Cognition 113 (2009) 128–133

Contents lists available at ScienceDirect

Cognition

journal homepage: www.elsevier.com/locate/COGNIT

Brief article

Dissociating the effects of angular disparity and image similarity in mental rotation and object recognition

Olivia S. Cheung [a,*], William G. Hayward [b], Isabel Gauthier [a]

[a] Department of Psychology, Vanderbilt University, PMB 407817, 2301 Vanderbilt Place, Nashville, TN 37240-7817, USA
[b] Department of Psychology, University of Hong Kong, Hong Kong

ARTICLE INFO

Article history:
Received 12 March 2009
Revised 14 July 2009
Accepted 16 July 2009

Keywords:
Mental rotation
Object recognition
Viewpoint effects
Visual similarity

ABSTRACT

Performance is often impaired linearly with increasing angular disparity between two objects in tasks that measure mental rotation or object recognition. But increased angular disparity is often accompanied by changes in the similarity between views of an object, confounding the impact of the two factors in these tasks. We examined separately the effects of angular disparity and image similarity on handedness (to test mental rotation) and identity (to test object recognition) judgments with 3-D novel objects. When similarity was approximately equated, an effect of angular disparity was only found for handedness but not identity judgments. With a fixed angular disparity, performance was better for similar than dissimilar image pairs in both tasks, with a larger effect for identity than handedness judgments. Our results suggest that mental rotation involves mental transformation procedures that depend on angular disparity, but that object recognition is predominately dependent on the similarity of image features.

1. Introduction

Mental rotation refers to the cognitive ability to rotate mental representations of objects. A typical mental rotation task requires observers to perform handedness matching judgments, in other words to determine whether two images show identical or mirror reflections of a rotated object (Shepard & Cooper, 1982; Shepard & Metzler, 1971). A mental rotation process is inferred in part because of a *viewpoint cost* – a linear increase in response times and/or a reduction in accuracy with increases in angular disparity between the two stimuli. The viewpoint cost is thought to correspond to the shortest rotation path between two stimuli, suggesting that mental representations may be analog to spatial transformations in the physical world (Shepard & Cooper, 1982).

Likewise, variations in the observer's perspective to physical objects change the perceived appearance of the objects and thus affect one's ability to recognize them. One kind of object recognition task, identity judgments, requires observers to discriminate whether two images show the same object, often revealing reduced performance which resembles a viewpoint cost observed for handedness judgments, when the images are from different views (Hayward & Williams, 2000; Jolicoeur, 1985; Lawson, 2004; Tarr, 1995; but see Biederman & Gerhardstein, 1993).

Because the viewpoint costs are often comparable during handedness and identity judgments, overlap between mental rotation and object recognition processes has been suggested. According to view-dependent object recognition theories, multiple 2-D images of an object are represented and stored when the object is seen across viewpoints (Bülthoff & Edelman, 1992; Edelman & Bülthoff, 1992; Poggio & Edelman, 1990; Tarr, 1995). To identify an object, some transformations must be performed when a new view of an object is encountered and matched

* Corresponding author. Address: Vanderbilt University, PMB 407817, 2301 Vanderbilt Place, Nashville, TN 37240-7817, USA. Tel.: +1 615 322 5594; fax: +1 615 322 4706.
E-mail address: olivia.cheung@vanderbilt.edu (O.S. Cheung).

0010-0277/$ - see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.cognition.2009.07.008

to the stored view representations. Such transformations may be based on key features of 3-D structural representations (Ullman, 1989), or on interpolation between 2-D representations (Bülthoff & Edelman, 1992; Poggio & Edelman, 1990). Alternatively, recognition could be based on processes similar to mental rotation, with novel views being transformed to match the nearest stored view (Jolicoeur, 1990; Tarr, 1995).

