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Reproduction of object shape is more accurate without the continued availability of visual information

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Abstract. An unfamiliar configuration lying in depth and viewed from a distance is typically seen as foreshortened. The hypothesis motivating this research was that a change in an observer's viewpoint even when the configuration is no longer visible induces an imaginal updating of the internal representation and thus reduces the degree of foreshortening. In experiment 1, observers attempted to reproduce configurations defined by three small glowing balls on a table 2 m distant under conditions of darkness following 'viewpoint change' instructions. In one condition, observers reproduced the continuously visible configuration using three other glowing balls on a nearer table while imagining standing at the distant table. In the other condition, observers viewed the configuration, it was then removed, and they walked in darkness to the far table and reproduced the configuration. Even though the observers received no additional information about the stimulus configuration in walking to the table, they were more accurate (less foreshortening) than in the other condition. In experiment 2, observers reproduced distant configurations on a nearer table more accurately when doing so from memory than when doing so while viewing the distant stimulus configuration. In experiment 3, observers performed both the real and imagined perspective change after memorizing the remote configuration. The results of the three experiments indicate that the continued visual presence of the target configuration impedes imaginary perspective-change performance and that an actual change in viewpoint does not increase reproduction accuracy substantially over that obtained with an imagined change in viewpoint.

1 Introduction

Even under full-cue conditions in natural outdoor environments, visual perception of spatial layout exhibits systematic error. An observer viewing a flat rectangular configuration on the ground some distance away will underestimate its depth relative to its width; the degree of perceptual foreshortening approaches a factor of 2.0 (Wagner 1985; Toye 1986; Loomis et al 1992) but is generally found to depend upon the egocentric distance of the configuration, reflecting to some extent the consequent effect on the slant and perspective of the configuration (Levin and Haber 1993; Philbeck and Loomis 1997). Equally important as this systematic error, however, is the fact that when an observer views a target on the ground at some distance and then attempts to walk to it with eyes closed, he/she will generally do so without systematic error (Thomson 1980, 1983; Laurent and Cavallo 1985; Corlett et al 1985; Elliott 1986, 1987; Steenhuis and Goodale 1988; Rieser et al 1990; Loomis et al 1992; Philbeck and Loomis 1997; Fukusima et al 1997). One interpretation of this latter result has been that observers accurately perceive the initial target location and correctly update an internal representation of its position during locomotion (Thomson 1983; Rieser et al 1990; Loomis et al 1992). If this interpretation is correct, the systematic error in the task involving exocentric intervals implies some dissociation of egocentric and exocentric distance perception (Loomis et al 1992; Loomis et al 1996). *Egocentric distance* is the distance between the observer and a point in space, whereas *exocentric distance* is the distance between two external points.

An interesting possibility is raised by the joint consideration of the above two facts—the accuracy in blind walking to a previewed target and the change in perceived shape of a configuration as it is approached with vision available. It is that whereas the shape of an object is misperceived when viewed from afar, it might be judged more correctly as an observer approaches it with eyes closed. That is, the mere act of walking with eyes closed to a previously viewed target might cause the observer to reassess its shape. This could happen if the changes in visual shape that occur when walking toward a configuration with eyes open are mimicked by changes in its internal representation during locomotion with eyes closed.

Research by Potegal (1971), Böök and Gärling (1981), Fukusima et al (1997), Rieser (1989), Loarer and Savoyant (1991), Loomis et al (1992, experiment 3), Presson and Montello (1994), and Easton and Sholl (1995) has already established that walking without vision induces a transformation of the 'perspective structure' of an internally represented scene that had been previously viewed. Just as walking with vision causes the perspective structure [the totality of directions and distances to points within the scene (Gibson 1979; Rieser 1989)] to undergo change, so does walking without vision cause the perspective structure of the imagined scene to transform in similar fashion. The studies cited show that after an observer has internalized the locations of one or more nearby objects as demonstrated by being able to point to them with eyes closed, walking through space induces an updating of the internal representation that is manifested by the observer's ability to point at the new directions of the objects with remarkably little error.

What distinguishes the previous results from what is being considered here is that perspective structure is observer-relative (Gibson 1979; Rieser 1989), whereas, the shape of a physical configuration, being part of the 'invariant structure' (Gibson 1979; Rieser 1989), is not. The angular separation of two points in a three-dimensional (3-D) configuration changes with observer location, but the physical distance between them does not. An observer who correctly perceives the spatial layout of a scene from the initial viewpoint and then correctly updates it during a blind traverse will manifest the changing perspective structure with his/her pointing but ought not indicate any change in the judged shapes of objects. Imaginal updating of object shape, should it occur, would have implications for our understanding of the link between visual space perception and visually guided action.

The original question addressed by this research was whether a real change in viewpoint can induce an observer, who initially misperceives the shape of a remote configuration, to reassess the shape of that configuration such that he/she judges its aspect ratio more veridically even though he/she receives no additional information while changing viewpoints. However, the results of the experiments, as will be seen, lead us in a slightly different direction. The research is still concerned with possible effects of perspective change but also raises the issue of the influence of continued visual input when observers attempt to imagine a perspective change. In experiment 1, we compared performance on configuration reproduction under two 'perspective change' conditions. Even though the observers received no additional information about the shape of the object in walking in darkness, they were more accurate (less foreshortening) when walking to the memorized configuration than when imagining the perspective change with the distant configuration visually available. Experiment 2 was conducted in order to assess the effect of continued visual input in the previous experiment when performing the imaginary perspective change. Observers more accurately reproduced distant configurations on the nearer table doing so from memory than when doing so while viewing the stimulus configuration on the far table. In order to evaluate the contribution of movement to internal updating of shape, a comparison of performance at both real and imaginary perspective change was performed in a third experiment.

Overall, results support the hypothesis that the visual presence of the object impedes imaginary perspective-change performance and that moving towards the memorized object location does not substantially increase the performance as compared to mere imaginary perspective change after memorizing object shape.

2 Experiment 1

When imagining a perspective change, observers viewing a remote configuration can update the object shape in a number of ways. For example, observers can compute the visual appearance of the object from a new vantage point while using the tacit knowledge acquired in everyday life about the change of perspective structure during locomotion, and then can try to compensate for the misperception of the object shape. As an alternative to such computations, observers can imagine a walk towards the memorized configuration (Thorndyke and Hayes-Roth 1982; Decety et al 1989; Jeannerod 1994). If the latter is true, walking blindly may help to 'embody' (May et al 1994) the imaginary perspective change and improve performance. We compared observers' performance on object shape reproduction after imaginary perspective change while they were viewing the distant object and after real ('embodied') perspective change toward the memorized remote object configuration.

