut to the right or left and away with the donut in front or behind). Because a subset of the toward and away trials were used, these were combined in the analyses. This resulted in a three object-facing direction (toward/away, right, left) × two donut location (right/left, front/back) × two reference frame (relative, intrinsic) × three presentation condition (delay, simultaneous, simultaneous-delay) analysis with presentation condition serving as the between-participant factor. The design of this analysis allowed us to compare facing directions that potentially afforded different cognitive strategies.

Results showed a significant effect of object-facing direction for accuracy, $F_{(2,\ 56)} = 38.445$, $P < 0.001$, MSE = 0.022, and for RT, $F_{(2,\ 56)} = 19.614$, $P < 0.001$, MSE = 126,538. Follow-up analyses for both measures showed significant differences when the object faced right or left compared to when it faced toward or away ($P < 0.005$). However, the pattern differed for the two measures. RT showed slower responses for toward/away than for either right or left. Accuracy showed greater accuracy for toward/away compared to right, but decreased accuracy compared to left. This accuracy pattern remains puzzling (but is replicated in experiment 3). This main effect was qualified by an interaction with reference frame for both accuracy, $F_{(2,\ 56)} = 38.445$, $P < 0.001$, MSE = 0.022, and RT, $F_{(2,\ 56)} = 38.356$, $P < 0.005$, MSE = 112,539. For both measures, object-facing direction did not affect responses based on the intrinsic frame as much as those based on the relative frame.

Object-facing direction also interacted with donut location for accuracy, $F_{(2,\ 56)} = 53.244$, $P < 0.001$, MSE = 0.020, but not for RT ($P > 0.30$). Object-facing direction did not affect responses when the donut was in front or in back of the object, but did when the donut was to the right or left of the object, wherein the pattern followed the main effect of object-facing direction. This interaction was qualified by a significant three-way interaction between the object-facing direction, donut location, and reference frame, $F_{(2,\ 56)} = 38.445$, $P < 0.001$, MSE = 0.022. Again, the object-facing direction by donut location interaction described above was only evident for the relative frame.

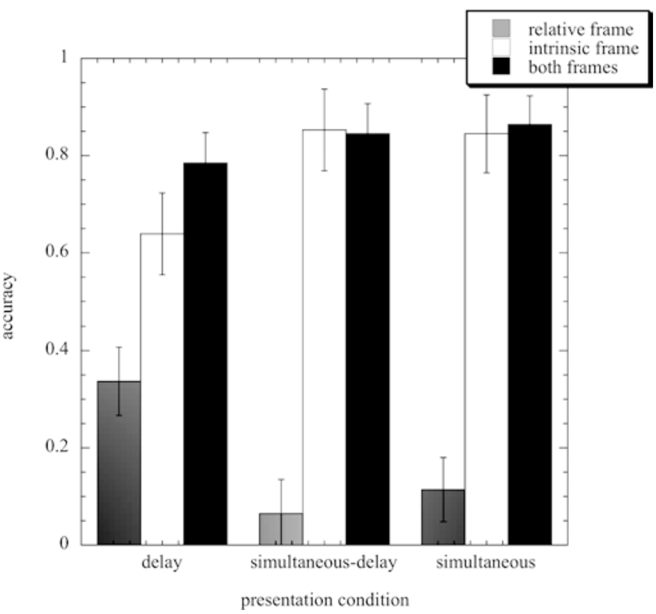

Fig. 2 Experiment 1 interaction between reference frame and presentation condition for accuracy data. Delay condition showed increased accuracy for relative frame and decreased accuracy for intrinsic frame

Descriptive term axis discrepancy and interactions

Analyses of descriptive term axis discrepancy examined whether reference frames used the same description axis (right/left or front/back) or different axes (front vs right, left vs back, etc.). In other words, when the reference frames conflicted if the correct term for the intrinsic frame was right, was the correct term for the relative frame on the same axis (left) or a different axis (e.g., front)? Embedded in this analysis was the question of which axis was used (right/left or front/back). When different axes were used, this variable was defined by the intrinsic frame. Therefore, this analysis involved a two descriptive axis discrepancy (same, different) × two intrinsic axis (right/left, front/back) × two reference frame (intrinsic, relative) × three presentation condition (delay, simultaneous, simultaneous-delay) analysis (for accuracy data only) in which presentation condition served as the between-participant factor.

The analyses showed a main effect of axis discrepancy for accuracy, $F_{(1,\ 28)} = 12.035$, $P < 0.005$, MSE = 0.014, and for RT, $F_{(1,\ 28)} = 350{,}858$, $P < 0.001$, MSE = 88,298. Participants responded more slowly, but also more accurately when terms corresponded to the same axis ($M = 0.505$ accuracy; $M = 1{,}554$ ms) compared to when they corresponded to different axes ($M = 0.453$; $M = 1{,}328$ ms). Axis discrepancy interacted with reference frame for accuracy, $F_{(1,\ 28)} = 5.203$, $P < 0.05$, MSE = 0.028, and for RT, $F_{(1,\ 28)} = 11.966$, $P < 0.005$, MSE = 94,409. Both measures showed a similar effect. When using the intrinsic frame, responses differed little between same or different axes conditions (both $M = 0.77$ for accuracy; $M = 1{,}466$ ms for same axis, 1,375 ms for different axes). Accuracy results when using the relative frame showed the axis discrepancy main effect ($M = 0.24$ and 1,643 ms for same axis; $M = 0.14$ and 1,281 ms for different axes).