However, the hypothesis that mental rotation can support object recognition has been challenged on both logical and empirical bases. Some researchers argue that an object must be recognized before its orientation can be determined and thus it is unlikely that mental rotation would precede object recognition (Corballis, 1988; Shepard & Cooper, 1982). Behavioral evidence shows that the viewpoint slopes are sharper for handedness than identity judgments (De Caro & Reeves, 2000; Gauthier et al., 2002; Hayward, Zhou, Gauthier, & Harris, 2006; Vanrie, Willems, & Wagemans, 2001). While the performance costs for handedness judgments are monotonically related to angular disparity (Shepard & Cooper, 1982; Shepard & Metzler, 1971), identification performance is less strictly tied to angular differences. The viewpoint cost for identification sometimes increases initially but fluctuates across a wide range of angular disparities up to 180° (Hayward, 1998; Hayward et al., 2006; Lawson & Humphreys, 1996; Lawson & Jolicoeur, 2003). Moreover, the viewpoint effect is sometimes absent during identification of highly familiar objects (Biederman & Gerhardstein, 1993; Harris & Dux, 2005) but linear viewpoint effects are still obtained during handedness judgments with highly familiar objects (e.g., alphanumerical shapes, body parts; Bonda, Petrides, Frey, & Evans, 1995; Cooper & Shepard, 1973, 1975; Corballis & McLaren, 1984). Furthermore, fMRI results suggest that the viewpoint effects for handedness and identity judgments are associated with different brain areas (Gauthier et al., 2002; Vanrie, Béatse, Wagemans, Sunaert, & Van Hecke, 2002; Wilson & Farah, 2006). Therefore, converging evidence demonstrates that mental rotation and object recognition can be dissociated despite similar viewpoint effects. But few studies have examined the basis of the dissociation.

What information underlies mental rotation and object recognition as revealed in handedness and identity judgments? Vanrie and colleagues (2001, 2002) began to address this issue by comparing viewpoint-dependent mental rotation with viewpoint-invariant object recognition. Here, we instead investigated the viewpoint-dependent effects in mental rotation and object recognition, by dissociating the effects of angular disparity and image similarity with objects rotated in depth. Angular disparity influences visual similarity to some extent, but these two factors are related in a complex, often non-linear, fashion, depending on the geometry of objects and the nature of the diagnostic information. While these two factors can in principle exert influences of different kinds, the fact that they can be difficult to disentangle suggests a potential problem in the results of studies where these issues are not considered. Although two images of an object may become more dissimilar with increasing angular disparity, especially when visible features become occluded or a main axis of elongation becomes foreshortened, angular disparity and image similarity can also be manipulated separately (Schwoebel & Srinivas, 2000). Indeed, images differing by a large angular disparity (e.g., 180°) may sometimes be more similar than images differing by a smaller rotation (Hayward, 1998). Because these factors are typically confounded or uncontrolled in mental rotation and object recognition studies, it is unclear to what extent the viewpoint costs for handedness and identity judgments are due to spatial processes that compensate for angular disparity vs. image matching processes that operate on the similarity between images of the same object.

Several studies have examined the effects of image similarity and/or angular disparity on object recognition but the two factors either have not been systematically manipulated or are confounded. For instance, Lawson and Humphreys (1996) assumed that images differing by a smaller rotation are more similar compared to images differing by a larger rotation. Schwoebel and Srinivas (2000) selected image pairs for each object based on subjective similarity ratings, but with similar pairs differing by a larger angular difference than dissimilar pairs. Hayward et al. (2006) predicted that image similarity might not be correlated with angular disparity across a wide range of views but did not systematically manipulate image similarity. While these studies suggest that image similarity can determine performance in object recognition, the role of this factor in identity judgments has not been systematically compared to that of angular disparity.

Our goal was to determine the contributions of angular disparity and image similarity to the viewpoint costs arising from mental rotation and object recognition that are measured via handedness and identity judgments, respectively. We used a set of 3-D novel objects, similar to those used in previous studies (Shepard & Metzler, 1971; Tarr, 1995), rotated along the vertical axis for both handedness and identity judgments. In our object set, the overall similarity among all non-occluded images was generally correlated with angular disparity. To dissociate the two factors, we selected image pairs that had been rated approximately equal in similarity but differing in angular disparity and other image pairs that were rated either highly similar or highly dissimilar, both separated by the same angular disparity. We predicted that viewpoint costs during identity judgments mainly reflect object recognition processes' sensitivity to image similarity, whereas the viewpoint costs during handedness judgments primarily reflect that mental rotation is sensitive to angular disparity.

2. Methods

2.1. Similarity ratings

2.1.1. Participants

Sixteen undergraduates (mean age = 19.1) at Vanderbilt University participated for course credit.

