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A test of the coordinate relations hypothesis: is prosopagnosia a consequence of damage to the coordinate recognition system?

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A test of the coordinate relations hypothesis:

Is prosopagnosia a consequence of damage to the coordinate recognition system?

by

Glenn Eric Casner

A dissertation submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

Co-Majors: Neuroscience; Psychology

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INTRODUCTION

Among vision researchers there is a growing consensus that there are two neurologically distinct visual recognition systems: one recognition system that subserves face recognition (and perhaps recognition of other classes of stimuli as well) and another recognition system that subserves most forms of basic-level object recognition, and that these two visual recognition systems differ in how they represent shape (Farah, 1995). There are multiple lines of evidence suggesting that the brain regions that underlie face recognition are distinct from the brain regions that underlie basic-level object recognition.

One of the strongest lines of evidence suggesting a distinction between face recognition and basic-level object recognition are disorders that show a double dissociation between the two processes. That is, there are brain-damaged patients, known as individuals with prosopagnosia, who are impaired at recognizing faces but show intact non-face object recognition, whereas there are brain damaged patients, known as individuals with object-agnosia, who are impaired at recognizing objects but show intact face recognition (see Farah, 1992, for a review). A second line of evidence is that numerous neuroimaging studies have found brain regions that respond selectively to faces (e.g., Kanwisher, McDermott, & Chun, 1997; McCarthy, Puce, Gore, & Allison, 1997; Sergent, Ohta, & MacDonald, 1992). In addition to providing evidence that there is a distinction between face recognition and basic-level object recognition, studies with brain-damaged patients, neuroimaging studies, and visual half-field studies all provide evidence that the recognition system that subserves face recognition is localized primarily in the right cerebral hemisphere (or operates more efficiently in the right cerebral hemisphere) (Burgund & Marsolek, 1997, 2000; Marsolek, 1999; Marsolek, Kosslyn, & Squire, 1992; Marsolek, Schacter, & Nicholas, 1996).

Many visual half-field studies have found that face recognition is faster and more accurate when the faces are presented in the left visual field and thus initially to the right cerebral hemisphere than when the faces are presented in the right visual field and thus initially to the left cerebral hemisphere (e.g., Hillger & Koenig, 1991; Leehey, Carey, Diamond, & Cahn, 1978; Levine, Banich, & Koch-Weser, 1988; Rhodes, 1993; see Davidoff, 1982, and Ellis, 1983, for reviews). In contrast, visual half-field studies typically find no hemispheric effect or a slight left hemisphere advantage for basic-level object recognition (e.g., Biederman & Cooper, 1991; Levine & Banich, 1982; Young, Bion, & Ellis, 1980). In contrast, studies typically find that the recognition system that subserves basic-level object recognition is bilateral (e.g., Brooks & Cooper, 2001). Although most individuals with prosopagnosia have bilateral lesions, lesions restricted to the right cerebral hemisphere can produce prosopagnosia (Damasio, Tranel, & Damasio, 1990; De Renzi, 1986; De Renzi, Perani, Carlesimo, & Silveri, 1994; Landis, Regard, Bliestle, & Kleihues, 1988; Whiteley & Warrington, 1977). Neuroimaging studies typically show preferential activation of the right fusiform gyrus (also known as fusiform face area) in response to faces (e.g., Kanwisher et al., 1997; McCarthy et al., 1997). Further, a variety of non-neurological evidence also supports the notion that objects and faces are recognized through different processes. Such evidence includes: the inversion effect (i.e., that inversion of faces impairs visual recognition far more than inversion of objects) (e.g., Diamond & Carey, 1986; Farah, Tanaka, & Drain, 1995); the photographic negation effect (i.e., that photographic negation of faces impairs visual recognition far more than does photographic negation of objects) (e.g., Liu & Chaudhuri, 1997; Vuong, Peissig, Harrison, & Tarr, 2005); and the finding that infants (1-2 months of

age) will fixate longer on faces or face-like images than they will for other types of stimuli (e.g., Walton, Armstrong, & Bower, 1997).

Although most vision researchers now agree that there is not one visual recognition system but actually two distinct systems (or more), there is currently a heated debate as to what sorts of recognition tasks these different systems subserv. The evidence now suggests that the face recognition system is not used solely to recognize faces, but is also used to recognize other classes of stimuli (e.g., Damasio, Damasio, & Van Hoesen, 1982; Diamond & Carey, 1986). However, the questions of exactly what sort of tasks are mediated by the two recognition systems, and how the representation of shape differs in the two systems remain open.

