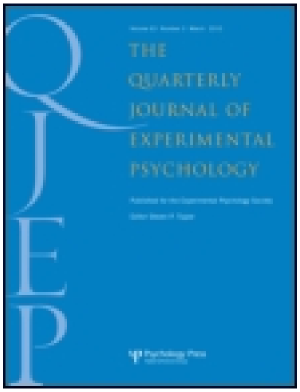

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Rapid communication

Functional equivalence and spatial path memory

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Loomis, Klatzky, Avraamides, Lippa and Golledge (2007) suggest that, when it comes to spatial information, verbal description and perceptual experience are nearly functionally equivalent with respect to the cognitive representations they produce. We tested this idea for the case of spatial memory for complex paths. Paths consisted entirely of unit-length segments followed by 90-degree turns, thus assuring that a path could be described with equal precision using either an egocentric verbal description or a virtual self-motion experience. The verbal description was analogous to driving directions (e.g., turn left and go one block, then turn right, etc.) except in three dimensions (allowing rotation followed by up or down movement). Virtual self-motion was depicted as first-person travel through a 3D grid of featureless corridors. Comparison of these two conditions produced a result that may be surprising to some, but nevertheless appears to support the notion of functional equivalence: Virtual self-motion does not produce better path memory than verbal description, when care is taken to present equally precise path information. This result holds for even very complex paths and despite evidence from proximity-based interference that the memory representation of the path is spatial.

Keywords: Spatial memory; Spatial cognition; Visualization; Self-motion; Mental imagery.

The subjective experience of seeing something is vastly different from the experience of reading or hearing a verbal description of it. Yet Loomis, Klatzky, Avraamides, Lippa, and Golledge (2007) suggest, based on the results of several studies, that perceptual experience and spatial language are often nearly functionally equivalent with respect to purely spatial content such as the relative locations of things. In these studies, object locations were either described verbally or presented perceptually using either 3D audio (Loomis, Lippa, Klatzky, & Golledge, 2002) or visual stimuli (Avraamides, Loomis, Klatzky, & Golledge, 2004). Accuracy of spatial representation was assessed using distance estimation, walking, and/or pointing. Performance was usually

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approximately equal for verbal and perceptual presentation.

This evidence for functional equivalence is important for many reasons, but especially because it suggests that at least some aspects of human spatial cognition are abstract and are not inextricably tied to a particular kind of perceptual experience. This appears to run counter to the increasing emphasis in cognitive science on grounded representations that link knowledge to perceptual information from the environment (e.g., Barsalou, 1999; Zwaan & Radvansky, 1998).

Not all studies, however, show evidence for functional equivalence. For example, Klatzky, Lippa, Loomis, and Golledge (2003) found an advantage for visual presentation over verbal description. This study illuminates an important issue—namely, the correspondence (or lack thereof) between different ways of conveying what should be the same spatial information. For example, part of the verbal description used by Klatzky et al. (2003) was a distance (e.g., "6 feet"). It is conceivable, perhaps even likely, that for most people, the verbal description "6 feet" does not convey exactly the same distance information as, say, seeing that distance marked on the ground. The Klatzky et al. (2003) results help clarify how people's mental representation of distance may differ between a verbal description and a visual experience.

So there are really two issues underlying a claim of functional equivalence for spatial information. The first is the extent to which verbal and visual input convey the exact same spatial information, at the same level of precision. The second is the extent to which, given that exactly the same information is conveyed, it is treated equivalently in further processing and in memory. To get a clear answer to the second question, one must set up a situation in which the information conveyed using different methods is equivalent.

In this paper, we describe an attempt to solve this problem using the task of visualizing complex three-dimensional paths, described from an egocentric point of view. We get around the inherent nonequivalence of visual and verbal depictions of a particular distance by using a symbolic metric of distance, in which all segments of a path are of unit length. We avoid inherent differences in the depiction of precise angular information by using 90-degree turns. For example, from a starting location facing forward, imagine turning left 90 degrees, then moving one unit, then imagine tipping back 90 degrees to face skyward, then moving (up) one unit, and so on. The task is to visualize the path as it develops, so that one can detect when the path intersects with itself. This requires that one transform these descriptions into a mental "picture" of the overall route, perhaps as if viewing the route from afar.