Axis discrepancy also interacted significantly with intrinsic axis for accuracy, $F_{(1,\ 28)} = 11.480$, $P < 0.005$, MSE = 0.034, but not for RT ($P > 0.50$). When the possible correct terms corresponded to the same axis, there was no difference based on axis ($M = 0.51$ for both front/back and right/left axes). When terms corresponded to different axes, participants responded more accurately to the right/left ($M = 0.50$) than to the front/back axis ($M = 0.40$). The accuracy analysis was qualified by a three-way interaction between axis discrepancy, intrinsic axis, and reference frame for accuracy, $F_{(1,\ 28)} = 7.628$, $P < 0.05$, MSE = 0.043, and for RT, $F_{(1,\ 28)} = 4.353$, $P < 0.05$, MSE = 74,057. For both measures, the interaction between axis discrepancy and intrinsic axis was only apparent for the relative frame.

Discussion

Results showed that participants rarely considered the relative frame when interpreting spatial terms. In fact, participants seemed to consider terms based on the relative frame to be incorrect (chance performance is 50% and response accuracy to the relative frame only reached 17%). In contrast, participants responded well above chance when the term fit the intrinsic frame. This finding parallels neurophysiological evidence from our lab (Taylor et al. 1999, 2001a). Taylor and colleagues showed a larger N400 when the intrinsic reference frame was not used. A larger N400 reflects a greater need for cognitive processing, generally in the form of further semantic integration (e.g., Holcomb 1993). In those tasks, the increase in cognitive processing most likely involved reconsideration of a spatial term's appropriateness.

Although participants clearly preferred the intrinsic frame, processing demands and features of the spatial scene affected reference frame use, both individually and in combination. In this experiment, processing demands took the form of memory load based on the presentation condition. Some participants determined spatial term appropriateness from memory (i.e., the delay condition), while others could view the spatial scene when responding (i.e., the simultaneous and simultaneous-delay conditions). While processing demands did not affect accuracy overall, they interacted with reference frame. Interestingly, relative frame response accuracy tripled (or better) when responding from memory (delay condition) compared to when the spatial scene remained visible, although remained below chance. This finding is the opposite of our prediction. Strategic processing, since presentation condition served as a between-participants variable, might account for this finding. When working from memory, participants may have processed the picture more fully knowing that it would not be available later. When the picture was available, participants appeared to follow the processing rules suggested by Clark and Chase (1974). That is, without having to process the picture completely, participants considered a single interpretation of the donut's location, corresponding to the reference object's framework.

Features of the spatial scene also interacted to affect reference frame use. These variables were examined in situations with conflicting reference frames. Although the main effect of object-facing direction is difficult to interpret because our two measures (accuracy and RT) showed different patterns, the interactions with object-facing direction showed consistent results. Object-facing direction had a more pronounced effect when the donut was to the right or left of the object compared to when it was in front or in back of the object. This finding supports the spatial framework hypothesis for frameworks centered on objects (Bryant and Tversky 1992). The spatial framework hypothesis describes differential responses based on object location, with faster responses to the front/back dimension than to the left/right dimension (Franklin and Tversky 1990). In part, this hypothesis reflects left/right confusability brought about by left/right symmetry. Object-facing direction also had a more pronounced effect for relative frame than for intrinsic frame use. However, since participants considered descriptions based on the relative frame to be incorrect, this interaction will be further explored in experiment 2.

Another way the features of the spatial scenes interacted involved the correspondence between reference frames and description axes. Axis discrepancy (the use of different axes) affected decisions with participants responding more slowly but more accurately when the terms corresponded to the same axis. This speed–accuracy trade-off was only evident when the spatial term corresponded to the relative frame as seen in the interaction between axis discrepancy and reference frame for both measures. Again, since participants generally considered the relative frame incorrect, this interaction will be further explored in experiment 2.

Results of experiment 1 provide support for our contentions that people use spatial reference frames flexibly, do not necessarily adopt a strategy that is cognitively most economical, and take into account the spatial scene. Participants showed a strong tendency to interpret the spatial terms using the intrinsic frame, a frame that requires greater cognitive computation. Indeed, they seemed to consider terms based on the relative frame to be incorrect. Yet, they also showed cognitive flexibility in that situational variables interacted significantly with reference frames. Object-facing direction and description axis discrepancy affected responses based on the relative frame. Although difficult to interpret in this experiment because participants perceived the relative frame as incorrect, the consistent influence of situational variables on relative frame responses deserves further exploration.

Experiment 2

The results of experiment 1 showed a strong preference for the intrinsic frame. The relative frame received attention when simple strategic rules could be used or when situational variables favored it. For strategic reasons, participants appeared to give more consideration to the relative frame when responding from memory. In other words, participants appeared to process the spatial scene more completely when they knew it would not be available during their response period. These points suggest flexibility in reference frame use.

Experiment 2 further examined such flexibility by explicitly instructing participants to consider both the intrinsic and relative frames. Carlson et al. (2002) showed differential reference frame processing with specific instructions, showing a greater competition effect between frames when participants were instructed to either consider both possible reference frames or to use the less preferred frame. While it would not be surprising to show that explicit processing instructions influence responses, the use of explicit instructions in this study speaks strongly to the issue of cognitive flexibility in reference frame processing. With the additional instructions, we predicted that the relative frame would be used to a similar extent as the intrinsic one. In addition, we expected to replicate the situational interactions demonstrated in experiment 1. These interactions would be more interpretable here because participants would be less likely to consider the relative frame as a plausible option.

