Title
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Journal
Proceedings of the Annual Meeting of the Cognitive Science Society, 31(31)

ISSN
1069-7977

Authors
Davies, Jim
Thomson, Robert

Publication Date
2009

Peer reviewed

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Robert Thomson (rthomson@connect.carleton.ca)
Institute of Cognitive Science, Carleton University
1125 Colonel By Drive, Ottawa, ON K1S5B6 Canada

Jim Davies (jim@jimdavies.org)
Institute of Cognitive Science, Carleton University
1125 Colonel By Drive, Ottawa, ON K1S5B6 Canada

Abstract

The present research utilizes a change detection paradigm to contrast two candidate processes by which distance is encoded. The first process is an intrinsic absolute metrical system, where distance is encoded in an underlying universal matrix, such as visual co-ordinates. The alternative is a local ad-hoc metrical system where distance is encoded as a ratio of the size of a salient object in the scene. Manipulating object size differentiated between these candidate processes. A forced-choice change detection task modeled after Cole, Kentride, Gellatly & Heywood (2003) and a mouse dragging task tested memory for recognition and production of distance respectively, with results indicating that changes in object size affected both memory for the recognition of- and the subsequent reproduction of past perceived distances.

Keywords: spatial cognition; change detection; distance

Introduction

Rodney Brooks (1991) has argued that the world acts as its own best representation, where much of behaviour can be governed by what is directly perceived. On the other hand, we have the ability to accurately store visuospatial information, with limitation. For example, after viewing a scene it is possible to recall the location of several objects (Vogel, Woodman, & Luck, 2001; 2006), estimate their approximate size (Baird & Wagner, 1991), and their approximate distance to each other (Frenz & Lappe, 2006).

When spatial information is recalled in the absence of visual perception, it is evident that the processing system relies solely on memory. What is less understood is the nature of the information being stored. There is strong evidence that an object's perceived size and distance are influenced by the size and distance of other objects that were recently the focus of attention (Makovski & Jiang, 2008), and which have also been perceived in conjunction with the object in question (Baird & Wagner, 1991).

Theories of Distance Encoding

While there is no question that we can estimate distance with varying accuracy when a task demands it, it is not clear whether we necessarily store metrical distance information. We encode very little of a perceived scene unless we are explicitly attending to the items in question (Henderson & Hollingworth, 1999), even though our subjective experience of the scene is robust. Evidence from transsaccadic memory shows that even when a visual image is shifted by up to 1.2° of visual angle or contracted by 20%, these changes often go unnoticed (McConkie & Currie, 1996). This change blindness (Rensink, O'Regan & Clark, 1997) suggests that observers do not necessarily use an independent metric of space to consolidate successive views, but instead rely on local information (Intraub, 1997). We will now examine the evidence behind two processes implicated in representing distance: metrical and categorical accounts.

Metrical Distance: Mental Scanning Paradigms

The most influential evidence that metrical distance information is stored during visual perception comes from studies on mental scanning (Kosslyn, Ball, & Reiser, 1978). In the predominant version of the mental scanning paradigm, several landmarks are studied in a pre-arranged configuration until their locations are memorized. This is generally referred to as generating a 'cognitive map' of the scene. For each trial, a landmark from the map is visualized and, when hearing the name of a second landmark, the participant has to mentally scan the distance between landmarks and press a button when scanning is complete.

Multiple studies have found a linear correlation between response time and distance between landmarks (Kosslyn, et al., 1978; Kosslyn, 1994; Cocude, Mellet, & Denis, 1999). This linear increase in response times has further been correlated with the actual visual scanning times in some participants (Cocude et al., 1999), and has also been found when the perceived map was described textually as hourly positions around an imaged clock (Denis & Cocude, 1992).

There are limitations to the theory that visual memory and imagery are in some way isomorphic with perception. The linear correlation between mental scanning and distance has been shown to be highly task and instruction-dependent. When the participant is asked to trace distance path by mentally following a dot along the distance, then the mental scanning times are linearly correlated with distance with a coefficient of determination up to 0.97 (Kosslyn et al., 1978). When this dot-following heuristic is left out of the instruction, however, a much lesser (or no) linear correlation is evidenced (Pylyshyn, 1981). Furthermore, if a participant is asked to imagine 'jumping' from one landmark to another rather than 'scanning,' no correlation between response times and landmark distance are found, presumably because no 'scanning' occurred within the participant's mental representation (Pylyshyn, 2002). This stands in contrast with previous research indicating that it was not possible to eliminate mental scanning effects (Kosslyn, 1994). Still, the fact that it is possible to exhibit a linear correlation between response time and distance implies that metrical distance is at least implicitly represented in memory (Pylyshyn, 2002).