REPRESENTATION OF RELATIONS IN MODERN THEORIES OF OBJECT RECOGNITION

Modern theories of object recognition for the most part can be divided into two groups on the basis of how the primitives of an object are represented and how the relations among the primitives are coded: structural description theories and template theories. Structural description theories (e.g., Biederman, 1987; Hummel & Biederman, 1992) posit that objects are represented as a collection of simple volumetric primitives (e.g., geons) that correspond roughly to the parts of the object, and that the locations of these visual primitives are specified using primitive-to-primitive, categorical relation such as “above”, “below”, and “side-of”. That is, in a categorical representation, the precise distances between the primitives are not specified, but rather only the categorical relations between each primitive and all others in the representation are coded. An example of how a categorical relations system might represent the spatial locations of the visual primitives in an object is illustrated in Figure 1. A categorical relations system might represent the spatial location of the left eye in the following manner: The left eye is to the “side-of” the right eye, “above” and to the “side-of” the nose, and “above” and to the “side-of” the mouth.

Note that in addition to using categorical relations such as “above”, “below”, and “side-of” to code the locations of these visual primitives, the categorical relations system is posited to use categorical relations such as “larger than”, “smaller than”, and “equal to” to code the relative size of the primitives and the categorical relations such as “parallel to”, “oblique to”, and “perpendicular to” to code the relative orientation of the primitives. For example, a categorical relations system might code the relative size of the primitive of the faces in Figure 1 as the left eye is “equal to” the right eye, “smaller than” the nose, and

“larger than” the mouth. Similarly, a categorical relations system might code the relative orientations of the primitives of the faces in Figure 1 as the left eye is “parallel to” the right eye, “perpendicular to” the nose, and “parallel to” the mouth. Note that these theoretical relative orientations assume that the relative orientations of primitives are based on the primitives’ major axes.

Categorical Relations



Left eye is side-of right eye,
above and side-of nose, and
above and side-of mouth.

Figure 1. Illustration of how the spatial position of the primitive corresponding to the left eye might be coded using categorical relations.

There are a number of computational advantages to using categorical coding of relations in a representation for visual identification. A categorical relations system would allow the same description to be generated regardless of the object’s size, position, or rotation in depth. For example, despite the fact that the retinal image produced by a given mug varies greatly depending on the size and shape of the cup, the distance from the viewer, and the degree of rotation in depth, a categorical relations system would generate the same description. Further (as shown in Figure 2) a structural description allows one to put

different examples of an object into the same category quickly. For example, despite the fact that the faces show wide variation in terms of the positions, sizes, and aspect ratios of their parts, a structural description representation would be able to quickly categorize each of these as a mug.

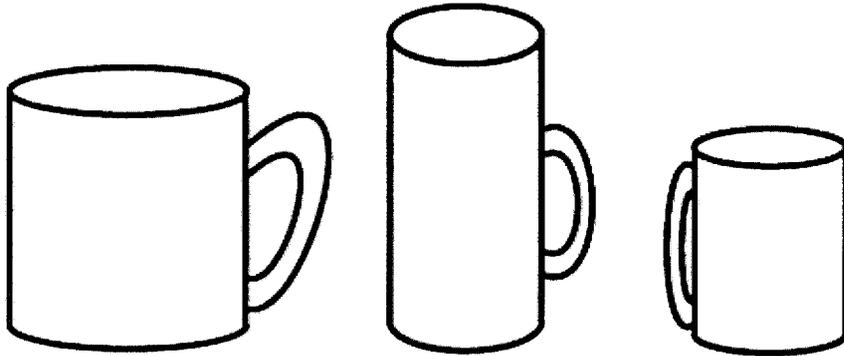


Figure 2. A recognition system using categorical spatial relations among the visual primitives might activate the same representation for all three of the above mugs (i.e., a curved cylinder to the side-of a cylinder), despite wide variation in the size, position, and aspect ratios of the primitives between the different mugs.

An additional advantage of using a categorical representation is that it allows for greater tolerance of noise at both the input level as well as in the recognition system itself because a categorical representation does not rely on determining precise distances between the primitives. For example, a structural description representation would be able to overcome partial occlusion as long as enough features remained to determine the parts and their relations (see Figure 3 for illustration).