2.1.2. Stimuli

Twelve 3-D objects were created using Carrara 5. All objects were asymmetrical in left–right/front–back configurations, except for one which was not used in the main experiment. For each object, images at each 20° rotation along the vertical axis (0–360°) were used. Any image with any fully occluded feature was replaced with an adjacent image (5° or 10° apart) if it showed all features, otherwise it was excluded. The images were then paired for various angular disparities (40°/80°/120°/160°), which led to 7–11 image pairs for each object at each disparity (with a total of 426 pairs).

2.1.3. Procedure

There were 12 blocks of trials, each for one of the 12 objects, with order randomized across participants. In each block, all the images of the object were first shown on a sheet of paper. Participants were asked to choose two images that were highly similar and another pair that was highly dissimilar. This procedure exposed participants to all images and helped establish a reference for later ratings. Each image pair was then shown once on a computer screen for up to 10 s, in a random order, and participants provided similarity ratings on a 1 (highly dissimilar) to 7 (highly similar) scale. Trials across the angular disparities were randomized.

2.1.4. Results

Based on the mean similarity ratings across participants, we selected image pairs for the Image Similarity and Angular Disparity conditions (Fig. 1). Different objects were used in the two conditions to prevent excessive familiarity with the objects during the course of the study. Critically however, the same images were used for both handedness and identity judgments. For the Image Similarity condition, a similar and a dissimilar pair differing by 40° were selected for each of the five objects (mean rating = 6.14 for similar, 4.2 for dissimilar). A one-way repeated measures ANOVA showed a significant effect of similarity ($F_{1,15} = 56.67$, $p < .0001$). For the Angular Disparity condition, an image pair was selected for each of the five other objects, differing by 40°, 80°, 120° or 160° (mean ratings = 4.18, 3.97, 3.72 and 3.50, respectively). Although the similarity ratings were different numerically, the effect of similarity was not significant for the selected pairs ($F_{3,45} = 2.45$, $p = .08$), nor did they show a significant effect of similarity when a linear trend over angular disparity was tested ($F_{1,15} = 3.00$, $p > .10$). More importantly, any effect of similarity as a function of disparity was greatly reduced compared to when all image pairs for the five objects were included ($F_{3,45} = 32.4$, $p < .0001$, mean ratings = 4.96, 3.76, 3.2 and 3.18, respectively).

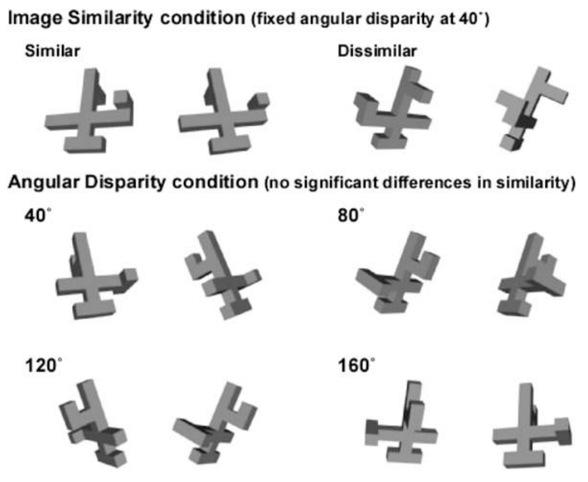

Fig. 1. Top panel shows two image pairs of an object used in the Image Similarity condition (similar vs. dissimilar, with a fixed angular disparity at 40°). Bottom panel shows four image pairs of another object used in the Angular Disparity condition (40° vs. 80° vs. 120° vs. 160°, with no significant differences in similarity across the angular disparities).

2.2. Main experiment

2.2.1. Participants

A separate group of 21 students (mean age = 21.6) at Vanderbilt University participated for payment or course credit. Data from five participants were excluded because of below-chance performance for handedness judgments.

2.2.2. Stimuli

According to the similarity ratings, 10 image pairs from 5 objects were selected for the Image Similarity condition and 20 pairs from the other 5 objects were selected for the Angular Disparity condition. For different trials in handedness judgment, images were created from rotating the mirror reflection of the original objects. For *different* identity judgment trials, images were randomly selected from the other four objects with the appropriate rotation.