2.1 *Method*

2.1.1 *General.* There were two conditions in this experiment. In both, the observer binocularly viewed a configuration of three luminous balls on a table 2 m away in a completely dark room. The configuration was a right triangle, with one leg defining a width interval in the observer's frontoparallel plane and the other orthogonal to it, defining an interval of depth. The widths and depths varied from trial to trial to produce variations in the aspect ratio of the triangle.

In the 'move' condition, the observer viewed the remote configuration, the configuration was then removed, and the observer walked in darkness to the table and attempted to reproduce the previously viewed configuration with three identical luminous targets. (Note that the observer actually walked with eyes open but received no visual feedback.) In the 'no-move' condition, the observer attempted to reproduce the configuration on a table immediately in front using three identical luminous balls. When standing either in front of the near table in the second condition or in front of the far table following the traverse in the first condition, the observer attempted to achieve the same result (reproduction of the configuration) using exactly the same manipulatory responses. If, in the process of moving from the initial viewpoint to the distant table, the observer transformed the internal representation of the previewed configuration in the same way that the configuration would perceptually transform if still visible, we reasoned that there ought to be much less error in the aspect ratio of the reproduced configuration than in the case where the reproduction is carried out on the near table.

2.1.2 *Experimental setup.* Two identical tables were used, one fixed and the other moveable. The upper horizontal surface of each was a 60 cm × 60 cm square positioned 110 cm above the ground. The surface was painted black and marked in pencil with a square grid of 1 cm spacing in both directions. The viewing point for all conditions was marked by two faintly glowing spots (1.4 cm diameter) on the ground; the observer placed the toes of his/her shoes just above these markers. The near edge of the fixed far table was exactly 2 m from these two markers, as measured along the floor; this means that the near edge was very nearly 2 m from the observer's eyes. The moveable near table, when employed, had its near edge positioned directly above the two luminous markers on the floor. An occluder made of black cardboard could be swung into and out of position just in front of the observer's eyes to prevent viewing of the stimulus configuration until the appropriate moment. The occluder also had a small luminous disk (1.4 cm diameter) mounted at its center; with the occluder in position in front of the observer, the observer used this small disk to properly position his/her head prior to presentation of the stimulus configuration.

The stimuli were white Styrofoam balls (2.0 cm diameter) that had been uniformly painted with phosphorescent paint; the balls had been inserted with thumbtacks forming a flat and heavy base to keep them from rolling. Three balls were used to define one of nine stimulus configurations on the far table; in addition, three identical balls were used by the observer in the attempted reproduction of this configuration, either at the near table or at the far table. Both the near and far tables had a single luminous spot (1.4 cm diameter) positioned on the upper surface adjacent to the midpoint of its near edge. The purpose of the spot on the far table was to allow the observer to locate the far table before colliding with it while walking toward it in darkness. A small vertical baffle occluded this spot from distant locations so that it could be seen only when the observer approached within 1 m of the table; thus, at the position from which the observer viewed the stimulus configuration, only the three balls were visible. A luminous spot was also mounted on the near table to equate the stimulation that the observer received when standing in front of it to that received when standing in front of the far table.

Nine configurations of the three balls were used in the experiment. Table 1 gives the coordinates of the three balls for each, as measured on the grid on the 60 cm × 60 cm table. The x coordinate extended from the left to right edges (from the observer's perspective) and the y coordinate from the near to far edges of the table. The table was oriented so that the midline of the grid corresponding to $y = 30$ cm extended directly from the observer's viewpoint, making this a line of pure 'depth'. Also given in table 1 are the depths (difference in y coordinates) and the widths (difference in x coordinates) and the stimulus aspect ratio (depth interval divided by width interval). As can be seen, the configurations varied in size and aspect ratio but were always positioned fairly close to the center of the grid.

Table 1. The stimulus configurations used in both conditions of the experiment. Coordinates of the three balls defining each configuration are given in centimeters along with the widths and depths so defined and the resulting aspect ratio (depth/width). The table was 60 cm × 60 cm; the x coordinate is distance from the left edge of the table (as seen by the observer) and the y coordinate is the distance from near edges of the table.

Configuration	Ball 1		Ball 2		Ball 3		Depth	Width	Ratio
	x	y	x	y	x	y			
1	29.5	49.5	29.5	29.5	39.5	29.5	20.0	10.0	2.00
2	29.5	39.5	29.5	29.5	49.5	29.5	10.0	20.0	0.50
3	29.5	44.5	29.5	29.5	44.5	29.5	15.0	15.0	1.00
4	25.0	40.0	25.0	25.0	35.0	25.0	15.0	10.0	1.50
5	25.0	35.0	25.0	25.0	40.0	25.0	10.0	15.0	0.67
6	25.0	35.0	25.0	25.0	35.0	25.0	10.0	10.0	1.00
7	20.5	35.5	20.5	20.5	40.5	20.5	15.0	20.0	0.75
8	20.5	40.5	20.5	20.5	35.5	20.5	20.0	15.0	1.33
9	20.5	40.5	20.5	20.5	40.5	20.5	20.0	20.0	1.00

2.2 *Observers*

The ten male and two female paid observers were in their 20s, except for a 16-year-old male and a 40-year-old male. As assessed by Keystone orthoscope, all observers had 20/30 or better visual acuity (with or without correction) and stereoscopic vision of 45% or better. None of the observers was aware of the purpose of the experiment.

2.3 *Procedure*

At no time did observers have the opportunity of seeing the experimental setup except under the minimal viewing conditions described. The observer entered the darkened laboratory and was led to an anteroom for vision testing and for instructions prior to each condition. The task for each condition was described with the aid of a diagram and one practice trial. At the beginning of each condition the observer was led in the dark to the viewing location and instructed on how to position himself/herself using the luminous markers on the ground and on the occluder that had been swung into position. Before the first trial and between subsequent trials the observer then faced in the opposite direction while the experimenters prepared the trial with the room lights on. The observer viewed a uniform white surface mounted on the wall (luminance = 27 cd m^{-2}) that maintained the observer in a state of moderate light adaptation. When the room lights were extinguished, the observer turned around and positioned himself/herself using the glowing spots on the ground and occluder. When the observer was ready, the experimenter swung the occluder away revealing the three luminous balls on the far table.