However, using a representation with categorical relations does have its drawbacks. Brooks and Cooper (2001) and Tarr and Bülthoff (1995) pointed out that a representation using categorical relations would be unable to distinguish between faces or between a dog

(such as a collie) and a fox. Notice that using a categorical relations system, the representations of different faces would be identical (see Figure 4 for an illustration).

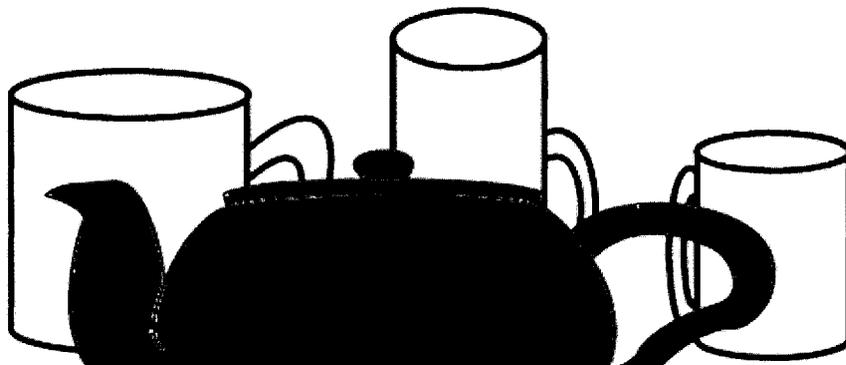


Figure 3. Illustration showing that despite partial occlusion by a teapot a recognition system using categorical spatial relations among the visual primitives would still be able to categorize all three of the partially occluded objects as mugs.

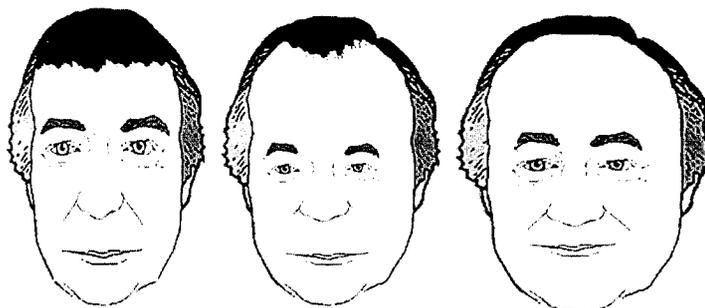


Figure 4. A recognition system using categorical relations among the visual primitives would activate the same representation for all three of the above faces, despite wide variation in the size, position, and aspect ratios of the primitives between the different faces because the categorical relations among the sizes, positions, and locations of the parts are the same in all three faces.

In contrast to structural description theories, template theories (e.g., Bulthoff & Edelman, 1992; Edelman & Weinshall, 1991; Ullman, 1989) typically do not break an object down into its parts, but rather rely on simpler primitives such as edges or pixels, and in

template theories the precise location of the primitives are coded via primitive-to-reference point coordinate relations (hereafter referred to as coordinate relations). In a coordinate relations representation the precise distance of each primitive from a fixed reference point or set of fixed reference points is represented. A coordinate relations systems representation would be equivalent to laying graph paper over an object and specifying the locations of the primitives in the representation relative to the origin of the graph. An example of how a coordinate relations system might represent the spatial locations of the visual primitives is illustrated in Figure 5. A coordinate relations system might represent the spatial location of the left eye in the following manner: The eye is 4 units below and 2.5 units to the right of the reference point.

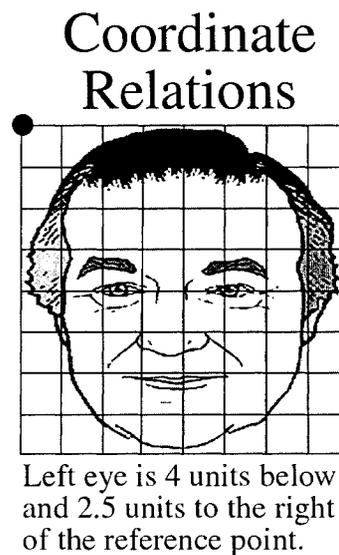


Figure 5. Illustration of how the spatial position of the primitive corresponding to the left eye might be coded using coordinate relations.

The main computation advantage of using a coordinate relations system would be that such a system would be capable of discriminating between objects that share a common

structural description. For example, discriminating between the three mugs in Figure 2 (three mugs that share a common structural description) would require use of a coordinate relations system because all three mugs would activate the same structural description. There are a number of disadvantages to using a coordinate relations system for representing shape including: 1) any input (e.g., retinal image) must be normalized (resized, rotated, repositioned, etc.) prior to matching to a corresponding stored representation and such a procedure would be laborious and time consuming, and 2) it is more difficult for coordinate systems to deal with rotation in depth, recognition of novel objects, and partial occlusion than structural description.