A preliminary analysis of these results is reported in Taylor et al. (2001a). This previous report addressed reference frame use and did not examine contextual influences.

Method

Participants

Sixty undergraduates, 39 female and 21 male, from Tufts University participated in partial fulfillment of a course credit. All participants were native English speakers.

Materials

Materials were identical to those used in experiment 1.

Procedure and design

The procedure and design matched that of experiment 1 with additional instructions. The new instructions explained that two different reference frames could be used to define the donut’s location (the intrinsic frame and the relative frame) and two examples describing the differences between them were presented. For example, participants were shown the jet facing to the left with the donut on the left side of the screen. The instructions explained that both of the terms left and front accurately described the donut’s location, with left employing their own (relative) reference frame and front using a reference frame defined by the jet (intrinsic frame). Participants were instructed that the correct response for this example was “yes” if the spatial term offered was left or front, otherwise it should be “no.”

Results

Analyses followed those used in experiment 1. The trimming procedure resulted in elimination of 2.5% of trials. As in experiment 1, the analysis comparing RTs in the delay and simultaneous-delay presentation conditions was not significant ($P > 0.05$), so analyses included the full data set.

Reference frame and presentation condition

Results showed a reference frame main effect for accuracy, $F_{(2,\ 114)} = 70.45$, $P < 0.001$, MSE = 0.051, and for RT, $F_{(2,\ 118)} = 24.28$, $P < 0.001$, MSE = 146,396. Participants were least accurate and slowest when the spatial term applied to the relative frame ($M = 0.74$ accuracy; $M = 1{,}774$ ms), more accurate and faster when the spatial term used the intrinsic frame ($M = 0.93$; $M = 1{,}629$ ms), and most accurate and fastest when the term used both frames ($M = 0.97$; $M = 1{,}533$ ms). Contrasts demonstrated that relative frame responses differed from intrinsic and both frame responses (all $P < 0.001$).

The results also showed an effect of presentation condition, $F_{(2,\ 57)} = 4.072$, $P < 0.05$, MSE = 0.006. Tukey's HSD test showed that responses in the delay condition ($M = 0.84$) were significantly less accurate than those in the simultaneous-delay condition ($M = 0.92$). No other comparisons reached significance. The accuracy results also revealed an interaction between reference frame and presentation condition, $F_{(4,\ 114)} = 2.575$, $P < 0.05$, MSE = 0.051. Each presentation condition showed the reference frame effect, but accuracy differed for the relative frame condition (see Fig. 3). Unlike experiment 1 in which reference frame accuracy increased in the delay condition, here relative frame accuracy was worse in the delay condition ($M = 0.65$) than in the simultaneous-delay condition ($M = 0.81$; $P < 0.05$); performance on the simultaneous condition ($M = 0.76$) fell in between, not differing from either of the other conditions (both $P > 0.15$). As stated earlier, presentation condition did not show an RT effect.

Object-facing direction and interactions

Results showed an effect of object-facing direction for RT, $F_{(2,\ 114)} = 42.141$, $P < 0.001$, MSE = 93,806, but not for accuracy ($P > 0.30$). Follow-up analyses showed slower responses when the object faced toward or away ($M = 1{,}852$ ms) than if it faced either right ($M = 0.83$) or left ($M = 0.83$; $P < 0.001$).

Object-facing direction interacted with reference frame for accuracy, $F_{(2,\ 114)} = 4.862$, $P < 0.01$, MSE = 0.016, but not for RT ($P > 0.80$). The source of the interaction occurred when the object faced right, in which case accuracy increased for the intrinsic frame and decreased for the relative frame. However, since the main effect of object-facing direction was not significant for accuracy, the interpret ability of this interaction is difficult.

Object-facing direction also interacted with donut location for accuracy, $F_{(2,\ 114)} = 39.81$, $P < 0.001$, MSE = 0.033, but not for RT ($P > 0.15$). This interaction showed that when the donut was in front or in back, accuracy increased if the object faced right or left, compared to if it was facing away from the participant. However, when the donut was to the right or the left, accuracy decreased if the object faced right or left compared to when it faced toward the participant. Thus, the interaction may simply reflect greater difficulty when the object faced toward the participant.

Results also showed a three-way interaction between object-facing direction, donut location, and reference frame for accuracy $F_{(2,\ 114)} = 26.515$, $P < 0.001$, MSE = 0.031, but not for RT ($P > 0.45$). This three-way interaction indicated that the object-facing direction by donut location interaction described above was only evident for the relative frame.