In the no-move condition, the observer then attempted to reproduce the configuration on the near table using the three balls held in one hand. The observer was instructed to reproduce the configuration under 'perspective-change' instructions, ie as he/she would if actually standing in front of the far table. The remote configuration remained in place while the observer made his/her response; the observer was allowed to tip the head up and down slightly to alternately view the far and near configurations, but was instructed to make no lateral motions of the head (a luminous spot attached to the observer's forehead allowed us to monitor head movements). The reproduction usually took from 5 to 10 s. Once satisfied, the observer turned around and the room lights were illuminated while the experimenters recorded the coordinates of the observer's response configuration.

In the move condition, the observer viewed the remote configuration for as long as desired (usually 5 s or less). He/she indicated when ready, closed the eyes, and the experimenter then quickly removed the three balls and said "go". The observer then opened the eyes and walked toward the table in darkness until the luminous spot at its near edge came into view. The observer continued right up to the table edge and then positioned the three balls carried in one hand to reproduce the configuration. The response, including walking in the dark, took only a few seconds longer than in the other condition. When satisfied, the observer turned around and walked back to the viewing position, guided by a luminous spot on the wall near the initial viewpoint.

It is important to note that during observation of the stimulus configuration and the response, the observer saw absolutely nothing in the room except the stimulus balls, the response balls, and the luminous spot on either the near or far table, depending on condition. Visual perception of the stimulus configuration and its reproduction on the table were signalled only by the static distance cues of monocular parallax (accommodation), binocular parallax (convergence), binocular disparity, angular elevation, and the relative and absolute sizes of the balls. In the move condition, the observer was able to sense the position of the far table over multiple trials using vestibular and proprioceptive cues. However, because the luminous spot on the table was never simultaneously visible with the stimulus balls, their locations on the table, as seen from the viewing location, were specified only by the cues mentioned above.

Photometric measurements with a Spectra Spotmeter (Model UBD-1/2) indicated that the luminous stimuli had a luminance (L) of 0.7 cd m^{-2} 5 s after the room lights were extinguished and that decayed in a fashion best described as $L/\mathrm{cd\ m}^{-2} = 2.48(t/\mathrm{s})^{-0.77}$, where t is time. Even for a response taking up to 30 s to complete, the final luminance of 0.18 cd m^{-2} was well above photopic threshold (0.01 cd m^{-2}).

Each observer participated in a single session lasting 2 h. During it, the observer experienced three conditions including the two (move and no-move) that have been described; the third, involving a completely different response, had a methodological flaw that was discovered later and hence is not being reported. There were six possible orders of the three conditions; each was given to two of the twelve observers. However, for the sake of simplicity we will consider that the observers were given only two orders (o1 = no-move/move; and o2 = move/no-move) and that each was given to half of the observers. In each of the two conditions reported here, the observer was presented twice with each of the nine stimulus configurations in random order, making a total of eighteen trials in each condition. Between conditions, the observer was returned to the lighted anteroom for instructions on the next task.

2.4 *Results*

The raw data were the coordinates of the three balls placed by the observer in correspondence with those of the stimulus. The observer's depth response was taken as the Euclidean distance between the positions of the two balls corresponding to those defining the depth interval in the stimulus. (For the stimulus, there was variation only in the y coordinate for the depth interval, but the observer's response typically exhibited some slight variation in x as well.) The observer's width response was measured in corresponding fashion. The response aspect ratio (A_r) was then defined as the depth response divided by the width response.

Our primary concern was with the shape of the response configuration, measured in terms of its aspect ratio, relative to that of the stimulus configuration, also measured in terms of its aspect ratio (A_s). Before considering these results, we note in passing some of the other measures of the observer's responses. The mean errors in placing the balls, averaged over observers, configurations, replications, and targets, were as follows. For the no-move condition, the mean error in x was -0.9 cm (slightly left) and the mean error in y was -7.8 cm (undershoot). For the move condition, the mean error in x was -1.5 cm and that for y was -9.9 cm. The mean errors in the width responses (4.5 cm and 5.2 cm for the no-move and move conditions, respectively) indicate a systematic tendency to overestimate the width of the configuration in both conditions. In contrast, there was a tendency to underestimate depth in the no-move condition (-1.3 cm error) and an opposite tendency to overestimate it in the move condition (1.6 cm). These opposite depth estimation errors in the move and no-move conditions give rise to the systematic differences in response aspect ratio for these conditions. It is this variation that is of primary interest.

Figure 1a gives response aspect ratio, A_r, averaged over observers and repetitions, as a function of stimulus aspect ratio, A_s, and the two response conditions. The error bars represent one standard error of the mean, computed on the twelve observers' scores (averaged over repetitions). (The results at the three configurations with $A_s = 1.0$ are averaged together.) A_r increases with A_s in both conditions, as would be expected, but the response value is generally smaller, sometimes by quite a margin. This means that, in general, observers underestimate depth relative to width. This is similar to earlier results (Wagner 1985; Toye 1986; Loomis et al 1992), but those studies involved full-cue conditions and much larger viewing distances. The most important result is that A_r was greater (and more accurate) for the move condition than for the no-move condition even though the observer carried out the response in virtually identical fashion (except for the blind traverse) and with the same information about the stimulus configuration. This is the result expected from the reasoning outlined in the introduction.