THE COORDINATE RELATIONS HYPOTHESIS

The coordinate relations hypothesis (Brooks & Cooper, 2001; Cooper & Wojan, 2000) attempts to account for the existence of the two visual recognition system in terms of the computational demands imposed by different recognition tasks. The coordinate relations hypothesis theorizes that the recognition system that mediates most basic-level object recognition is a structural description that represents shape using categorical relations whereas the recognition system that mediates face recognition represents shape via a coordinate relations representation.

According to the coordinate relations hypothesis, the factor determining which visual recognition system mediates a given recognition task is the computational demands of the task. That is, because the basic-level object recognition system is usually more efficient (i.e., faster) than the face recognition system, if the recognition task can be performed using a structural description representation then the task will be performed by the basic-level object recognition system. Ullman (1989) posited that a structural description system would likely be faster than a recognition system that codes precise distances between the primitives because the latter would also have to posit time-consuming alignment procedures in which the size, position, and orientation of the input are normalized to match stored representation prior to recognition. According to the coordinate relations hypothesis, if the visual recognition task cannot be performed using a structural description representation, then the task will be performed by the face recognition system using a coordinate relations representation. That is, if the task requires distinctions to be made among stimuli that share the same structural description, then the task will be performed by the face recognition system and show a right hemisphere advantage. Further, the coordinate relations hypothesis

predicts that any task requiring discrimination between objects that share the same structural description should be difficult for prosopagnosics because their coordinate system has been damaged, because according to the coordinate relations hypothesis, prosopagnosia results from damage to the coordinate recognition system which is required for any task that cannot be performed using a structural description representation.

CURRENT ALTERNATIVES TO THE COORDINATE RELATIONS HYPOTHESIS

Currently, three main alternatives to the coordinate relations hypothesis dominate the literature in this area. In the following section, each of these hypotheses will be discussed, some of the evidence for each will be listed, and I will note how the coordinate relations hypothesis can account for the data that have been offered in support of each of the alternatives.

The Biological Recognition Hypothesis. One of the main theories that attempts to account for the dissociation in the neural subsystems used for visual recognition posits that the face recognition system mediates the recognition of all biological stimuli and the basic-level object system mediates the recognition of non-biological stimuli (Cappa et al., 1998; Caramazza & Shelton, 1998; Chao, Haxby, & Martin, 1999, Chao, Martin, & Haxby, 1999; Perani et al., 1999). Many neuroimaging studies, including positron emission tomography (PET) studies and functional magnetic resonance imaging (fMRI) studies, have found brain regions in the lateral fusiform gyrus that respond maximally to biological stimuli (e.g., animals and faces) whereas brain regions in the medial fusiform gyrus respond maximally to non-biological stimuli (e.g., tools and houses) (Chao, Haxby, et al., 1999; Chao, Martin, et al., 1999). Further, the most common co-occurring symptom of prosopagnosia is an inability to distinguish among four-legged animals (Chao, Martin, et al., 1999). Although the fact that damage localized to the right hemisphere can lead to an inability to recognize faces and animals is not conclusive evidence for the biological recognition hypothesis, it does provide strong evidence that the recognition of faces and animals (both biological stimuli) have neural hardware in common.

Note that the coordinate relations hypothesis can also account for why decisions concerning biological stimuli might tend to show a right hemisphere advantage whereas decisions concerning non-biological stimuli do not. As mentioned before, many biological stimuli share structural descriptions (e.g., a dog and a fox share a common structural description) whereas non-biological stimuli tend not to share the same structural descriptions. According to the coordinate relations hypothesis, distinguishing between two things that have the same structural descriptions requires the use of the coordinate relations system and therefore should show a right hemisphere advantage. Thus, according to the coordinate relations hypothesis, it is not the biological/non-biological distinction that determines which visual recognition system mediates a task; it is the computational demands of the recognition task.