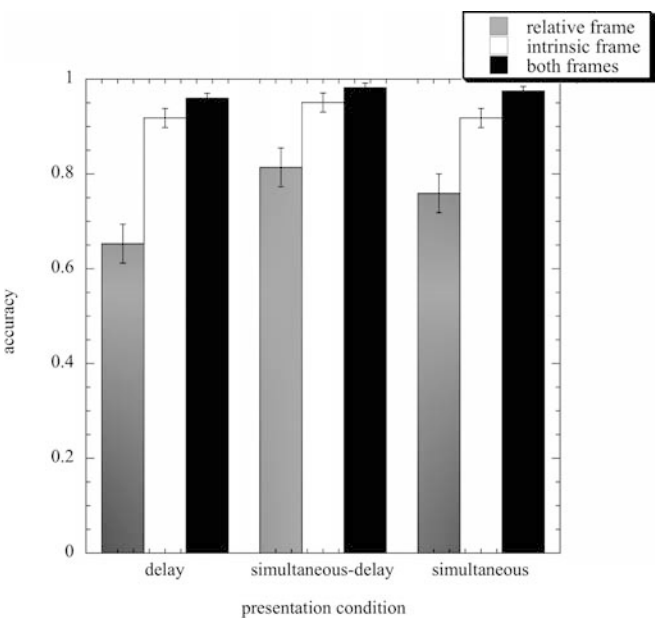

Fig. 3 Experiment 2 interaction between reference frame and presentation condition for accuracy data. Responses to the relative frame differed across the three presentation conditions

Descriptive term axis discrepancy and interactions

The analyses showed a main effect of axis discrepancy for RT, $F_{(1,\ 57)} = 64.86$, $P < 0.001$, MSE = 83,622, but not for accuracy ($P > 0.25$). Participants responded more slowly when the descriptive terms used the same axis ($M = 1{,}852$ ms) than when they used different axes ($M = 1{,}639$ ms). Axis discrepancy interacted with reference frame for accuracy, $F_{(1,\ 57)} = 5.821$, $P < 0.05$, MSE = 0.014, but not for RT ($P > 0.90$). For the intrinsic frame, accuracy was slightly higher when terms corresponded to different axes. For the relative frame, accuracy was slightly lower when terms corresponded to different axes.

Axis discrepancy also interacted significantly with intrinsic axis for accuracy, $F_{(1,\ 57)} = 44.459$, $P < 0.001$, MSE = 0.027, and was marginally significant for RT, $F_{(1,\ 57)} = 3.404$, $P = 0.07$, MSE = 121,752. This analysis indicated that when terms corresponded to the same axis, participants responded more accurately to the right/left than to the front/back axis ($P < 0.005$) and responded equally, and quickly to both axes ($P > 0.25$). When the terms corresponded to different axes, participants responded faster and more accurately when the intrinsic frame used the front/back axis than when it used the right/left axis ($P < 0.001$). The accuracy analyses were qualified by a three way interaction between axis discrepancy, intrinsic axis, and reference frame for accuracy, $F_{(1,\ 57)} = 32.36$, $P = 0.001$, MSE = 0.039. The interaction between axis discrepancy and intrinsic axis was only apparent for the relative frame.

Discussion

Experiment 2 replicated many of experiment 1's findings, providing additional evidence of cognitive flexibility. Even with instructions to consider both reference frames, participants still provided less accurate and slower responses when using the relative frame. Accuracy rates did, however, reach an above chance level (73%) for the relative frame, far above the 17% accuracy rate seen in experiment 1. Thus, people can consider multiple reference frames when interpreting spatial descriptions, suggesting flexibility in reference frame use; however they continue to maintain a preference for the intrinsic frame.

As in experiment 1, use of the relative frame was influenced by perceptual availability. Unlike experiment 1, response accuracy for the relative frame was higher when the scene remained available. These contrary findings can be attributed to the additional instructions. Since participants knew they could consider both frames, the task of doing so was easier when the scene remained perceptually available.

As with experiment 1, spatial scene features interacted with reference frame use; in particular spatial scene elements affected responses based on the relative frame, but not those based on the intrinsic frame. Specifically, the interaction between object-facing direction and donut location was only apparent for the relative frame. The interaction between description axis discrepancy and intrinsic axis was also only evident for the relative frame. Although this was also true in experiment 1, its replication here increases interpret ability. This interaction suggests that participants must put more cognitive effort into processing their non-preferred reference frame and consequently give greater consideration to the spatial scene features. Use of the preferred intrinsic frame does not require the same consideration of features.

Experiment 3

Experiments 1 and 2 have both demonstrated that participants prefer to use the intrinsic reference frame when verifying spatial descriptions. Even when told to consider the relative frame, participants continued to respond faster and more accurately to intrinsically defined locations. At the same time, however, both studies suggest cognitive flexibility. Contextual variables of the spatial scene also affected spatial description verification.

The responses to these different reference frames support rules of sentence–picture verification put forward by Clark and Chase (1974). Their findings also suggest that the order in which people encode pictures and verify accompanying descriptions has an impact on response processes. When participants were asked to read a verification sentence after viewing a picture, they followed several rules. Interestingly, response patterns differed if participants read the sentence prior to viewing the picture. In these cases, participants tended to observe only a single rule: verification latencies demonstrated that participants evaluated the pictures with respect to the particular spatial orientation described in the sentence (e.g., above or below). According to the authors, "In the sentence-first verification tasks, then, Ss are apparently forced by some rather well established strategy to replace their natural coding preferences by a contingent (a priori) coding scheme" (Clark and Chase 1974).

Therefore, experiment 3 attempted to replicate our reference frame findings, but examined whether knowing the spatial relationship to be verified, i.e., reading the description first, would influence the verification process. With respect to our data, participants comparing an earlier presented picture to a sentence could rely on any of the three rules. As a matter of point, Clark and Chase's findings would implicate, as a main rule, the use of the reference object as a stable, prominent object. However, participants comparing a sentence followed by a picture should develop an expectation for the object orientations, and verify pictures based on an a priori mental image of the relationship between the donut and the object.