2.2.3. Procedure[1]

Four blocks of Image Similarity trials and four blocks of Angular Disparity trials were interleaved. Within each of these blocks, there were 16 interleaved 5-trial blocks of handedness or identity judgments. The order of the Image Similarity/Angular Disparity blocks and Tasks was counterbalanced across participants. The trial order of Similarity Level (similar/dissimilar) and Angular Disparity (40°/80°/120°/160°) was randomized for each participant. An instruction screen (3 s) showing "Same Version?" (for handedness judgment) or "Same Object?" (for identity judgment) was presented prior to each task. On each trial, a fixation was presented (200 ms), followed by a blank screen (50 ms), then by a study image (1 s), then by a blank screen (400 ms), then by a test image (2.15 s). A trial timed out if a response was not made during the presentation of a test image. In the Image Similarity condition, there were 40 trials in each combination of Similarity Level, Task and Response (same/different). In the Angular Disparity condition, there were 20 trials in each combination of Angular Disparity, Task and Response. There were a total of 640 trials. No feedback was given.

Practice trials were given prior to testing, including 40 matching trials (10 Image Similarity and 10 Angular Disparity trials for handedness and identity judgments, respectively). Based on pilot work, to facilitate performance mainly for handedness judgments, the full rotation

[1] The procedure was to mirror a future neuroimaging study.

path of the original and mirror versions of all objects were also shown in brief (6 s) video clips. Participants judged the handedness or identity of objects in separate blocks: they matched whether a test image, which was presented along with the last image of each video, was identical or mirror reflection of/different from the object presented in the video. Auditory feedback was presented after 3 s or after an incorrect response. These data were not analyzed. The entire study lasted approximately 1 h.

3. Results

The mean *d*' and RT for correct same trials are illustrated in Fig. 2 for the Image Similarity condition and in Fig. 3 for the Angular Disparity condition. Two-way ANOVAs with within-factors Task (handedness judgment/identity judgment) and Similarity Level (similar/dissimilar), or Task and Angular Disparity (40°/80°/120°/160°), were conducted.

3.1. Effects of image similarity

A significant main effect of Task revealed longer RT for handedness than identity judgments ($F_{1,15} = 29.90$, $p < .0001$, not significant in *d*', $F_{1,15} = 1.92$, $p = .19$). A significant main effect of Similarity Level revealed that similar pairs were matched better and faster than dissimilar pairs (*d*': $F_{1,15} = 16.79$, $p = .001$; RT: $F_{1,15} = 5.04$, $p = .04$). There was a significant interaction between Task and Similarity in *d*' ($F_{1,15} = 4.36$, $p = .05$; not significant in RT: $F_{1,15} = .71$, $p = .41$). While the advantage in *d*' for similar pairs was larger for identity than handedness judgments, similarity benefitted both tasks (Scheffé's *p*s < .025).

3.2. Effects of angular disparity

A significant main effect of Task revealed better and faster performance for identity than handedness judgments (*d*': $F_{1,15} = 12.80$, $p < .005$; RT: $F_{1,15} = 17.45$, $p < .001$). The non-significant effect of Angular Disparity (*d*': $F_{3,45} = 1.33$, $p = .28$, RT: $F_{3,45} = 2.57$, $p = .066$) was modulated by a significant interaction between Task and Angular Disparity in RT, $F_{3,45} = 5.40$, $p < .005$ (not in *d*': $F_{3,45} = 1.81$, $p = .16$). Linear trend analyses also showed a significant interaction between Task and Angular Disparity in RT ($F_{1,15} = 25.31$, $p < .0001$), revealing that RT increased linearly with angular disparity for handedness judgment ($p < .005$) but not for identity judgment ($p > .31$).

4. Discussion

The effects of angular disparity and image similarity on mental rotation and object recognition can be dissociated. While the viewpoint cost in handedness judgments is affected by variations in both angular disparity and image similarity, the primary source of view-dependence in identity judgments is the similarity of image features.

For handedness judgments, a portion of the so-called "viewpoint cost" may be associated with spatial transformation processes (Shepard & Metzler, 1971), as mental rotation depends on the angular difference between views of the objects. Observers may complete this task by imagining analog rotations of objects (Shepard & Metzler, 1971), or covertly simulating motor rotation (Kosslyn, 1994; Wexler, Kosslyn, & Berthoz, 1998). In such cases, intermediate representations between the two target images are likely formed and responses are slowed depending on the rotation distance between them. Additionally, handedness judgments can also depend on how similar two images are. Observers may rely on image similarity to suggest shared features between images, facilitating the alignment of two views within the same reference frame. Moreover, there is still some overlap in the neural networks engaged for both handedness and identity judgments (Gauthier et al., 2002; Schendan & Stern, 2007). Thus, handedness judgments are also likely to be affected by factors that influence object recognition if the appropriate information is available, which may be why similarity influenced both tasks.