This task, called *path visualization*, was used by Lyon, Gunzelmann, and Gluck (2008) to measure and model various aspects of spatial representation. Path visualization is a descendent of methods used by Brooks (1968), Attneave and Curlee (1983), Kerr (1987, 1993), and Diwadkar, Carpenter, and Just (2000), and similar in some ways to a task used by Barshi and Healy (2002) and Schneider, Barshi, and Healy (2004). In Lyon et al. (2008), participants read a sequence of verbal descriptions of segments of a path, attempted to build a mental image of the path as it was described, and used this visualization to decide, for each new path segment, whether or not that segment intersected with any previous part of the path. Paths were relatively long (15 segments). Because the task was to detect path intersections as they occurred, participants needed to construct a spatial representation of each path segment as it was presented, rather than merely rehearse the raw verbal descriptions and then reconstruct the path after all segments had been presented.

Lyon et al. (2008) tested a computational model of the underlying processes that limit people's ability to visualize complex 3D paths. They concluded that a proximity-based spatial interference process is a major source of visualization capacity limits. The evidence for spatial interference was that path segments entering crowded areas of the (imaginary) space were far more likely to result in an error than path segments entering empty areas of the space. Lyon et al. also found evidence for more standard decay and associative interference effects, but the existence of very strong spatial interference effects in path visualization confirms its spatial nature.

The computational model developed to account for the variety of path visualization effects in the Lyon et al. (2008) study uses an amodal representation, rather than an explicitly visual, depictive representation. This amodal representation treats spatial proximity as simply another dimension of object similarity, at least with regard to its effect on memory. In this respect, the model embodies the suggestion (e.g., Loomis et al., 2007) that amodal spatial representations exist.

In the version of the path visualization task used by Lyon et al. (2008), each path segment was described verbally. However, it is also possible to describe the same path by depicting first-person-perspective travel along the path using a virtual self-motion display. In the latter case, the experience is like moving through a featureless tunnel. Instead of a verbal instruction to turn 90 degrees to the left and move one unit, the participant experiences the visual effects of a 90-degree turn and movement of a fixed distance down a hall. Verbal description and virtual motion descriptions are illustrated in Figure 1.

This kind of virtual motion uses an inherently egocentric frame of reference and therefore corresponds to egocentric verbal descriptions, in which the instruction "Left" means to rotate one's imagined body 90 degrees to the left, rather than to face the left side of the overall space (cf. Lyon & Gunzelmann, 2009). The depiction of "Up" corresponds to a body rotation around the horizontal axis. From an upright start, one would then be on one's back, and moving toward the top of the space.

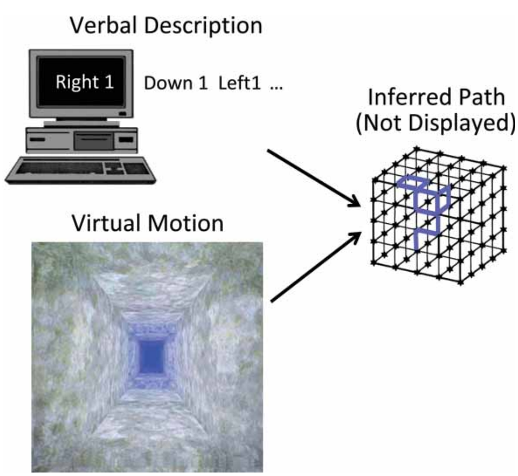

Figure 1. *Illustration of verbal description and virtual motion conditions of the path visualization task. To view a colour version of this figure, please see the online issue of the Journal.*

Under these conditions, the two kinds of path description are completely isomorphic. The goal, the paths, the timing, and the measure of accuracy for virtual motion and verbal description are identical as well. Do these two different kinds of descriptions result in functionally equivalent spatial representations? Or, is one of the representations more vivid, more durable? If so, which description produces the more durable representation—verbal description, or virtual motion?

A case could be made for either description. Virtual motion provides a rich visual experience that verbal description lacks. This experience may leave a useful visual episodic memory trace that could reinforce memory for the route. For this reason, and perhaps others, one might expect that the inherently visuospatial experience provided by the virtual motion would facilitate encoding the visuospatial information about the path travelled. On the other hand, it is conceivable that the visual depiction of virtual motion might interfere with visualizing the emerging path. This would follow a rich literature demonstrating the deleterious impact of a secondary task when it draws upon similar cognitive resources to those for the primary task (e.g., Brooks, 1968; Wickens, 1980).