Further, experiment 3 explicitly examined the effects of instructions to consider multiple reference frames. Half of the participants received such instructions, while the other half received no explicit instructions. Given the results of experiments 1 and 2, instructions should impact verification performance for the relative frame, but should not outweigh the preference for intrinsic frame processing.

Method

Participants

Forty undergraduates, 22 females and 18 males, from Tufts University participated in partial fulfillment of a course credit. All were native English speakers.

Materials

Materials were identical to those used in experiments 1 and 2.

Procedure

The procedure followed that used in experiments 1 and 2, with the following changes. All participants completed a modified version of the delay condition wherein a spatial term appeared for 1,000 ms and was then replaced by a picture. Participants were randomly assigned to one of two instruction conditions. Participants in the "explicit instruction" condition received instructions explaining that the donut's location could be defined by two possible reference frames (i.e., experiment 2 instructions). Participants in the "no instruction" condition received the experiment 1 instructions that did not explicitly introduce the two reference frames.

Design

The design followed that used in experiments 1 and 2 with a change to the between-participant variable. The presentation-condition variable of earlier experiments was replaced by the instruction-condition variable (explicit instructions, no instructions).

Results

The trimming procedure described in experiment 1 resulted in elimination of 2.5% of trials.

Reference frame and instruction condition

Results showed a reference frame effect for accuracy, $F_{(2,\ 76)}=280.47$, $P<0.001$, MSE = 0.048, and for RT, $F_{(2,\ 76)}=16.473$, $P<0.001$, MSE = 158,116. The results patterns differed for the two measures. Participants were less accurate when the spatial term described the relative frame ($M=0.41$), than when it used the intrinsic frame ($M=0.90$) or both frames ($M=0.93$; all $P<0.001$). For RT, participants responded faster when both frames were used ($M=1{,}315$ ms), while responses to the individual frames were similarly slowed ($M=1{,}529$ ms for relative, and $M=1{,}541$ ms for intrinsic; all $P<0.001$).

Results also showed a main effect of instructions for accuracy, $F_{(1,\ 38)}=137.15$, $P<0.001$, MSE = 0.006, and for RT, $F_{(1,\ 38)}=4.346$, $P<0.05$, MSE = 263,606. Participant responses were more accurate, but slower following explicit instructions ($M=0.89$; $M=1{,}631$ ms) than after no instructions ($M=0.60$; $M=1{,}293$ ms), indicating that they used the relative frame more often, but had to carefully consider its use.

As expected, this main effect was qualified by an interaction with reference frame for accuracy, $F_{(2,\ 76)}=95.514$, $P<0.001$, MSE = 0.048, and for RT, $F_{(2,\ 76)}=9.397$, $P<0.001$, MSE = 158,116. For accuracy, the instructions impacted relative frame use (see Fig. 4). Not unexpectedly, the RT interaction showed that instructions did not affect responses when both frames were used.

Object-facing direction and interactions

Analyses showed an effect of object-facing direction for accuracy, $F_{(2,\ 76)}=7.194$, $P<0.005$, MSE = 0.015, and for RT, $F_{(2,\ 76)}=39.725$, $P<0.001$, MSE = 128,616. As in experiment 1, this pattern differed for the two measures. RT showed slower responses for toward/away than for either right or left. Greater accuracy was obtained for toward/away compared to left, but accuracy decreased for toward/away compared to right. As with experiment 1, this accuracy pattern is puzzling.

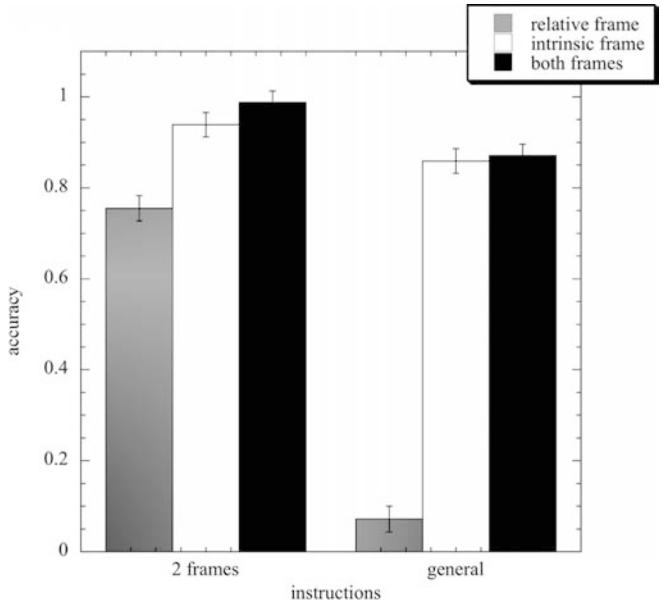

Fig. 4 Experiment 3 interaction between reference frame and instructions for accuracy data. The instructions impacted use of the relative reference frame

Unlike experiments 1 and 2, object-facing direction did not interact with reference frame. Object-facing direction did interact with donut location for accuracy, $F_{(2,\ 76)}=16.826$, $P<0.001$, MSE = 0.019. This interaction indicated that the puzzling main effect pattern was only evident for donuts placed to the right or left of the object. For donuts in front of and in back of the object, participants responded less accurately when the object faced away than when it faced either right or left. This interaction was qualified by a three way interaction between object-facing direction, donut location, and reference frame, $F_{(2,\ 76)}=5.701$, $P<0.01$, MSE = 0.026. The interaction between object-facing direction and donut location was only evident for the relative frame.