Our findings with identity judgments are in sharp contrast with the results in handedness judgments and support the claim that mental rotation is unlikely to be the underlying mechanism for object recognition (Hayward et al., 2006; Lawson & Humphreys, 1996; Lawson & Jolico-

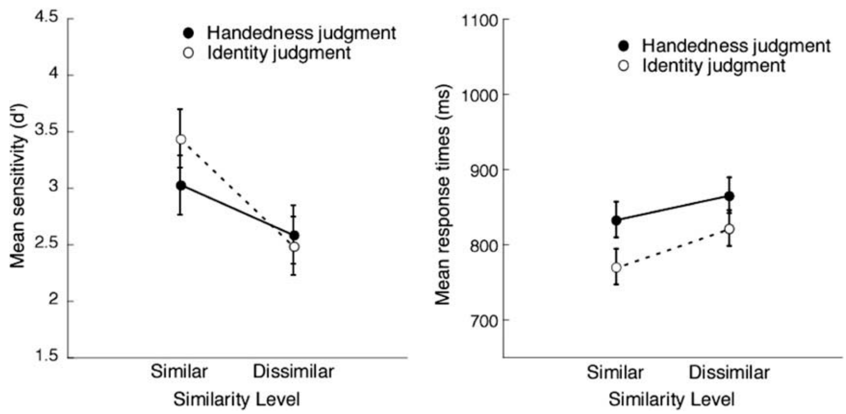

Fig. 2. Mean *d*' and RT for correct same trials (ms) in the Image Similarity condition (with a fixed angular disparity at 40°), plotting across Task and Similarity Level. The error bars represent 95% confidence intervals of the interaction of Task and Similarity Level.

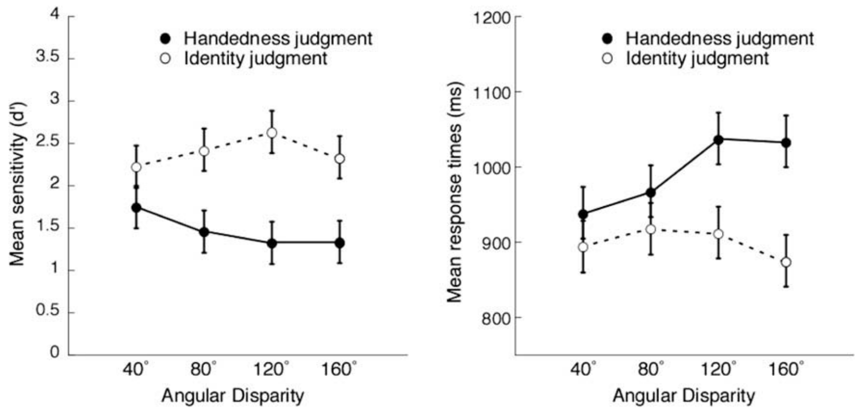

Fig. 3. Mean *d*' and RT for correct same trials (ms) in the Angular Disparity condition (with no significant differences in similarity across the angular disparities), plotting across Task and Angular Disparity. The error bars represent 95% confidence intervals of the interaction of Task and Angular Disparity.

eur, 2003). We demonstrate that the source of the view-dependent effect for object recognition, previously conceived as a "viewpoint cost", may not depend on angular disparity. Instead, object recognition relies on matching image similarity of objects seen in different perspectives (Bülthoff & Edelman, 1992; Edelman & Bülthoff, 1992; Logothetis, Pauls, Bülthoff, & Poggio, 1994; Perrett, Oram, & Ashbridge, 1998). Our results expand on previous findings and distinguish confounded factors: image similarity is typically confounded with angular disparity, because object rotation can cause self-occlusion of visual features or foreshortening of axis elongation, compromising the matching of different images of an object. But the main influence on performance appears to be the similarity of images, rather than angular disparity *per se*.

One possible concern regarding our findings is that we were unable to entirely disentangle angular disparity from image similarity. Thus, some of the effects in the Angular Disparity condition might have been due to similarities of image features, rather than rotational differences between viewpoints. However, since our results successfully dissociated the two factors in the two tasks, the most plausible explanation for our divergent results remains the large differences in image similarity and angular disparity that we introduced in the Image Similarity and Angular Disparity conditions, respectively.