The Subordinate-level Recognition Hypothesis. Another theory that attempts to account for the dissociation in neural subsystems for visual recognition posits that the face recognition system mediates subordinate-level recognition, whereas the basic-level recognition system mediates basic-level recognition (Damasio et al., 1982; Gauthier et al., 1997; Gauthier, Skudlarski, Gore, & Anderson, 2000). Subordinate-level tasks are tasks that require distinguishing between members of the same basic-level category (e.g., distinguishing between a 1967 Mustang and a 1968 Mustang). One line of evidence for the subordinate-level hypothesis is that some neuroimaging studies have shown that subordinate-level recognition tasks produce higher levels of activation in the fusiform face area (Gauthier, 1997). Also, recent visual half-field studies have found a right hemisphere advantage for subordinate-level object recognition (Marsolek, 1999; Marsolek et al., 1992).

Note that the coordinate relations hypothesis can account for the data supporting the subordinate-level recognition hypothesis. Members of the same basic-level category often share the same general structural description and thus would require the use of the coordinate relations system to distinguish between them. In contrast, distinguishing objects at the basic-level typically involves different structural descriptions and thus could be accomplished using the categorical relations system.

The Expert Recognition Hypothesis. The third current theory that attempts to account for the dissociation in neural subsystems used for visual recognition posits that the neural subsystem that mediates face recognition mediates any recognition task at which the individual is an expert (Diamond & Carey, 1986; Gauthier et al., 2000; Gauthier & Tarr, 1997; Tarr & Gauthier, 2000). Face recognition, under this view, is an instance of a visual recognition task at which all humans are experts. One of the lines of evidence in support of the expert recognition hypothesis is that experts show an inversion effect for recognizing classes of objects in which they are experts that is very similar to the inversion effect found for recognizing faces (Diamond & Carey, 1986). An inversion effect refers to a pattern of data in which stimuli that have been inverted are dramatically more difficult to recognize than when they are upright. For example, dog and car experts show similar inversion effects for recognizing objects within their class of perceptual expertise similar to the inversion effect neurologically intact individuals show with faces (Diamond & Carey, 1986). Another line of evidence in support for the expert recognition hypothesis is that fMRI studies show that perceptual expertise recruits regions similar to those used in face recognition (Gauthier et al., 2000; Gauthier et al., 1999). However, as Kanwisher (2000) pointed out, the expert

recognition hypothesis fails to explain why certain classes of expert perceptual recognition tasks (e.g., recognition of alphanumeric stimuli) fail to show a right hemisphere advantage.

Note that the coordinate relations hypothesis can account for these data as well. The recognition tasks that have been used to support the expert recognition process require the use of the coordinate relations system, but recognition of alphanumeric stimuli can be accomplished via the categorical relations system. For example, distinguishing between most breeds of dogs or between most makes of cars would require the use of the coordinate relations system while distinguishing between an “a” and a “b” would not. Notice that the fatal flaw of the biological recognition hypothesis, the subordinate-level recognition hypothesis, and the expert recognition hypothesis is that these theories fail to specify how or why the representation of the primitives of the object differs for one class of stimuli as compared to another (e.g., biological versus non-biological stimuli). The coordinate relations hypothesis provides a clear description of how the representations mediating the two recognition systems differ, thus allowing for a clear test of its predictions.

PURPOSE OF THIS DISSERTATION

Over the years, numerous articles have been published that study various prosopagnosic individuals with the apparent sole aim to simply investigate what visual abilities have been lost and which visual abilities remain (see Farah, 1992, for a review). For example, often articles simply characterize how a prosopagnosic individual's ability to recognize one type of stimuli (e.g., faces) differs from that of another (e.g., objects) with little concern for why. While such work has been and is a valuable tool for science, such studies are missing a unique opportunity to utilize prosopagnosia to determine what about the task of face recognition makes face recognition "special". In recent years, a few prosopagnosic studies have attempted to test some of the leading theories concerning the difference between face recognition and object recognition (e.g., Farah, Levinson, & Klein, 1995); however, no such studies have provided a clear test of the coordinate relations hypothesis. The purpose of the experiments presented in this dissertation is to provide the first test of the coordinate relations hypothesis comparing the data from an individual diagnosed with prosopagnosia to that of neurologically intact controls.

According to the coordinate relations hypothesis, prosopagnosia results from damage to the coordinate recognition system which is required for any task that cannot be performed using a structural description representation. Therefore, the theory predicts that any recognition tasks that require the use of coordinate relations should be difficult for individuals with prosopagnosia. However, according to the coordinate relations hypothesis, individuals with prosopagnosia should be relatively unimpaired at visual recognition tasks that can be performed using a structural description representation.