With the intent of normalizing the data for A_s and obtaining greater uniformity of response variance, each computed A_r was divided by A_s. This A_r/A_s ratio is plotted in figure 1b as a function of A_s and response condition. The error bars represent one standard error of the mean. A value of 1.0 corresponds to accurate reproduction of

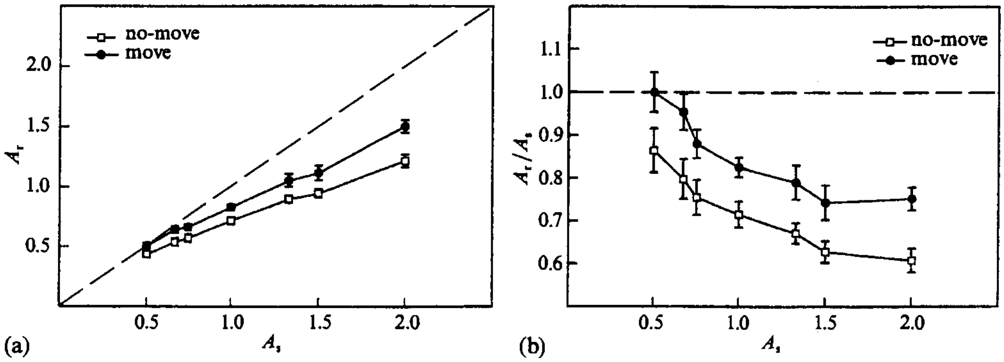

Figure 1. Experiment 1. Means and standard errors of (a) response aspect ratio, A_r; and (b) ratio of the response aspect ratio to the stimulus aspect ratio, A_r/A_s, for each viewpoint change condition as a function of stimulus aspect ratio, A_s. Dotted lines indicate correct reproduction. For details see text.

stimulus shape. A Response type × Configuration × Order ANOVA indicated highly significant effects of response type ($F_{1,11} = 31.1$, $p = 0.0002$) and configuration ($F_{8,88} = 14.9$, $p < 0.0001$). $A_s < 1$ led to significantly ($F_{1,20} = 48.3$, $p < 0.0001$) more accurate responses (mean = 0.88) than $A_s > 1$ (mean = 0.70). Neither the main effects of order and repetition nor any of the interactions were significant.

Table 2 shows the mean A_r/A_s, averaged over configurations and repetitions, by observer and response type for each task order. All twelve observers showed a higher A_r/A_s for the move condition than for the no-move condition, with nine (starred in table 2) showing a sizeable increase. However, none of the observers showed complete compensation for the initially perceived error, as would be indicated by a ratio equal to 1.0 in the move condition.

In order to confirm the effect of response condition without any contamination of possible sequence effects, we compared the performance of the observers on each response type considering only the first task for each subject (see table 2), ie no-move condition in order o1 (mean = 0.74) versus move condition in o2 (mean = 0.87). Comparison of these two groups showed a significant effect ($F_{1,10} = 19.86$, $p = 0.0012$) of response type. A similar comparison of the two other groups (move o1 versus no-move o2) also showed a significant ($F_{1,10} = 18.95$, $p = 0.0014$) response type effect. There is evidence of a small sequence effect because for both response conditions, performing the first task (ie response type condition) had a slight effect on performance of the second task (mean move o1 = 0.82 < mean move o2 = 0.87; and mean no-move o2 = 0.70 < mean no-move o1 = 0.74).

Table 2. Mean values of A_r/A_s (response aspect ratio/stimulus aspect ratio) in experiment 1. Standard deviations are given in parentheses. Asterisks indicate the observers for whom there was a notable difference in values for the two conditions.

Observer	No-move condition	Move condition	Observer	No-move condition	Move condition
No-move/move order (o1)			Move/no-move order (o2)		
1	0.73 (0.15)	0.75 (0.16)	2*	0.68 (0.12)	0.89 (0.17)
3	0.88 (0.18)	0.91 (0.11)	4*	0.66 (0.12)	0.79 (0.12)
5*	0.85 (0.12)	0.97 (0.18)	6*	0.69 (0.09)	0.84 (0.13)
7*	0.63 (0.10)	0.77 (0.13)	8*	0.60 (0.09)	0.89 (0.15)
9*	0.57 (0.10)	0.72 (0.12)	10*	0.83 (0.12)	0.89 (0.13)
11	0.78 (0.20)	0.82 (0.15)	12*	0.75 (0.13)	0.88 (0.19)
Mean	0.74 (0.19)	0.82 (0.17)		0.70 (0.13)	0.87 (0.16)

2.5 *Magnitude of the effects*

A quantitative estimation of the magnitude of the parent effect is very important from a theoretical standpoint, and goes beyond the fact of simply asserting the existence of an effect. The heuristic value of this procedure is its predictive approach, since it allows quantification of the parent effect with respect to the gathered data. Since the ANOVA on A_r/A_s showed a significant difference between response types, the magnitude of this difference needed to be estimated. By using Bayesian ANOVA techniques (Rouanet and Lecoutre 1983) it is possible to build a distribution over the parent effect δ ($\delta = \mu_1 - \mu_2$) from the experimental data. The distribution is centered on the observed effect d ($d = m_1 - m_2$), and its dispersion [ie, $(d/F^{1/2})^2$, that is, the observed effect d divided by the square root of its corresponding analysis of variance F ratio value, at the power of two] translates the potential of generalizability over δ which is carried by the experimental information. The magnitude of the effect can be assessed through credibility limits obtained from this distribution (Bernard 1994; Rouanet 1996).

Descriptively, the observed 'response-type' effect on the A_r/A_s ratio was 0.13, (mean for the move condition minus mean for the no-move condition). Its corresponding theoretical distribution is $t_{11}(0.13, 0.02^2)$, ie a generalized t distribution centered on the observed effect and with a dispersion index $(d/F^{1/2})^2$. From the usual t distribution tables we can find that we have a Bayes-fiducial probability (guarantee) of 95% that the effect in the population is at least +0.06. This means that we can confidently state that an increase of 0.06 occurs in the move condition as compared to the no-move condition. A next step in the analysis by the Bayesian approach is to verify if the effect is notable (reliable) for most individuals or not. Considering that an individual 'response type' effect is notable when it is at least 0.06, we find that nine observers (starred in table 2) out of twelve showed a notable effect, that is 75%. When considering the observed 'response type' effect for first tasks only ($0.87 - 0.74 = 0.13$) we have the same guarantee that this effect is at least +0.08.

Descriptively, the observed difference A_r/A_s between $A_s < 1$ (mean = 0.88) and $A_s > 1$ (mean = 0.70) was 0.18. We have a guarantee of 95% that this difference in the parent population is at least +0.14. Considering that this effect is notable when at least 0.14, we find that nine subjects out of twelve showed a notable effect, that is 75%.