Categorical Distance: Mental Model Theory

Mental models claim that distance is generally encoded categorically in a symmetrical mental array where ‘cells’ contain object labels. Adjacent cells represent categorical spatial relations (e.g., above, left-of) equidistant to each other, with no metrical distance (Johnson-Laird & Byrne, 1991; Knauff et al., 2004). While some instantiations of this model take a more literal interpretation of the representation as array-like (see Glasgow & Papadias, 1992) the notion of a mental array is generally presented as a heuristic to explain certain consistencies in experimental results.

Spatial mental model theories have their own predictions about stored spatial information. These theories hold that metrical distance information is not generally necessary (and thus not always stored) for much of spatial reasoning. This is especially true for simple environments or situations where the underdetermined spatial information leads to multiple possible interpretations. To take an example from driving directions, if we need to know to turn left at the gas station, then we don’t need to know the exact distance to it.

While mental models focus on the categorical links between objects in representations of spatial configurations, there is an implicit notion of distance estimation within their array-like behaviour. The assumption that ‘cells’ (or for a less leading term, indexes) are symmetrical leads to several consequences. The first is that a limited distance metric is available. Symmetry implies that there is the possibility of empty cells to maintain consistency within the configuration of the data structure, strengthening the analogy of the mental model as array-like. Any array-like data structure, especially a 2D one, is functionally analogous to a Cartesian co-ordinate system. Along a single ‘row’ it is possible to judge whether an object is farther away than another by examining how many indexes apart two objects are. While this judgment is not metrical in an absolute sense (i.e., the size of cells does not necessarily conform to the same length across trials), the use of tacit knowledge (e.g. knowledge of object size or scale) can consolidate this sparse distance information into a judgment of metrical distance.

Neuro-physiological Evidence

fMRI studies have found that many regions in the primary visual cortex implicated in perception are also implicated in visual mental imagery. However, this overlap is not uniform with Borst & Kosslyn (2008) finding less activation in the primary visual cortex during imagery. Additionally, they found increased activation in the frontal and parietal regions implicated in top-down processing. This implies that some memory (re-)construction is occurring. Still, there is enough evidence to assume some representational similarities between our perception and our mental image of a percept.

Located within the entorhinal cortex is a region where topological spatial information appears to be consolidated within two layers of cells, aptly named grid cells and place cells (Fyne et al., 2004). Grid cells are topologically-encoded bundles of neurons arranged in a periodic hexagonal grid. Different ‘levels’ of grid cells activate in terms of different ‘sizes’ of their corresponding receptive fields, indicating that the brain processes signals into progressively more precise spatial regions. At first glance, it therefore appears that some preference should be afforded to spatial layouts whose objects fall into specific spatial regions denoted by the firing rate of a specific bundle of grid cells. Grid cells at different levels appear to have different firing patterns, limiting a purely topographical interpretation (O’Keefe & Nadel, 1978).

Place cells, on the other hand, do not exhibit any periodic properties and instead fire only when an object occupies a specific region of the visual field. When experiencing a novel environment, the organization of place cells is rapidly determined, although not in any topological organization.

Ad-Hoc Metrics

If people encode spatial information in an absolute metrical system, then having knowledge of even basic coordinate information would make it possible to generate complete spatial information of a given scene (Ligozat & Edwards, 2002). It would also be a simple matter to compare distances across scenes as it is simply a matter of scalar comparison. From the evidence previously outlined, it is evident that people do not exhibit perfect spatial recall, especially with regards to distance.

In a system of locally-generated ad-hoc metrics, it is difficult to directly compare distances across scenes because the metrics used are usually different, since different objects are present. Inter-scene comparison is possible by using additional (e.g., tacit) reasoning to scale the relative sizes of the objects forming the metrics. This could occur at a semantic level (e.g., knowing that a car is approximately 16ft long so 3 car lengths is approximately 50ft away) or from past experience (e.g., knowledge that a bicycle is about 1/3 the size of a car thus 6 bicycle lengths is 2 car lengths). Within the ad-hoc theory, errors can occur at multiple points, for example: semantic information involved might be incorrect (e.g., cars can be as short as 8ft long in the case of a compact, or 30ft long in the case of a limousine), or the visual estimate of distance might be incorrect (e.g. it was actually 4 car lengths). This theory does not make the strong claim that we only store distance in terms of object-ratios, but simply that this is one heuristic used which is as valid as, or can be seen as an extension of, mental model theory.