TYPICAL PRESENTATION OF PROSOPAGNOSIA

Prosopagnosia is a disorder classically characterized as an inability to visually recognize faces despite otherwise normal visual and mental function (Mayer & Rossion, 2005). One of the defining characteristics of the disorder is that the individual is able to recognize people via other cues: such as voice or other visual traits (e.g., size, gait, mannerism, clothes, hairstyle, or even facial features (mustache, scar, blemish, or even style of make-up)). Such findings illustrate that individuals with prosopagnosia typically have otherwise intact visual and mental functioning. For example, individuals with prosopagnosia, in general, are able to make fine visual discriminations (e.g., they often show intact reading abilities) (Mayer & Rossion, 2005).

Prosopagnosia in isolation is extremely rare, but if prosopagnosia is considered as one symptom among other visual or neuropsychological deficits, the frequency of occurrence is much higher (Mayer & Rossion, 2005). According to Kumral, Bayulkem, Ataç, and Alper (2004), the typical cause of prosopagnosia is posterior cerebral artery infarcts (PCAI). The posterior cerebral arteries are paired arteries that supply part of the midbrain, the subthalamic nucleus, the basal nucleus, the thalamus, the medial inferior temporal lobe, and the occipital and occipitoparietal cortices (Maulaz, Bezerra, & Bogousslavsky, 2005). Thus a stroke that disrupts blood flow of the posterior cerebral arteries typically result in infarcts (i.e., areas of tissue death due to lack of oxygen) in the regions supplied by these arteries. Although most individuals show evidence of bilateral damage, a few individuals with prosopagnosia have damage restricted to the right hemisphere (Cals, Devuyst, Afsar, Karapanayiotides, & Bogousslavsky, 2002; De Renzi et al., 1994; Grüsser & Landis, 1991; Uttner, Bliem, & Danek, 2002; and Wada & Yamamoto, 2002). Among vision researchers, there is a growing

consensus that a right hemisphere lesion is necessary, if not sufficient, to cause prosopagnosia (e.g., see Mattson, Levin, & Grafman, 2000). The lesions causing prosopagnosia are generally located in the infero-medial part of the temporo-occipital cortex, specifically the fusiform gyrus, the lingual gyrus, and the posterior part of the parahippocampal gyrus (Bouvier & Engel, 2005; Damasio et al., 1982; Grüsser & Landis, 1991; Meadows, 1974). (See Figure 6 for an illustration.)

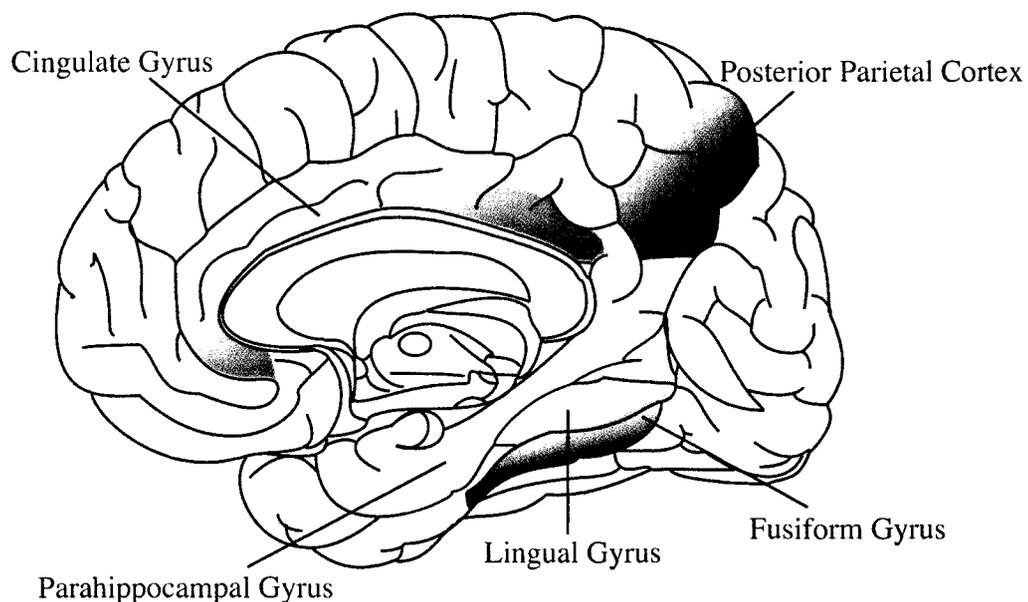


Figure 6. An illustration showing the posterior parietal cortex, the cingulate gyrus, and the infero-medial part of the temporo-occipital cortex (specifically the fusiform gyrus, the lingual gyrus, and the posterior part of the parahippocampal gyrus).