2.6 *Discussion*

Merely walking to the location of a distant configuration without receiving additional information about its shape leads observers to reproduce the configuration more accurately (with less foreshortening) than in the case where the observer reproduces the configuration from the initial viewing location. This contribution of actual movement to accuracy in configuration reproduction was evaluated to be at least +0.06 in the parent population, and at least +0.08 when considering first tasks only. Overall, results support the original hypothesis, stated in the introduction, that locomotion induces a change in the shape of an internal representation that mimics the optical change in the corresponding physical shape apparent under conditions of continuous viewing while locomoting. However, there is a significant effect of the object aspect ratio on performance which leads observers to perform better (at least +0.14) in evaluating the shape of objects whose aspect ratio is less than one; interestingly, the magnitude of this effect is larger than that of the response type.

It is important to recognize, however, that the induced change in imagined object shape far from fully compensates for the error in perceived shape at the initial viewpoint, even for those observers exhibiting considerable compensation. As one explanation it is possible that the observers found it odd constructing a shape at the far table different from what they had just seen moments before at the point of observation and thus chose to compromise between two different response proclivities, with some observers favoring that based on the initial perception. Indeed, one observer commented on how strange it was to create a configuration at the far table that looked different from the way it appeared from the initial viewing location.

In the no-move condition, observers were instructed to imagine a perspective change appropriate to the far-table location. It could be expected that observers would have shown the same degree of updating as in the move condition, as reflected by comparable response aspect ratios. However, the results clearly indicate that this did not happen, for the perspective change associated with actual locomotion produced more veridical reproductions of the stimulus configurations, indicating greater perspective change. A possible reason was that there was less updating associated with the imagined perspective change perhaps because the continuously available information about the stimulus configuration may have conflicted with the imagined change in perspective. Experiment 2 was conducted to assess whether the continuous presence of visual stimulus information does indeed exert an influence on the reproduction of a stimulus configuration.

3 Experiment 2

In order to assess the influence of continuously available visual information, we employed two conditions, one being the no-move condition of experiment 1 and another differing from it only in that the reproduction of the configuration was carried out on the basis of memory of the viewed configuration. In this second condition, the subject looked at the stimulus configuration on the far table for as long as desired, it was removed, and the subject then attempted to reproduce it on the near table. We compared the observers' performance on both of these 'imagined viewpoint change' conditions, differing in terms of whether visual information about the configuration was continuously present.

3.1 *Observers*

The five male and three female paid observers were all in their 20s. As assessed by Keystone orthoscope, all observers had 20/30 or better visual acuity (with or without correction) and stereoscopic vision of 65% or better. None of the observers was aware of the purpose of the experiment.

3.2 *Procedure*

The experimental apparatus and procedure in the no-move condition were the same as in experiment 1. The stimulus configuration on the far table was continuously present while the observer reproduced it on the near table.

The delay condition was the same as the no-move condition except that the observer had to reproduce the stimulus configuration from memory. The observer viewed the remote configuration for as long as desired (usually 5 s or less). He/she indicated when ready, closed the eyes, and the experimenter then quickly removed the three balls and after a delay of 5 s said "okay". The observer then opened the eyes and positioned three balls held in one hand to reproduce the configuration on the near table. Once satisfied, the observer turned around and the room lights were illuminated while the experimenters recorded the coordinates of the observer's response configuration.

Each observer participated in both conditions during a single session lasting 1.5 h. There were two possible orders of the two conditions; each was given to four of the eight observers. In each of the two conditions, the observer was presented twice with each of the nine stimulus configurations in random order, making a total of eighteen trials in each condition. Between conditions, the observer was returned to the lighted anteroom for instructions on the next task.

3.3 *Results*

The mean errors in placing the balls, averaged over observers, configurations, replications, and targets, were as follows. For the no-move condition, the mean error in x was -3.96 cm (slightly left) and the mean error in y was -5.3 cm (undershoot). For the delay condition, the mean error in x was -3.3 cm and that for y was -3.7 cm. The mean errors in the width responses (6.1 cm and 5.9 cm for the no-move and delay conditions, respectively) indicate, as in experiment 1, a systematic tendency to overestimate the width of the configuration in both conditions. In contrast, there was a tendency to underestimate depth in the no-move condition (-0.5 cm error) and an opposite tendency to overestimate in the delay condition (0.6 cm). As in experiment 1, we were interested in how these opposite depth estimation errors in the no-move and delay conditions give rise to the systematic differences in A_r for these conditions.

Figure 2a gives A_r, averaged over observers and repetitions, as a function of A_s and the two response conditions. The error bars represent one standard error of the mean, computed on the scores of the eight observers (averaged over repetitions). (The data for the three configurations with $A_s = 1.0$ were averaged together.) As in experiment 1, observers underestimated depth relative to width, as indicated by response values smaller than the corresponding A_s. More importantly, A_r was greater and more accurate for the delay condition than for the no-move condition. The A_r/A_s ratio is plotted in figure 2b as a function of A_s and response condition. The error bars represent one standard error of the mean. A value of 1.0 corresponds to accurate reproduction of stimulus shape. Table 3 shows the mean A_r/A_s, averaged over configurations and repetitions, by observer and response type for each task order. All but observer 15 showed a higher A_r/A_s for the delay condition than for the no-move condition.

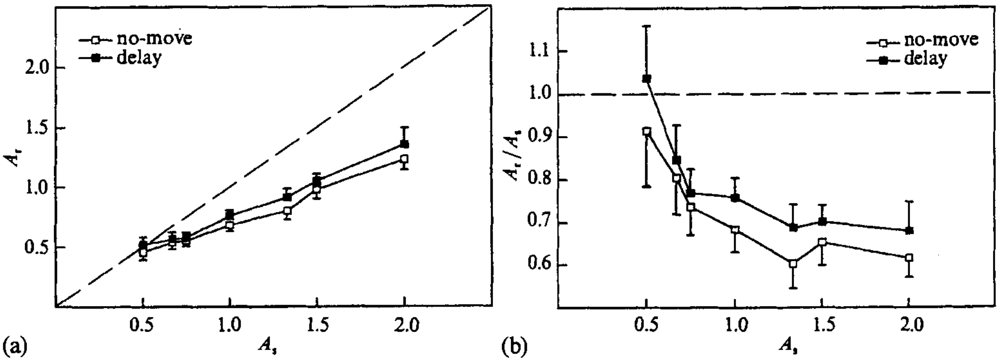

Figure 2. Experiment 2. Means and standard errors of (a) response aspect ratio, A_r; and (b) ratio of the response aspect ratio to the stimulus aspect ratio, A_r/A_s, for each viewpoint change condition as a function of stimulus aspect ratio, A_s. Dotted lines indicate correct reproduction. For details see text.