Present Research

The present research will provide empirical evidence to determine the role object size plays in estimating distance. If object-size does not significantly impact judgments of distance, then the results would be consistent with a theory of absolute distance, otherwise if object-size impacts distance judgments then results would be consistent with a theory of ad-hoc metrics.

The one-shot change detection paradigm (Cole et al., 2003) was adapted to measure which visuospatial aspects of a scene are initially encoded and available for future comparison. In the present experiments, distances are compared between sequentially-presented images of two monochrome squares symmetrically located around the center of the display. These simple squares were used to control for semantic effects and have stimuli which are symmetric around both horizontal and vertical planes.

Experiment 1 is a forced-choice task with object size and distance systematically varied to examine the interaction of object size on distance judgments. Judgments are made using a trinary CLOSER-SAME-FARTHER decision tree.

Experiment 2 expands upon this exploration of distance encoding through the use of a mouse dragging task. After presentation of the same first image as in Experiment 1, with one square anchored, participants drag the other square to re-create the distance from the first image. This dragging will allow more fine-grained examination of the influence object size has on perceived distance and compare memory for recognition versus memory for production.

Experiment 1: Forced-Choice Task

The objective of this forced-choice change detection task is to provide reasonable evidence about the nature and accuracy of observers' preliminary processing of distance between objects in a visual scene. Object size was manipulated between images to determine its effect on distance judgments. The use of the one-shot change detection paradigm minimizes the role of eye movement and long-term memory (Rensink, 2002).

If participants underestimate distance when object size is increased (and overestimate when object size is decreased) then the ad-hoc metric hypothesis will be supported. In contrast, if distance judgments are unaffected by object size, then evidence would point towards an absolute metrical system where distance is encoded irrespective of object size.

The use of the trinary CLOSER-SAME-FARTHER judgment served to further address the accuracy of people's change detection that a simple SAME-DIFFERENT binary judgment could not. Binary judgments only determine that a size change has been made, but not its exact influence (i.e. increase/decrease) on perceived distance. In this experiment, both accuracy and response times were recorded.

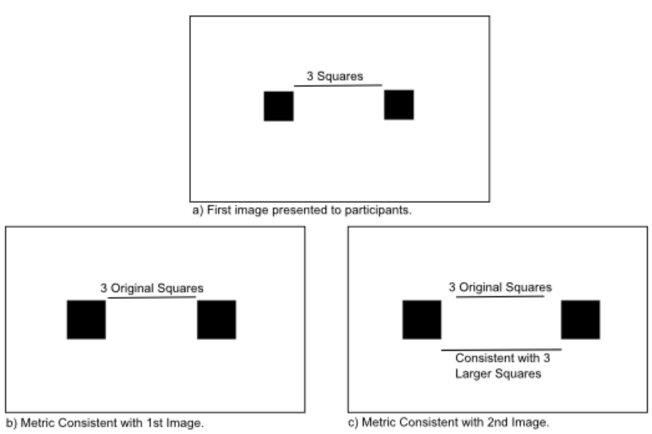

Figure 1. Sample paired stimulus from Experiment 1. 1b) and 1c) identify how the change in distance metric is seen.

Method

Participants

Twenty-nine undergraduate students with normal or corrected-to-normal vision were provided with course credit for their participation. One participant was excused for repeatedly failing to follow task procedures.

Materials

The first image (see Figure 1) was presented for 1200ms. A white-noise mask was presented for 600ms, followed by the second image until a response was received. Durations for the stimuli were derived from a one-shot change detection methodology from Cole et al., (2003).

Each stimulus consisted of sequentially-presented paired images, with two identically-sized squares in each image. This study was conducted with stimuli of nine different sizes between 0.65° - 2.25° in 0.20° increments. The first image presented consisted of three different stimuli sizes (1.05°, 1.45°, and 1.85°) and the size was varied in the second image presented by 0°, +/- 0.20°, or 0.40°. The size of the objects was determined from change detection studies (Vogel, Woodman, & Luck 2001; Cole et al., 2003) which ranged from 0.65°- 2.8° of the visual field. The white noise mask eliminated any retinal afterimage, which might have provided an index for spatial position.