Descriptive term axis discrepancy and interactions

The analyses showed a main effect of axis discrepancy for RT, $F_{(1,\ 38)}=54.371$, $P<0.001$, MSE = 134,614, but not for accuracy ($P>0.30$). Participants responded more slowly when the terms corresponded to the same axis ($M=1{,}708$ ms) than when they corresponded to different axes ($M=1{,}406$ ms). Axis discrepancy did not interact with reference frame for either measure.

Axis discrepancy did interact with intrinsic axis for accuracy, $F_{(1,\ 38)}=29.059$, $P<0.001$, MSE = 0.020, but not for RT ($P>0.10$). When the possible correct terms corresponded to the same axis, participants responded more accurately to the right/left ($M=0.70$) than to the front/back axis ($M=0.63$; $P<0.005$). When terms corresponded to different axes, participants responded more accurately when the intrinsic frame used the front/back ($M=0.71$) axis compared to when it used the right/

left axis ($M = 0.63$; $P < 0.005$). The accuracy analyses was qualified by a three-way interaction between axis discrepancy, intrinsic axis, and reference frame for accuracy, $F_{(1,\ 38)} = 8.605$, $P < 0.01$, MSE = 0.027. The interaction between axis discrepancy and intrinsic axis was only apparent for the relative frame.

Discussion

Once again, participants responded less accurately using the relative frame. However, instructions to consider alternate interpretations of the term influenced responses, as seen in the interaction between reference frame and instructions. Responses to the relative frame without explicit instructions fell far below the chance level of 50%, reaching only approximately 8% accuracy. In contrast, when people received explicit instructions, responses to the relative frame exceeded chance, reaching approximately 75%.

Although the results cannot be directly compared, it appears that the order in which sentences and pictures are presented can make a difference. This difference appears most strongly in responses to the relative frame. In experiment 1, when the picture preceded the spatial term, response accuracy to the relative frame for the delay presentation reached approximately 33%. In experiment 3, again using the delay presentation, but presenting the spatial term prior to the picture, response accuracy reached only 8%. Thus, when the spatial term is presented first, it appears to be interpreted with respect to the intrinsic frame and compared to the picture using this interpretation. When the picture precedes the spatial term in the verification task, participants appeared to give greater consideration to the relative frame.

Spatial scene features again interacted with reference frame use, impacting relative frame. As in experiments 1 and 2, interactions between situational variables (e.g., object-facing direction × donut location; description axis discrepancy × intrinsic axis) were only evident for relative frame responses.

General discussion

Three experiments examined how cognitive processing demands and spatial scene elements interact to affect spatial reference frame processing using simple, two-object scenarios. In each experiment, participants viewed a picture depicting a reference object with intrinsic sides, and a located object (always a donut). Each picture was paired with a projective spatial term (front, back, left, or right). Participants decided whether the spatial term described the donut's location.

All three experiments showed a preference for the intrinsic frame. This preference was particularly evident when participants were not told that more than one reference frame could potentially be used. Without instructions, accuracy to terms describing the relative frame fell far below chance, as low as 8% with chance defined at 50%. With instructions, accuracy rose above chance, but still fell below intrinsic responses. This finding parallels ERP results indicating the need for additional semantic processing when the intrinsic frame was not used (Taylor et al. 1999, 2001a).

Importantly, participants preferred the intrinsic frame for both of our verification tasks (in experiments 1 and 2, the sentence followed the picture and in experiment 3, the picture followed the sentence). The ordering of stimuli in the verification task carries implications for how the spatial information is mentally represented. When the picture precedes the description, people scan the picture for possible spatial relations. The description is then compared to these possibilities. When the description precedes the picture, they build a mental representation of the described relation to later compare to a picture. Our findings demonstrate that whether participants developed this frame a priori, based on a textual description of the array, or used a particular object from an array as a reference point, their default frame followed an object-oriented viewpoint.

Our results are in line with Clark and Chase's (1974) ordered rules of sentence–picture verification. According to these rules, participants rely on prior knowledge or preferences, stable reference objects, and directional biases (in that order) to develop descriptions of object arrays. In our study, participants relied on a reference object (e.g., chair or car) to construct descriptions. Their responses were faster and more accurate when verifying descriptions referenced to an intrinsic frame.

The strong tendency to consider only the intrinsic frame was certainly the average and the preferred strategy, but an examination of the results by participant reveal that it was not the only strategy. Experiment 1 provides the best indication of participants' natural reference frame choice since no reference frame instructions were provided. In experiment 1, 21 of 31 participants used only the intrinsic frame. However, two participants used only the relative frame and one used both frames. Interestingly, seven participants used the intrinsic frame for right/left donut locations, but adopted a relative frame for front/back locations. Similar individual differences were seen in the other two experiments.

Participants' performance also suggests that they employed strategies when verifying the spatial displays, and these strategies demonstrated cognitive flexibility. With reference to this possibility, Clark and Chase's first rule seems an appropriate point at which to hypothesize that participants consider potential processing difficulties when selecting reference. For example, participants in our delay conditions may have worked to instantiate an intrinsic framework for their responses, based on the awareness that such a framework would be easier to use while the stimulus array was perceptually available. The intrinsic frame required additional cognitive operations. This conjecture fits our results based on presentation condition. Without instructions about reference frames (experiment 1), participants used the relative frame more often when the picture and spatial term appeared simultaneously. Strategic processing was also evident when participants received instructions about reference frames. In this case, they used the picture to their advantage when it was available in the simultaneous-delay condition, spending more time processing it.