In the present study, we use both paths presented verbally (as in Lyon et al., 2008) and paths presented using virtual motion. By comparing performance on these two (subjectively very different) kinds of spatial description, we can look for evidence of functional equivalence in the context of spatial memory for abstract, landmark-free paths.

EXPERIMENT

Method

Twelve paid participants were each given ten 30-trial path visualization sessions, five using text, and five using virtual motion, in counterbalanced order. On each trial, a path within an imaginary three-dimensional $5 \times 5 \times 5$ grid was described by a sequence of 15 path segments presented for 3 s each. For text, each segment was described in a phrase giving its egocentric direction and distance (e.g., "Left 1"; all distances were 1). The four possible descriptions were "Left 1", "Right 1", "Up 1", and "Down 1", so each new path segment represented a 90-degree rotation from the previous segment. For virtual motion, each segment depicted a first-person, left, right, up, or down rotate-and-move. For both methods, the participant decided whether the endpoint of each new segment intersected with any previously presented part of the path and responded "yes" or "no" with a key press before the next segment was presented. Both accuracy and response time were recorded, although the primary measure of interest was accuracy because response times were limited by the stimulus presentation time.

Since each new segment followed a 90-degree turn, it was impossible for the first three path segments to intersect. Participants were informed of this and were instructed to respond "No" for the first three segments of each path. Accuracy was calculated separately for Segments 4 through 15.

Results

Figure 2 shows intersection-detection accuracy by memory load (current path length) for both text description and virtual motion conditions. Following Lyon et al. (2008), intersection-detection accuracy declined steadily as memory load increased, but verbal description and virtual motion conditions did not differ in either accuracy, $F(1, 11) = 0.16$, *ns*, or response time, $F(1, 11) = 0.20$, *ns*. There was no interaction between presentation type and memory load, $F(11, 121) = 1.28$, *ns*; in fact, as Figure 2 indicates, the effect of load on accuracy is very similar for text and virtual motion.

As noted earlier, the path visualization task requires an internal spatial representation of the path. Each new segment must be checked immediately to see whether it produces an intersection with

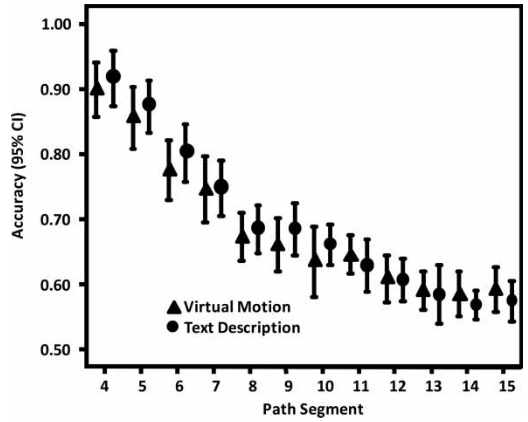

Figure 2. *Path visualization accuracy (by path segment) for paths experienced through virtual self-motion and paths described verbally (from an egocentric perspective). Experiencing rich virtual self-motion along a path does not result in more accurate visualization.*

prior path segments. It is not sufficient to simply rehearse the path as one might do in verbal list recall. As in previous studies, the spatial nature of this representation was confirmed by the presence of a strong spatial proximity effect (Lyon et al., 2008). Participants were much less likely to be accurate when the currently described path segment took the path into an area of imaginary space crowded by prior path segments. Figure 3

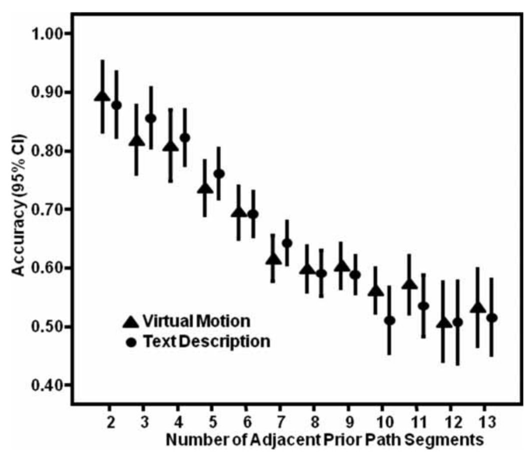

Figure 3. *Path visualization accuracy by number of adjacent prior path segments ("crowding effect") for both verbal description and virtual self-motion conditions.*

shows accuracy by the number of prior path segments that are adjacent to the current path segment, a measure of the spatial proximity, or crowding, effect. It is clear that a very strong spatial proximity effect occurs for both kinds of description.