Distances between objects ranged from 2, 3, or 4 object-sizes apart, calculated from the inner edge of the objects. The distance metric was also varied, with distances in the second image remaining unchanged or changing to the object-ratio of the object size in the second image. In addition to distance, the orientation of the stimuli was also varied (horizontal and vertical presentation). Due to the majority of distance estimations occurring along the horizontal plane (i.e., ground level) it is possible that horizontal distance judgments would be more accurate.

In total, 180 experimental trials were completed. In addition to the experimental trials, 36 control trials were also developed where distance varied but object size did not. The experiment was divided into two blocks with half the trials consisting of horizontally-oriented stimuli and the other half vertically-oriented, with the corresponding vertically- and horizontally-oriented stimuli in the other block. Trial order was randomized between participants.

Apparatus

The experiment was developed using the VisionEgg 1.1 wrapper for Python. Stimuli were presented on a 24" LCD monitor at a resolution of 1920x1200. Responses were recorded on a three-button mouse.

Procedure

The experimental room was setup such that the computer monitor was the only object visible on the desk. To control for lights and to reduce the possibility that the texture of the wall in the background would be used as a heuristic for determining relative distance, the desk and walls were covered with a minimally-reflective black plastic.

Participants entered the experiment room and sat in an adjustable chair such that their eyes are centred 60cm (~25”) from the screen. They were instructed to focus their gaze to the centre of the screen and to minimize head and body movements as much as comfortably possible. They then underwent four practice trials to learn the task procedure, with no feedback provided about the accuracy of their response. Speed and accuracy were equally stressed, as was the requirement to judge distances from the inner edge of the stimuli. Responses were recorded on a three-button mouse as follows (from left-button to right-): CLOSER, SAME, and FARTHER. The spacebar was pressed to advance between trials. Response times were recorded from the onset of the second image to the pressing of the mouse button.

Results and Discussion

A repeated-measures ANOVA was conducted with accuracy and response time as the dependent variables. The independent variables examined include the change in object size, the metric (whether distance changed or not between images), and orientation. Initial size and distance were aggregated to focus on the main prediction that object size influences distance judgments, and neither had exhibited any significant effect in preliminary analyses.

The main effect of changing object size exhibited the strongest influence on both accuracy and response time, $F(2.878, 28) = 36.757$, $MSE = 2.331$, $p < .001$, $\eta^2 = .472$ and $F(2.719, 28) = 14.403$, $MSE = 1220000$, $p < .001$, $\eta^2 = .659$ respectively (Greenhouse-Geisser adjusted). This supports the hypothesis that object size is a determining factor in the judgment of distance. Additionally, larger absolute changes in object size caused an linearly increasing latency irrespective of object size increasing or decreasing.

Interestingly, there was no main effect of distance metric on response times, $F(1, 28) = .053$, $MSE = 3479$, $p = .820$, implying that the mental processing demands are similar whether distance changes or not. On the other hand changing the distance metric negatively impacted accuracy, $F(1, 28) = 8.315$. $MSE = 1.456$, $\eta^2 = .103$, which implies that changing the size of the object was not the only visual process at work. Another visual process is likely at work detecting when the distance is the same, such as a visual indexing mechanism. It is possible, however, that people are exhibiting a SAME bias when uncertain of distance change.

To attempt to respond to a ‘SAME’ bias argument, a significant change x distance metric interaction occurs in the accuracy data, $F (4, 28) = 43.672$, $MSE = 1.753$, $\eta^2 = .412$, and to a lesser degree in the response time data, $F(4, 28) = 2.453$, $MSE = 155600$, $p = 0.50$, $\eta^2 = .084$. As seen in Figure 2, when the distance did not change, participants remained highly accurate at maintaining an index of the distance with the smaller 0.20° changes, with accuracy dropping off at the larger 0.40° changes. When the distance metric does not change, all correct responses are SAME. When the distance metric does change at the smaller 0.20° size changes, participants incorrectly report a SAME response.