The present study used novel 3-D objects rotated in depth but the results may also have implications for other object types. Note, however, that recognition of familiar objects is also influenced by other factors such as semantic processing (Curby, Hayward, & Gauthier, 2004), while image similarity is more likely the primary source of information for matching novel objects. The effect of image similarity in object recognition may also depend on the features that are used at different levels of categorization (Zhang & Cottrell, 2005). Moreover, the effects could differ for picture plane transformations that do not affect feature visibility but affect both left/right and top/down feature relations. The relative importance of angular disparity and image similarity in these conditions remains to be examined. It will also be important to investigate the possible generalization of our results from sequential matching to other experimental paradigms (e.g., simultaneous matching, naming tasks).

Future work should also further examine the roles of the neural substrates that support handedness or identity judgments. Since angular disparity and image similarity were not examined independently in previous studies (e.g., Gauthier et al., 2002; Richter, Ugurbil, Georgopoulous, & Kim, 1997; Tagaris et al., 1997), it is as of now impossible to specify the nature of the information processed in occipitotemporal areas and parietal areas for the two tasks. Our work provides a method to address these issues.

5. Conclusion

Our findings have important implications for future research. Specifically, although angular disparity and image similarity are often correlated (e.g., with all image pairs in our Angular Disparity condition), their effects can be dissociated (e.g., with our selected pairs). If experimenters are interested in spatial transformation processes engaged by mental rotation, image similarity should be controlled. When interpreting view-sensitive effects in object recognition, it is important to distinguish the sources of the effects.

Acknowledgments

This work was supported by Grants from the Hong Kong Research Grants Council (project Nos. HKU 4260/03H and HKU 7649/06H), the Temporal Dynamics of Learning Center (NSF Science of Learning Center SBE-0542013) and the James S. McDonnell Foundation.

References

Biederman, I., & Gerhardstein, P. C. (1993). Recognizing depth-rotated objects: Evidence and conditions for three-dimensional viewpoint invariance. *Journal of Experimental Psychology: Human Perception and Performance, 19*(6), 1162–1182.

Bonda, E., Petrides, M., Frey, S., & Evans, A. (1995). Neural correlates of mental transformations of the body-in-space. *Proceedings of the National Academy of Sciences USA, 92*(24), 11180–11184.