Table 3. Mean values of A_r/A_s (response aspect ratio/stimulus aspect ratio) in experiment 2. Standard deviations are given in parentheses. Asterisks indicate the observers for whom there was a notable difference in values for the two conditions.

Observer	No-move condition	Delay condition	Observer	No-move condition	Delay condition
No-move/delay order (o1)			Delay/no-move order (o2)		
13*	0.75 (0.17)	0.84 (0.26)	14*	0.84 (0.20)	0.89 (0.36)
15	0.81 (0.12)	0.81 (0.13)	16*	0.85 (0.23)	0.91 (0.26)
17	0.42 (0.14)	0.44 (0.13)	18*	0.72 (0.13)	0.79 (0.16)
19*	0.60 (0.10)	0.80 (0.19)	20*	0.68 (0.44)	0.75 (0.15)
Mean	0.65 (0.21)	0.72 (0.25)		0.77 (0.29)	0.83 (0.26)

The observed 'response-type' effect on the A_r/A_s was 0.07 (mean for the delay condition minus mean for the no-move condition). A Response type × Configuration × Order ANOVA indicated a significant effect of response type ($F_{1,7} = 10.9$, $p = 0.013$). Using Bayesian procedures we found with a guarantee of 95% that this effect in the parent population is at least +0.03. This means that we can confidently state that an increase of 0.03 occurs in the delay condition as compared to the no-move condition. Considering that an individual 'response-type' effect is notable when 0.03 or greater, we conclude that six subjects (starred in table 3) out of eight showed a notable effect, that is 75%.

The ANOVA also showed a significant effect of the 'configuration' factor ($F_{8,56} = 6.4$, $p < 0.0001$). More specifically, $A_s < 1.0$ led to significantly ($F_{1,12} = 45.5$, $p < 0.0001$) more accurate response (mean = 0.85) than $A_s > 1.0$ (mean = 0.66). The observed difference in A_r/A_s between $A_s < 1.0$ and $A_s > 1.0$ was 0.19. We have a guarantee of 95% that this difference in the parent population is at least +0.14. Considering that this effect is notable when at least +0.14, we found that five subjects out of eight showed a notable effect, that is 62.5%.

Neither the main effects of order and repetition nor any of the interactions were significant. However, participating in the delay condition first improved the performance in the subsequent no-move condition (mean no-move o2 = 0.77 > mean no-move o1 = 0.65); participating in the no-move condition first worsened subsequent performance in the delay condition (mean delay o1 = 0.72 < mean delay o2 = 0.83). This is indicated by a significant ($F_{1,6} = 35.25$, $p = 0.001$) effect of the response-type factor when comparing first tasks (mean no-move o1 versus mean delay o2) performances, and a nonsignificant ($F_{1,6} = 2.6$, $p > 0.10$) effect when comparing the two other 'second tasks' groups.

3.4 *Discussion*

The results support the hypothesis that the visual presence of the remote misperceived configuration impedes imaginal updating of object shape after imagined perspective change. Indeed, one subject reported that when he was performing the imagined perspective change in the no-move condition he was attending to the visual appearance, whereas when doing it from memory (delay condition), he was more able to follow the instructions, which in both conditions were to perform the task "as if standing in front of the far table".

Several studies using open-loop motoric tasks (Elliott and Leonard 1986; Steenhuis and Goodale 1988; Elliott et al 1990) showed indeed that for up to 30 s there is no effect of delay on localization performance. This suggests that the more accurate object shape production in the delay condition is not due to spontaneous transformation of the memorized object configuration. Moreover, other studies showed evidence that there are no significant differences between distance estimates based on memory and those based on imagery (Hubbard et al 1989) in which an imagined object overflows the visual field (Kosslyn 1978; Hubbard and Baird 1988).

From the results of experiment 2, we can conclude that memorizing the object shape adds at least +0.03 (in terms of A_r/A_s) to the perspective-change performance, as compared to the baseline condition where one has visual access to the configuration. From the results of experiment 1, we conclude that perspective change resulting from actual movement adds at least +0.06 to the baseline performance. Whether the perspective change with actual movement is greater than the imagined perspective change (without conflicting visual information) can be answered with an experiment directly comparing these two conditions.

4 Experiment 3

The results of experiment 2 showed that the visual presence of remote configuration may impede imaginal perspective change and updating of object shape, as compared to a condition without vision of the stimulus. In order to assess the contribution of actual movement to perspective-change performance we compare the results of observers performing both the delay and move conditions.

4.1 *Observers*

The three male and one female paid observers were in their 20s, except for one male aged 38 years. As assessed by Keystone orthoscope, all observers had at least 20/30 visual acuity (with or without correction) and stereoscopic vision of 70% or better. None of the observers was aware of the purpose of the experiment.

4.2 *Procedure*

The experimental apparatus was the same as that used in the previous experiments. Each observer participated in the move condition of experiment 1 and the delay condition of experiment 2 during a single session of 1.5 h. There were two possible orders of the two conditions; each was given to two of the observers. In each of the two conditions reported here, the observer was presented twice with each of the nine stimulus configurations in random order, making a total of eighteen trials in each condition. Between conditions, the observer was returned to the lighted anteroom for instructions on the next task.

4.3 *Results*

The mean errors in placing the balls, averaged over observers, configurations, replications, and targets, were as follows. For the move condition, the mean error in x was -0.05 cm and the mean error in y was -2.5 cm (slight undershoot). For the delay condition, the mean error in x was -1.6 cm (slightly left) and that for y was -2.8 cm. The mean errors in the width responses (6.3 cm and 8.5 cm for the move and delay conditions, respectively) indicate, as in experiments 1 and 2, a systematic tendency to overestimate the width of the configuration in both conditions. There was the same tendency to overestimate depth in both conditions although to a smaller extent in the move (2.3 cm error) as compared to the delay condition (4.1 cm).

As in experiments 1 and 2, we were interested in how these different depth estimation errors in the move and delay conditions give rise to the systematic differences in A_r/A_s for these conditions. Table 4 shows the mean A_r/A_s, averaged over configurations and repetitions, by observer, response type, and order.