To assure that this effect was not an artefact of aggregating over memory load, we conducted a partial correlation analysis of accuracy for each combination of path length and number of adjacent prior segments, holding memory load constant. For both text presentation and virtual self-motion, the correlation between accuracy and adjacent segments was highly significant even with memory load controlled: text presentation, $r(99) = -.62$, $p < .001$; virtual travel, $r(99) = -.54$, $p < .001$. Again, text and virtual motion did not differ ($z = 0.39$, *ns*).

Discussion

The results suggest that, when compared to a simple egocentric verbal description, the experience of virtual self-motion along a landmark-free path does not enhance memory for the path. To the extent that this result is surprising, it may be because, on the surface, virtual self-motion and verbal descriptions are quite different. The subjective experience is, of course, vastly different. So, perhaps, is the level of abstractness. Verbal descriptions seem abstract and symbolic, whereas virtual motion is concrete and depictive. One might have supposed that to produce equal accuracy under these two conditions, additional presentation time would have been required in the verbal description condition to allow people to generate a concrete internal representation. But in the present study no additional presentation time was necessary. Perhaps this was because the representation provided by the verbal description, was abstract, but was sufficient to be as memorable as the one derived from virtual travel. Another possibility is that the representation produced by the verbal description was not abstract, but was in fact richly embodied, producing a representation similar to that produced by virtual self-motion.

Although we found no significant difference between verbal description and virtual motion presentations, we acknowledge the possibility that very small differences might exist that would be detectable using a much larger number of participants. Although there exist formal methods for testing the claim of absolute statistical equality (cf. Rogers, Howard, & Vessey, 1993; Tryon, 2001), it is not the main issue of interest here. Even if a much larger experiment were to show a small but significant advantage of one condition over the other, a key aspect of the result, for present purposes, would still be the functional near-equivalence of path memory for these two very different sensory experiences, confirming and extending the conclusions of Loomis et al. (2007).

Moreover, the results indicate that two crucial variables, memory load, and spatial proximity of prior path segments (“crowding”), both affect path memory accuracy in the same way and to approximately the same extent. This finding is perhaps even better evidence that the cognitive representation that determines spatial memory accuracy is functionally equivalent for these two conditions.

Thus, the present results support the conclusion of Loomis et al. (2007; Loomis et al., 2002) that both perceptual and linguistic descriptions can result in functionally equivalent cognitive spatial representations (see also Klatzky, Wu, & Stetton, 2008). Loomis et al. (2002) propose the term “spatial image” for this representation. They argue that a spatial image is different from a depictive, more pictorial 2D mental image (cf. Kosslyn, Thompson, & Ganis, 2006; Thompson, Slotnick, Burrage, & Kosslyn, 2009). In particular, a spatial image is conceived to be a 3D representation, rather than a 2D projection of a 3D view. Further, when a person moves in space, the relative 3D positions of the objects in that person’s spatial image are updated. This updating can even result in objects becoming occluded or unoccluded by other objects (Loomis et al., 2007). Although our results support the idea of a spatial representation that is not dependent upon the visual sensations accompanying virtual self-motion, they do not necessarily provide evidence for all of the other characteristics of the spatial image as described by Loomis et al. (2002).

Of course, we would not expect our results to hold when there are clear differences in the information being conveyed by verbal description and virtual motion. For example, in real-world navigation, landmarks play a key role. One would expect that a virtual travel experience that included visual depiction of landmarks might be far more helpful than a verbal description.

CONCLUSION

We studied the accuracy of spatial memory for very complex, landmark-free paths in three dimensions. By requiring participants to continuously detect intersections within the paths, we assured that the spatial aspects of the paths were being processed. By using paths that could be verbally described without ambiguity, we assured that the same information was conveyed using either egocentric verbal descriptions or the experience of virtual motion. Our results suggest that memory for these complex paths is not degraded when the subjective experience of virtual self-motion is absent. In fact, landmark-free virtual travel and verbal description support nearly identical spatial memory performance. In this sense, they seem to be functionally equivalent. The spatial memory for the path itself apparently transcends both the visual and the verbal aspects of its depiction.

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