Bülthoff, H. H., & Edelman, S. (1992). Psychophysical support for a two-dimensional view interpolation theory of object recognition. *Proceedings of the National Academy of Sciences USA, 89*, 60–64.
Cooper, L. A., & Shepard, R. N. (1973). Chronometric studies of the rotation of visual images. In W. G. Chase (Ed.), *Visual information processing* (pp. 75–176). New York: Academic Press.
Cooper, L. A., & Shepard, R. N. (1975). Mental transformations in the identification of left and right hands. *Journal of Experimental Psychology: Human Perception and Performance, 104*(1), 48–56.
Corballis, M. C. (1988). Recognition of disoriented shapes. *Psychological Review, 95*(1), 115–123.
Corballis, M. C., & McLaren, R. (1984). Winding one's *P*s and *Q*s: Mental rotation and mirror-image discrimination. *Journal of Experimental Psychology: Human Perception and Performance, 10*(2), 318–327.
Curby, K. M., Hayward, W. G., & Gauthier, I. (2004). Laterality effects in the recognition of depth-rotated novel objects. *Cognitive, Affective and Behavioral Neuroscience, 4*(1), 100–111.
De Caro, S. A., & Reeves, A. (2000). Rotating objects to determine orientation, not identity: Evidence from a backward-masking/dual-task procedure. *Perception and Psychophysics, 62*(7), 1356–1366.
Edelman, S., & Bülthoff, H. H. (1992). Orientation dependence in the recognition of familiar and novel views of three-dimensional objects. *Vision Research, 32*(12), 2385–2400.
Gauthier, I., Hayward, W. G., Tarr, M. J., Anderson, A. W., Skudlarski, P., & Gore, J. C. (2002). BOLD activity during mental rotation and viewpoint-dependent object recognition. *Neuron, 34*(1), 161–171.
Harris, I. M., & Dux, P. E. (2005). Orientation-invariant object recognition: Evidence from repetition blindness. *Cognition, 95*(1), 73–93.
Hayward, W. G. (1998). Effects of outline shape in object recognition. *Journal of Experimental Psychology: Human Perception and Performance, 24*(2), 427–440.
Hayward, W. G., & Williams, P. (2000). Viewpoint dependence and object discriminability. *Psychological Science, 11*(1), 7–12.
Hayward, W. G., Zhou, G., Gauthier, I., & Harris, I. M. (2006). Dissociating viewpoint costs in mental rotation and object recognition. *Psychonomic Bulletin and Review, 13*(5), 820–825.
Jolicoeur, P. (1985). The time to name disoriented natural objects. *Memory and Cognition, 13*(4), 289–303.
Jolicoeur, P. (1990). Orientation congruency effects on the identification of disoriented shapes. *Journal of Experimental Psychology: Human Perception and Performance, 16*(2), 351–364.
Kosslyn, S. M. (1994). *Image and brain*. Cambrige: MIT Press.
Lawson, R. (2004). View sensitivity increases for same-shape matches if mismatches show pairs of more similar shapes. *Psychonomic Bulletin and Review, 11*(5), 896–902.
Lawson, R., & Humphreys, G. (1996). View specificity in object processing: Evidence from picture matching. *Journal of Experimental Psychology: Human Perception and Performance, 22*(2), 395–416.
Lawson, R., & Jolicoeur, P. (2003). Recognition thresholds for plane-rotated pictures of familiar objects. *Acta Psychologica, 112*(1), 17–41.
Logothetis, N., Pauls, J., Bülthoff, H., & Poggio, T. (1994). View-dependent object recognition by monkeys. *Current Biology, 4*(5), 401–414.
Perrett, D. I., Oram, M. W., & Ashbridge, E. (1998). Evidence accumulation in cell populations responsive to faces: An account of generalisation of recognition without mental transformations. *Cognition, 67*, 111–145.
Poggio, T., & Edelman, S. (1990). A network that learns to recognize three-dimensional objects. *Nature, 343*(6255), 263–266.
Richter, W., Ugurbil, K., Georgopoulous, A., & Kim, S.-G. (1997). Time-resolved fMRI of mental rotation. *NeuroReport, 8*, 3697–3702.
Schendan, H. E., & Stern, C. E. (2007). Mental rotation and object categorization share a common network of prefrontal and dorsal and ventral regions of posterior cortex. *Neuroimage, 35*(3), 1264–1277.
Schwoebel, J., & Srinivas, K. (2000). Recognizing objects seen from novel viewpoints: Effects of view similarity and time. *Journal of Experimental Psychology: Learning, Memory and Cognition, 26*(4), 915–928.
Shepard, R. N., & Cooper, J. A. (1982). *Mental images and their transformations*. Cambridge, MA: MIT Press.
Shepard, R. N., & Metzler, J. (1971). Mental rotation of three-dimensional objects. *Science, 171*(972), 701–703.
Tagaris, G. A., Kim, S.-G., Strupp, J. P., Anderson, P., Ugurbil, K., & Georgopoulos, A. P. (1997). Mental rotation studied by functional magnetic resonance imaging at high field (4 Tesla): Performance and cortical activation. *Journal of Cognitive Neuroscience, 9*(4), 419–432.
Tarr, M. J. (1995). Rotating objects to recognize them: A case study on the role of viewpoint dependency in the recognition of three-dimensional objects. *Psychonomic Bulletin and Review, 2*(1), 55–82.
Ullman, S. (1989). Aligning pictorial descriptions: An approach to object recognition. *Cognition, 32*(3), 193–254.
Vanrie, J., Béatse, E., Wagemans, J., Sunaert, S., & Van Hecke, P. (2002). Mental rotation versus invariant features in object perception from different viewpoints: An fMRI study. *Neuropsychologia, 40*, 917–930.
Vanrie, J., Willems, B., & Wagemans, J. (2001). Multiple routes to object matching from different viewpoints: Mental rotation versus invariant features. *Perception, 30*, 1047–1056.
Wexler, M., Kosslyn, S. M., & Berthoz, A. (1998). Motor processes in mental rotation. *Cognition, 68*, 77–94.
Wilson, K. D., & Farah, M. J. (2006). Distinct patterns of viewpoint-dependent BOLD activity during common-object recognition and mental rotation. *Perception, 35*(10), 1351–1366.
Zhang, L., & Cottrell, G. W. (2005). Holistic processing develops because it is good. In *Proceedings of the 27th annual cognitive science conference, Stresa, Italy*. Mahwah: Lawrence Erlbaum.