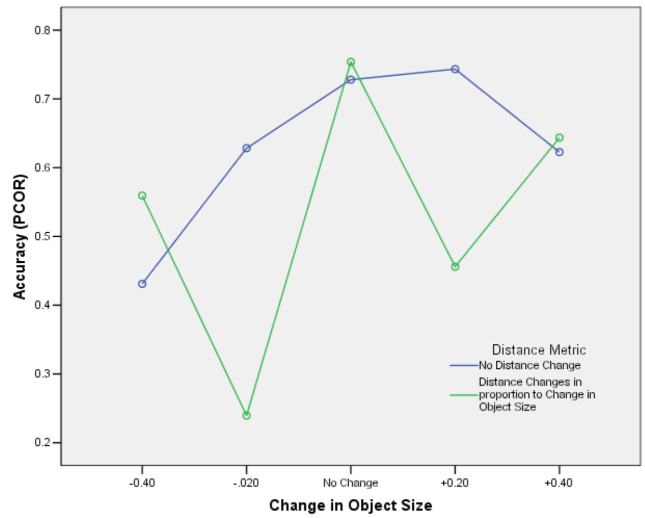

Figure 2: The effect of Change in Object Size on Accuracy

Examining a subset of trials where the absolute distance change is the same as in the control trials (where distance changes but object size remains constant), participants respond with an accuracy of .7443 (SD = .4369, N = 348) in the control trials as opposed to .4871 (SD=.5001, N = 696) in the experimental trials, a highly significant result; $t(1042) = 8.1608$, $p < 0.0001$. This significant result indicates that, if a SAME bias occurs, it is not due an inability to perceive the distance change.

Another possible interpretation is that participants are automatically scaling the second image when the distance metric changes. Since the distance is the same proportion as in the first image, participants will respond SAME. If this was the case, then we would expect to see larger relative error rates when object size changes and distance does not, since the distance metric is no longer in the same proportion. As seen in Figure 2, accuracy does not drop to the same extent at +/- 0.20° object size when distance does not change, indicating that scaling could not be the only participants are not scaling the image. However, a strategy involving both scaling and visual indices and processes would be consistent with the above results. Still, the ‘scaling’ argument would imply that participants were unaware of the size change. Post-test questionnaires and experimenter discussion with participants detail that participants were aware of the object size change.

Participants exhibited similar performance in both horizontal and vertical presentation: orientation exhibited no main effect on either accuracy or response time, $F(1,28) = 0.006$, $MSE = .000$, $p > .939$; $F(1,28) = 0.092$, $MSE = 6690$, $p > .764$ respectively. No significant cognitive preference given to horizontally-presented stimuli.

A significant distance metric x orientation interaction was found only for response time, $F(1, 28) = 16.589$, $MSE = 1180000$, $p < .001$, $\eta^2 = .160$, where responses were quicker when vertical stimuli were judged with a distance change, as opposed to horizontal stimuli where responses were slower when a distance change occurred. This was later found to be an artefact of practice effects due to an error in the randomization of stimuli, where more vertical stimuli with no distance changes were present in the first block of trials. Similarly, this confounding artefact also accounts for the significant change x metric interaction with regards to response times.

This initial experiment provided evidence that changes in object size inhibits accuracy of responses in this forced-choice change detection task. The nature of change detection tasks further implies that a more absolute encoding of distance (e.g. natural visual coordinates) is either not present or not accessible in the time-course allowed by this methodology. A limit of this methodology is that it only tests memory for recognition, and does not provide any quantitative estimates about changes in object size influencing distance.

Experiment 2: Drag-and-Drop Task

To examine in more detail the effects of object size on distance judgments, a follow-up experiment was conducted using a drag-and-drop change detection methodology. The main limitation in change detection tasks is that they are equally consistent between accounts due to a deficit in *encoding* or a deficit in *comparing* encodings (Cole et al., 2003; Rensink, 2002). To explain, it may be the case that the distance encoded from the initial image is either blended with- or overridden by the distance perceived in the second image, due in part to the similarities of both images.

Furthermore, Experiment 2 involves the *production* of distance, which provides a more quantitative measure of distance encoding than the forced-choice methodology in Experiment 1, to determine whether changing object size influences distance judgments proportionately.

Method

Participants

Twenty-three undergraduate students with normal or corrected-to-normal vision were provided course credit for their participation.

Materials and Procedures

Materials consist of the same stimuli as Experiment 1 but with the following procedural difference: in the second image the objects were initially adjacent to each other with one anchored and the participant was instructed to drag the other object the same distance apart as they recalled from the first image (see Figure 2). The anchored object was always in the same location as was presented in the first image. It is important to remember that the initial image is centered in the screen with the stimuli symmetrical in both the horizontal and vertical planes. To control for any dragging preferences, trials included both the left and right object being anchored. The control trials were eliminated as there was no change in distance between images.