Neuroimaging studies (e.g., PET and fMRI investigations) conducted on neurologically intact individuals have identified a small area within the right midfusiform gyrus that shows maximal activation to face stimuli (e.g., Kanwisher et al., 1997; McCarthy

et al., 1997; Sergent et al., 1992) and has been termed the 'fusiform face area' (FFA, Kanwisher et al., 1997). Interestingly, in a meta-analysis of 73 prosopagnosic cases, Bouvier and Engel (2005) found that area of maximal lesion overlap was a small area in the right inferior occipital gyrus and included the FFA once again showing the importance of this region to face recognition.

Prosopagnosics often have a number of other deficits such as achromatopsia (a severe deficit in color perception), topographical disorientation, (see Grüsser & Landis, 1991, and Bouvier & Engel, 2005, for reviews), and visual field defects, especially in the upper left quadrant (Bouvier & Engel, 2005; Goldsmith & Liu, 2001; Grüsser & Landis, 1991). In a meta-analysis of 92 cases of achromatopsia and 100 cases of prosopagnosia (note that there were not 192 separate cases in the meta-analysis as many of the individuals had both disorders), Bouvier and Engel (2005) found that 72% of the 92 cases of achromatopsia also had prosopagnosia. As Bouvier and Engel's (2005) paper was primarily a meta-analysis of achromatopsia, the precise percentage of the 100 cases of prosopagnosia who also had achromatopsia was not reported. Achromatopsia is typically associated with a bilateral or right unilateral lesion of the temporo-occipital cortex (Zeki, 1990). Another deficit frequently associated with both prosopagnosia and achromatopsia is topographical disorientation, with four types of topographical disorientation often being described: a) egocentric disorientation (in which the individual is unable to represent the location of objects with respect to self, typical lesion site is posterior parietal cortex), b) heading disorientation (in which the individual is unable to represent direction of orientation with respect to external environment, typical lesion site is posterior cingulate gyrus), c) landmark agnosia (in which the individual is unable to represent the appearance of salient

environmental stimuli (or landmarks), typical lesion site is the lingual gyrus), and d) anterograde disorientation (in which the individual is unable to create new representations of environmental information, typical lesion location is the parahippocampal gyrus) (Aguirre & D'Esposito, 1999; Habib & Sirigu, 1987). (See Figure 6 for an illustration showing the aforementioned locations). Note that these regions are adjacent to those associated with prosopagnosia and achromatopsia. A third deficit often associated with prosopagnosia is visual field defect, specifically a left superior quadrantanopia (i.e., blindness in the left upper quadrant of visual field) (Bouvier & Engel, 2005; Meadows, 1974). Note the unique pattern of deficits typically associated with prosopagnosia and the fact that the majority of these disorders (prosopagnosia, achromatopsia, and topographical disorientation) are associated primarily with lesions to adjacent regions of the right cerebral cortex.

CHARACTERIZATION OF THE INDIVIDUAL WITH PROSOPAGNOSIA

At 39 years of age, LB (a 41-year-old retired junior high math teacher at the time of the investigation) suffered a posterior cerebral artery stroke causing bilateral inferiortemporal damage and partial unilateral hippocampus damage. LB is of above average intelligence. LB has subsequently been diagnosed with prosopagnosia, achromatopsia (i.e., color blindness), anomia (i.e., a naming deficit), topographical disorientation, and right upper quadrantanopia (i.e., blindness in the right upper quadrant of visual field) and left homonymous hemianopia (i.e., blindness in the left half of the visual field).

Since the time of her accident, LB shows evidence of some general memory problems (e.g., memory for dates and names, episodic memory problems). Long-term memory, procedural memory, and motor skills are intact. In her remaining intact quadrant of visual field (the lower right quadrant), LB has normal visual acuity. LB spontaneously reported visual recognition problems with the following: face recognition; recognition of some types of food, plants, animals, buildings (particularly distinguishing between similar looking houses or office buildings), and money (such as telling play money from real money); and topographic disorientation (e.g., difficulty following verbal directions or maps describing locations). Note, that LB's general visual recognition problems all involve tasks that require metrically precise information. LB's pattern of deficit and neurological damage closely matches those typically reported in a case of acquired prosopagnosia (see Bouvier & Engel, 2005, and Mayer & Rossion, 2005 for reviews). In fact, LB is the prototypical prosopagnosic. LB, like the typical prosopagnosic, presents with a number of other deficits such as achromatopsia, topographical disorientation, and visual field defect. Also, as is the norm, LB's disorders are due to a posterior cerebral artery stroke resulting in bilateral inferior

temporal lobe damage. LB's additional symptom of anomia likely results from her slight unilateral hippocampus damage.