A Response type × Configuration × Order ANOVA indicated no significant effect of response type ($F_{1,3} = 0.02, p > 0.10$) on A_r/A_s, but a significant effect of configuration ($F_{8,24} = 5.65, p = 0.0004$). $A_s < 1.0$ led to significantly ($F_{1,4} = 58.9, p = 0.002$) more correct response (mean $= 0.94$) than $A_s > 1.0$ (mean $= 0.76$). The observed difference in A_r/A_s between $A_s < 1.0$ and $A_s > 1.0$ was 0.18. We have a Bayes-fiducial guarantee of 95% that this difference in the parent population is at least +0.13. Considering that this effect is notable when at least +0.13, we conclude that three subjects out of four showed a notable effect, that is 75%.

Table 4. Mean values of A_r/A_s (response aspect ratio/stimulus aspect ratio) in experiment 3. Standard deviations are given in parentheses.

Observer	Move condition	Delay condition	Observer	Move condition	Delay condition
Move/delay order (o1)			Delay/move order (o2)		
21	0.52 (0.15)	0.60 (0.10)	22	0.96 (0.12)	0.97 (0.15)
23	0.92 (0.16)	0.94 (0.31)	24	0.96 (0.20)	0.86 (0.15)
Mean	0.72 (0.26)	0.77 (0.29)		0.96 (0.17)	0.91 (0.16)

The mean A_r/A_s, averaged over configurations and repetitions, is plotted in figure 3a as a function of experiment number, task position (1st or 2nd), and response type. Neither the main effects of order and repetition nor any of the interactions were significant. A comparison of first task performance in experiment 3 showed (marginally) significantly ($F_{1,2} = 16.7$, $p = 0.055$) better results for the delay condition than for the move condition (mean delay o2 = 0.91 > mean move o1 = 0.72). However, comparison of second task performance showed a marginally significant ($F_{1,2} = 15.44$, $p = 0.059$) opposite tendency. This reflects the fact that doing the move condition first worsens subsequent performance in the delay condition (mean delay o1 = 0.77 < mean delay o2 = 0.91); whereas, doing the delay condition first seems to improve the performance in the subsequent move condition (mean move o2 = 0.96 > mean move o1 = 0.72).

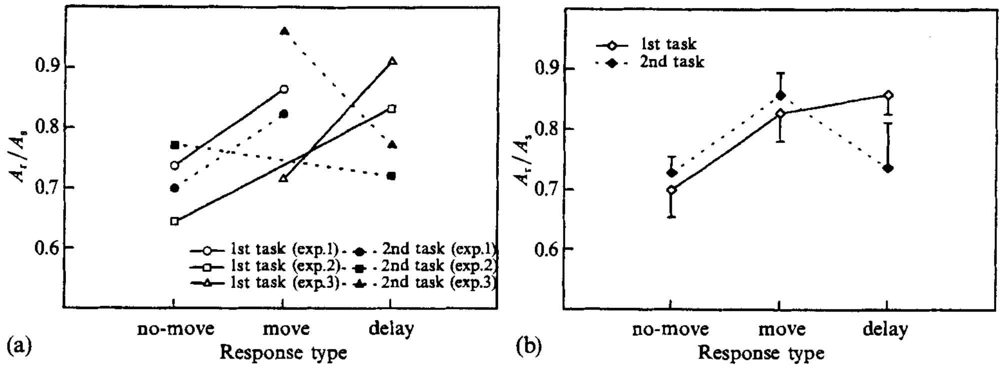

Figure 3. (a) Means of A_r/A_s for each task position (1st or 2nd) and experiment number as a function of response type (viewpoint-change) condition. (b) Means and standard errors of A_r/A_s, averaged over experiments, for each task position as a function of viewpoint-change conditions. For details see text.

Figure 3b illustrates the mean A_r/A_s (error bars represent one standard error of the mean), averaged over experiments, configurations, and repetitions, as a function of task position (1st or 2nd) and response type. A Response type × Task position ANOVA on A_r/A_s was conducted with the data of the three experiments by dividing the subjects in two groups per response type depending on whether they executed the task first or second. An unpaired comparison of the task position groups for each response type showed no significant effect on the task position. On the other hand, the ANOVA showed an overall response-type effect which was significant ($F_{2,21} = 3.61$, $p = 0.045$) when the tasks were done first, and marginally significant when they were done second ($F_{2,21} = 2.9$, $p = 0.077$). More precisely, when done first, the delay and move conditions put together show significantly ($F_{1,21} = 7.02$, $p = 0.015$) better performance as compared to the no-move type of response. In contrast, when the tasks are done second, it is the move condition that leads to the best performance ($F_{1,21} = 5.78$, $p = 0.026$) as compared to the no-move and delay types of response. Finally, it appears that reproduction of object shape is overall significantly ($F_{1,42} = 8.98$, $p = 0.005$) more accurate in the move and delay conditions put together as compared to the no-move condition.

4.4 *Discussion*

Overall, it seems that when the tasks are performed first, there is no real benefit in imaginal updating associated with actual walking over and above the benefit of imaginal updating while standing at the near table. This result is consistent with the conclusion of a few studies showing that prior awareness of the new vantage point leads to more accurate localization performance of previewed objects than when observers are unaware of the arrival point before being blindfolded (Loarer 1990; Loarer and Savoyant 1991), especially when the final point of observation is known to the observer and when the imaginary perspective change is a translational one (May et al 1994), as was the case in the present study.

As in experiments 1 and 2, we replicated the finding that observers are better able to evaluate the stimulus shape (at least +0.13) when $A_r < 1$ than when $A_r > 1$. A related finding concerning the shape of the configuration is that observers in the three experiments showed a general tendency to overestimate width in relation to true distance and to depth. This finding is fully consistent with data by Haber and collaborators (Haber et al 1993; Levin and Haber 1993) showing that the interobject (exocentric) distances perpendicular to the line of sight are overestimated in relation to true distance and to distances parallel to the line of sight. As a matter of fact, Haber and colleagues worked with natural scenes where a large variety of cues are available to determine visual space (Cutting and Vishton 1995). In contrast, we worked in so-called 'reduced-cues' conditions (Loomis et al 1996; Amorim et al 1997; Philbeck and Loomis 1997; Philbeck et al 1997), using glowing objects in complete darkness. Under such conditions, it has been shown that angular elevation was the cue which exerted the main influence on perceived distance as compared to binocular parallax and absolute motion parallax (Philbeck and Loomis 1997). Given our replication of the finding of Haber and colleagues (1993) of an elongation along the dimension perpendicular to the line of sight in the representations of visual scene, our results extend to reduced-cues conditions the conclusions that they have drawn from results obtained in full-cues conditions.