Participants may have also worked to strategically instantiate an intrinsic approach because the reference object changed from trial to trial, both in identity (six different objects) and orientation (four facing directions). Thus on each trial, participants had to determine both the intrinsic sides of the object, based on its identity, and which way it was facing. We suggest, then, that the privileged response to intrinsic verifications may stem from a strategic preference to encode information in such a manner. Further evaluation of strategies such as this in more complex arrays may provide an indication as to how participants' goals and preferences can influence their pattern of verification latencies and judgments.

Features of the spatial scene interacted with reference frame use. We examined two questions of interest. First, did participants use different strategies as a function of object-facing direction? Although the present data cannot speak directly about which strategies may have been adopted, mental rotation for right/left facing directions and switching for toward/away directions are candidates (Kanomori and Yagi 2002). Participants in all three experiments consistently responded more slowly when the donut faced toward or away from them than when it faced right or left. It was clear, however, that object-facing direction alone did not dictate response strategies since facing direction interacted with both donut location and reference frame. The effect of facing direction was only true when the donut appeared to the right or left of the object, which can by explained by either the symmetry of the left/right dimension (Clark 1973) and/or the greater processing difficulty associated with this dimension, as described by the spatial framework hypothesis (Bryant et al. 1992; Franklin and Tversky 1990; Franklin et al. 1992). Additionally the effect of object-facing direction could only be seen for responses using the relative frame. Therefore, strategy differences appear to be most prevalent in the most cognitively difficult processing situations.

The second question examined cognitive consequences of conflicting reference frames using the same descriptive axis. In all three experiments, participants consistently responded more slowly when terms used same axis than when they used different axes. Since participants preferred the intrinsic frame, this suggests that use of the same axis by the relative frame caused some confusion or hesitation in response. In contrast, participants could easily disentangle the reference frames when the descriptions used different axes.

When reference frames used the same descriptive term axis, accuracy was consistently greater for the right/left axis compared to the front/back axis. Both axes have processing difficulties associated with them, including the symmetry of the left/right axis (Clark 1973) and the response variability and language differences in defining front and back using the relative frame (Hill 1982). The latter of these difficulties appears to have dominated responses in these studies, thereby validating empirical findings of response variability in defining front and back (Taylor et al. 2001b).

With these simple, two-object scenarios, information processing demands and scene elements affected spatial description interpretation. More specifically, we suggest that these factors changed how participants strategically verified spatial relations. No doubt the influences examined here make up but a portion of possible influences. Others may include, but are not limited to the specific spatial relations under investigation, the spatial scene complexity, the elements of the scene, or the scale of the scene. Spatial relations in the vertical plane bring to bear effects of gravity, a feature that weighs heavily in defining spatial relations (e.g., Friederici and Levelt 1990).

Even with the simple scenarios used here, participants consistently used the intrinsic frame for verifying spatial relations. Behavioral and neuropsychological evidence supports a distinction between processing object-to-object spatial relations and processing objects relative to one's body as an observer, a self-to-object representational system (e.g., Kozhevnikov and Hegarty 2001; Wraga et al. 2000; Zacks et al. 1999).

Although the distinction between the processing frames is clear, not all research shows the same reference frame preference that we describe in this article. Zacks et al. (1999) showed differential brain activation for processing object-to-object relations and person-to-object relations. In contrast to our findings, participants in their study provided faster responses to egocentric transformations compared to those involving object-to-object relations. Their scenarios, however, differed from ours since their "object" was a human body. Whether the reference object is animate or not, or perhaps whether it is a human or realistic, may present yet another influence on reference frame use. What seems clear is that even with seemingly strong preferences, a change in the circumstances surrounding the description of a spatial scene could shift this preference to a different reference frame. The context of a description or spatial array is an important component for potentially disambiguating spatial descriptions. Although in many cases we can elect to ask for more detail (i.e., your moving service asking for clarification on exactly where you wanted your end table), basic spatial representations are constructed as a function of the contextual, referential, and spatial features of everyday scenes.

Acknowledgements We would like to thank Justin Belmont, Lauren Brodsky, Nicole Gregoire, and Belkiss Murati for assistance in data collection. We would also like to thank Laura Carlson and Phil Holcomb for helpful discussions on portions of the data. All studies have been approved for ethical use of human participants by the Institutional Review Board of Tufts University.

References

Arguin M, Bub DN (1993) Evidence for an independent stimulus-centered spatial reference frame from a case of visual hemineglect. Cortex 29:349–357

Bryant DJ, Tversky B (1992) Assessing spatial frameworks with object and direction probes. B Psychonomic Soc 30:29–32

Bryant DJ, Tversky B (1999) Mental representations of spatial relations from diagrams and models. J Exp Psychol Learn 25:137–156

Bryant DJ, Tversky B, Franklin N (1992) Internal and external spatial frameworks for representing described scenes. J Mem Lang 31:74–98

Bryant DJ, Tversky B, Lanca M (2001) Retrieving spatial relations from observation and memory. In: Zee E van der, Nikanne U (eds) Conceptual structure and its interfaces with other modules of representation. Oxford University Press, Oxford, pp 116–139

Carlson LA, West R, Taylor HA, Herndon RW (2002) Neural correlates of spatial term use. J Exp Psychol Human 28:1391–1408