Both accuracy and response times were recorded for this experiment. Accuracy was considered the dragged object's %deviation from its distance as seen in the first image.

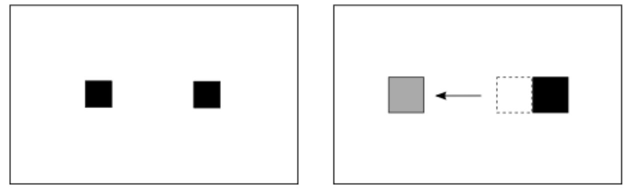

Figure 2: Paired stimulus from Experiment 2

Results and Discussion

A repeated-measures ADNOVA was conducted with accuracy and response time as the dependent measures. Initial size, orientation, and anchor (left or right object) were aggregated after finding no significant main effects.

Supporting the results of Experiment 1, there was a strong main effect of changing object size, $F(4,23) = 305.236$, $MSE = 12.761$, $p < .001$, $\eta^2 = .821$, indicating that changing object size influences distance production such that reducing object size leads to underestimation of distance and conversely increasing object size causing distance overestimation. There was a smaller main effect of distance, $F(2,23) = 55.529$, $MSE = 3.472$, $p < .001$, $\eta^2 = .165$, due to the fact that the critical accuracy measure is %deviation, so similar deviation in terms of absolute screen co-ordinates will result is smaller %deviation with larger stimuli and distances.

While changing object size affected %deviation, it did not do so in perfect linear proportion. Changes in object size explained a significant proportion of unique variance in %deviation scores, $R^2 = .466$, $F(4,23) = 601.523$, $p < .001$, but was not sufficient to be the only factor involved.

Interestingly, the only significant response time measure was a main effect of distance, $F(2,23) = 9.929$, $MSE = 39347181.04$, $p < .003$, $\eta^2 = .735$, indicating simply that it took longer to drag the mouse cursor larger distances. While puzzling, it is important to note that all judgments took relatively longer in this task than Experiment 1. It is possible that changes in response times have been subsumed by the time it takes to drag the objects in the second image. In future work, response times will be gathered from the initial mouse-button press to see if participants are making their decision while dragging, or simply refining their decision before pressing any mouse-button.

Another possibility is that with larger distances the visual system has only a limited visual resolution in the periphery of the stimuli (Borst & Kosslyn, 2008), and has increased difficulty maintaining any visual index without reference to any other point, such as the edge of the screen (Pylyshyn, 2002). Thus, it is difficult to maintain fixation in blank space as the eye has little information to focus on, compounding error across saccades.

General Discussion

Taken together, the results from Experiments 1 and 2 have identified that changes in object size affect distance judgments both in tasks involving memory for recognition and memory for production.

If distance perception is regarded as a predominantly categorical system as defined in the ad-hoc metrical theory, then in Experiment 2 any change in object size should cause a proportional change in produced distance. Similarly, in Experiment 1 there should a bias towards increases in object size in the second image causing a false CLOSER response when distance is actually the same, and decreases in object size should cause a false FARTHER response.

Evidence has been presented detailing the strong effect object size plays in distance perception, but changes in distance did not elicit a perfectly proportional change in distance perception. Our results support a multiple process interpretation, where the ad-hoc metrical theory is one encoding process receiving feedback from a visual indexing mechanism, such as in FINST theory (Pylyshyn, 2002)

The advantage of ad-hoc metrics is in parsimony: neither the perceived size of the object nor any precise distance measure need be encoded to accurately gauge relative distances, only the ratio of object-size to distance is needed. The constancy of the external environment serves as the medium with which much of spatial information resides. From this point, distance can be accurately recalled using tacit knowledge about object size and performing a simple calculation to estimate a more precise distance.

Further data analysis needs to be completed to determine whether participants adopted different strategies, which would also have implications as to whether the application of ad-hoc metrics is a function of visual memory or a task heuristic. Additionally, space limitations have precluded the discussion of visual illusion and the role of size constancy in this methodology (McKee & Welch, 1992)

Acknowledgements

We would like to thank Dr. Aryn Pyke for her assistance with experimental design and early drafts of this paper.

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