5 General discussion

Our initial expectation was that merely walking to the location of a memorized distant configuration without receiving additional information about its shape leads observers to reproduce the configuration more accurately (with less foreshortening) than in the case where the observer reproduces the configuration from the initial viewing location while having visual access to the remote stimulus. Results of experiment 1 supported this hypothesis, stated in the introduction, that locomotion induces a change in the shape of an internal representation that mimics the optical change in the corresponding physical shape apparent under conditions of continuous viewing while locomoting. However, experiments 2 and 3 produced evidence that walking to the location of the object does *not* produce *more* updating of the object shape *than* merely imagining being at the location of the object, provided that the object is not simultaneously present, for visual presence of the object does limit the imaginal updating. This overriding of 'cognition' by visual perception is consistent with Glenberg's (1997) 'suppression hypothesis' according to which suppression of environmental input is necessary in order for conceptualization (ie the encoding of patterns of possible physical interaction with a three-dimensional world) to take place. An example of the effect of such a suppression is the fact that when one must simulate mentally a previously executed walk in order to estimate its duration, more accurate estimates are given when eyes are closed rather than when they are open during mental simulation (Kebeck et al 1990). Similarly, when working on a difficult intellectual problem (which should require suppression of the environment), we reduce the rate at which we are walking to avoid injury (Glenberg 1997). A related finding by Glenberg et al (1995) is that people avert their gaze when working on moderately difficult recollection tasks (but not on easy ones), and that this behavior enhances accurate remembering. In sum, although subjects were instructed to reproduce the distant object shape under 'objective instructions' (Carlson 1977), ie implicitly compensating for the visual distortions, their performance indicated that, overall, reproduction of object shape is more accurate without the continued availability of visual information (that is in move and delay conditions), as predicted by the suppression hypothesis.

Indeed, when we view a 3-D shape, we perceive considerable distortion in the form of a compression of its depth relative to its width. However, accompanying our perception is implicit knowledge that is closer to the real shape of the object; perhaps, this 'cognitive representation' is more accurate because our vast experience with changing perspective tells us that the 3-D object looks different from any given perspective than what we get from multiple perspectives. Although we have this more correct representation in mind, we may not be conscious of the discrepancy between it and what we are presently seeing. An example of this shape-constancy phenomenon (Epstein 1977) is that we implicitly know the approximate size of a human being even though a person is far away from our current spatial location, or when seen as smaller if standing in a background of a photograph as compared to another person in the foreground. Now, when we close our eyes, the perceptual representation disappears leaving only the more general representation. So when we attempt to indicate our knowledge of the perceived object, we default to the more correct cognitive representation.

In fact, the exact picture of our results is more complex than it appears when examining the results of each experiment independently from the others. Closer examination of the overall data obtained from the three experiments shows the presence of an order effect—the reproduction of object shape depends on whether the task used to respond was used first or subsequently to another task. Earlier work had demonstrated that walking without vision induces a transformation of the imagined directions to objects within the internal representation of a previously viewed scene (Potegal 1971; Böök and Gärling 1981; Rieser 1989; Loarer and Savoyant 1991; Loomis et al 1992; Fukusima et al 1997; Philbeck and Loomis 1997). We also find such a result but *only* when reproduction of object shape after nonvisual locomotion is used *subsequent* to use of another type of response (ie no-move and delay conditions). In contrast, when the tasks are performed first, both the delayed match (from memory) and that following a nonvisual navigation show a more veridical reproduction than when the visual information is continuously available, as predicted by Glenberg's (1997) suppression hypothesis.

It is important to recognize, however, that the induced change in imagined object shape either from imagined or 'embodied' (blind-walking) perspective change far from fully compensates for the error in perceived shape at the initial viewpoint, even for those observers exhibiting considerable compensation. Importantly, this depends on the object aspect ratio, for we have shown that aspect ratios less than 1 are updated better than aspect ratios greater than 1. However, it is possible that evidence of more complete compensation would have resulted had the observer performed a response that did not require such conscious consideration of the perceived depth and width of the configuration; one response that does not is configuring the hand to grasp a small triangular shape viewed from the initial viewpoint. In work with a patient suffering from visual form agnosia, Goodale et al (1991) have provided unequivocal evidence of dissociation between visually guided reaching and visual perception—even though the patient was unable to discriminate between objects of different sizes or to mold the hand to match the extents of the objects, she performed normally when asked to reach and grasp the objects; a similar dissociation involving object orientation was also reported. Work with neurologically intact patients has also indicated a dissociation between visuomotor control and conscious visual perception (Bridgeman et al 1979, 1981; Goodale et al 1986). Goodale (1988) has argued that tasks requiring observers to abstract various aspects of their conscious visual experience, as is the case with width and depth matching, may fail to reveal information that is accessible to visuomotor processing.

At the same time, however, circumspection is called for because it would be incorrect to assume that all visually controlled action is carried out by modules independent of those involved in conscious visual experience.

The imaginal updating demonstrated here, though it only partially compensates for initial perceptual error, has important implications for our understanding of the link between visual space perception and visually guided action. It indicates that one cannot assess the functional accuracy of a perceptual representation without knowing to what use it will be put. That an observer misperceives a visual environment from some remote vantage point does not imply that the observer will make errors of action when moving about within that environment, even if no additional information about the environment has been obtained during travel to it. A common experience will serve to clarify this point. Sometimes while driving, a parking space which up ahead appears too small to accommodate one's vehicle is subsequently judged adequate when being closely approached. It is possible that one's judgment of the adequacy of the space would also be altered if the approach were made without additional visual information about it, such as if it were occluded on its side during the approach. The present results suggest that imaginal updating, whether or not accompanied by the corresponding physical movement, does compensate partially for perceptual error, but much more needs to be done to establish the role of internal representations and their imaginal transformations in the control of action. If they are shown to play a major role, the utility of traditional psychophysical studies of visual space for understanding visually controlled action will be limited considerably.

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