Carlson-Radvansky LA, Irwin DA (1993) Frames of reference in vision and language: where is above? Cognition 46:223–244

Carlson-Radvansky LA, Irwin DE (1994) Reference frame activation during spatial term assignment. J Mem Lang 33:646–671

Carlson-Radvansky LA, Jiang Y (1998) Inhibition accompanies reference-frame selection. Psychol Sci 9:386–391

Carlson-Radvansky LA, Radvansky GA (1996) The influence of functional relations on spatial term selection. Psychol Sci 7:56–60

Carlson-Radvansky LA, Covey ES, Lattanzi KM (1999) "What" effects on "where"? Functional influences on spatial relations. Psychol Sci 10:516–521

Chase WG, Clark HH (1971) Semantics in the perception of verticality. Br J Psychol 62:311–326

Chase WG, Clark HH (1972) Mental operations in the comparison of sentences and pictures. In: Gregg L (ed) Cognition in learning and memory. Wiley, New York, pp 205–232

Clark HH (1973) Space, time, semantics, and the child. In: Moore TE (ed) Cognitive development and the acquisition of language. Academic, New York, pp 27–63

Clark HH, Chase WG (1972) On the process of comparing sentences against pictures. Cogn Psychol 3:472–517

Clark HH, Chase WG (1974) Perceptual coding strategies in the formation and verification of descriptions. Mem Cogn 2:101–111

De Vega M, Rodrigo MJ (2001) Updating spatial layouts mediated by pointing and labelling under physical and imaginary rotation. Eur J Cogn Psychol 13:369–393

Frank AU (1998) Formal models for cognition: taxonomy of spatial location description and frames of reference. In: Freksa C, Habel C, Wender K (eds) Spatial cognition: an interdisciplinary approach to representing and processing spatial knowledge. Springer, Berlin Heidelberg New York, pp 293–312

Franklin N, Tversky B (1990) Searching imagined environments. J Exp Psychol Gen 119:63–76

Franklin N, Tversky B, Coon V (1992) Switching points of view in spatial mental models. Mem Cogn 20:507–518

Friederici A, Levelt WJM (1990) Spatial references in weightlessness: perceptual factors and mental representations. Percept Psychophys 47:253–266

Hill C (1982) Up/down, front/back, left/right: a contrastive study of Hausa and English. In: Weissen J, Klein W (eds) Here and there: cross-linguistic studies on deixis and demonstration. Benjamins, Amsterdam, pp 13–42

Holcomb PJ (1993) Semantic priming and stimulus degradation: implications for the role of the N400 in language processing. Psychophysiology 30:47–61

Kanomori N, Yagi A (2002) The difference between flipping strategy and spinning strategy in mental rotation. Perception 31:1459–1466

Kozhevnikov M, Hegarty M (2001) A dissociation between object manipulation spatial ability and spatial orientation ability. Mem Cogn 29:745–756

Levelt WJM (1982) Cognitive styles in the use of spatial direction terms. In: Jarvella RJ, Klein W (eds) Speech, place, and action. Wiley, Chichester, pp 251–268

Levelt WJM (1984) Some perceptual limitations on talking about space. In: van Doorn AJ, van der Grind WA, Koenderink JJ (eds) Limits in perception. VNU Science Press, Utrecht, pp 323–358

Levelt WJM (1989) Speaking: from intentions to articulation. MIT Press, Cambridge

Levinson SC (1996) Frames of reference and Molyneux's question: crosslinguistic evidence. In: Bloom P, Peterson MA, Nadel L, Garrett M (eds) Language and space. MIT Press, Cambridge, pp 109–169

Linde C, Labov W (1975) Spatial structure as a site for the study of language and thought. Language 51:924–939

Logan GD, Sadler DD (1996) A computational analysis of the apprehension of spatial relations. In: Bloom P, Peterson MA, Nadel L, Garrett M (eds) Language and space. MIT Press, Cambridge, pp 493–529

Shepard RN, Metzler J (1971) Mental rotation of three-dimensional objects. Science 171:701–703

Taylor HA, Naylor SJ, Faust RR, Holcomb PJ (1999) "Could you hand me those keys on the right?" Disentangling spatial reference frames using different methodologies. Spat Cogn Comp 1:381–397

Taylor HA, Faust RR, Sitnikova T, Holcomb PJ, Naylor SJ (2001a) Is the donut in front of the car? An electrophysiological study examining spatial reference frame processing. Can J Exp Psychol 55:177–186

Taylor HA, Uttal DH, Fisher J, Mazepa M (2001b) Ambiguity in acquiring spatial representation from descriptions compared to depictions: the role of spatial orientation. In: Montello DR (ed) Spatial information theory: foundations of geographic information science, vol. 2205. Springer, Berlin Heidelberg New York, pp 278–291

Tversky B (1996) Spatial perspective in descriptions. In: Bloom P, Peterson M, Nadel L, Garrett M (eds) Language and space. MIT Press, Cambridge, pp 463-492

Woodin ME, Allport A (1998) Independent reference frames in human spatial memory: body-centered and environment-centered coding in near and far space. Mem Cogn 26:1109–1116

Wraga M, Creem SH, Profitt DR (2000) Updating displays after imagined object and viewer rotations. J Exp Psychol Learn 26:151–168

Zacks J, Rypma A, Gabrieli JDE, Tversky B, Glover GH (1999) Imagined transformations of bodies: an fMRI investigation. Neuropsychologia 37:1029–1040