Due to the anatomical organization of the visual system, information presented in the left visual field is initially presented to the right cerebral hemisphere, whereas, information presented in the right visual field is initially presented to the left cerebral hemisphere. Visual half-field studies (a.k.a., laterality studies) utilize this fact and present information very briefly (i.e., less than the time it takes for the superior colliculus to generate an eye saccade (200 msec)) in one visual field or the other and look at reaction time and error rates to see if one hemisphere is better at recognition of a given type of stimuli. For example, as mentioned previously, one of the lines of evidence for two neurologically distinct visual recognition systems is the finding that the right cerebral hemisphere is typically slightly better (i.e., slightly faster and makes fewer errors) than the left cerebral hemisphere at face recognition (see Davidoff, 1982, and Ellis, 1983, for reviews). Due to LB's visual field deficits, using a laterality paradigm to test her was not possible. Also, LB's smaller functioning visual field means that she often needs multiple eye saccades to project enough of a given image onto her functioning visual field to mediate recognition.

EXPERIMENT 1: PHYSICALLY DISCRIMINATING COMMON STRUCTURAL DESCRIPTION ANIMALS VS. DIFFERENT STRUCTURAL DESCRIPTION ANIMALS

The central tenet of the coordinate relations hypothesis is that the critical factor that determines which neural subsystem mediates a given visual recognition task is whether the computational demands of the task are better solved using a coordinate relations or a structural description (categorical) representation. If a given visual recognition task cannot be performed using a structural description representation (e.g., distinguishing between two objects that share the same categorical structural descriptions, such as distinguishing between the cups in Figure 2 or the faces in Figure 4), then the task must be performed using the coordinate recognition system. Recall that according to the coordinate relations hypothesis, prosopagnosia results from damage to the coordinate recognition system, which is required for any task that cannot be performed using a structural description representation.

Therefore, the coordinate relations hypothesis predicts that any recognition tasks that require the use of coordinate relations should be difficult for individuals with prosopagnosia.

However, according to the coordinate relations hypothesis, individuals with prosopagnosia should be relatively unimpaired at visual recognition tasks that can be performed using a structural description representation (because that system has presumably been left intact).

The purpose of Experiment 1 was to provide a direct test of whether prosopagnosia does result from damage to the coordinate recognition system and to test the coordinate recognition hypothesis against the biological recognition hypothesis, the subordinate-level recognition hypothesis, and the expert recognition hypothesis. Participants in Experiment 1 performed discriminations of gray scale photographs of 34 animals. All animals chosen for use in Experiment 1 were animals that share their three largest geons and relations with

another animal from a different basic-level category (e.g., dog and a coyote share the same three largest geons and relations). During each trial of the experiment, participants were presented with a pair of animals separated by a pattern mask, and their task for each trial was to decide if the animals were members of the same species (e.g., if presented with two dogs then the correct answer would be “same”, but if presented with a dog and a coyote then the correct answer would be “different”). On no occasion were identical images shown on a single trial. On half of the trials the animals were members of the same species (e.g., see panel 1 of Figure 7). On the trials in which the animals were not members of the same species, the species change could fall into one of two categories: a different animal species but one that shares the largest three geons and relations with the previous animal (e.g., dog and coyote) (hereafter referred to as SSD (for Same Structural Description) trials) (e.g., see panel 2 of Figure 7), or a different animal species that does not share the largest three geons and relations with the previous animal (e.g., dog and horse) (hereafter referred to as DSD (for Different Structural Description) trials) (e.g., see panel 3 of Figure 7).

The coordinate relations hypothesis predicts that discriminating between two animals that are different species but share a common structural description (i.e., SSD trials) should be significantly more difficult for individuals with prosopagnosia than for controls. However, according to the coordinate relations hypothesis, distinguishing between two animals with different structural descriptions (i.e., DSD trials) should not be significantly more difficult for individuals with prosopagnosia than for controls. Note that none of the leading alternative to the coordinate relations hypothesis (i.e., the biological recognition hypothesis, the expert recognition hypothesis, or the subordinate-level recognition hypothesis) make such a prediction. According to the biological recognition hypothesis,

Task: Indicate via button press if two animals presented one after another are members of the same species.

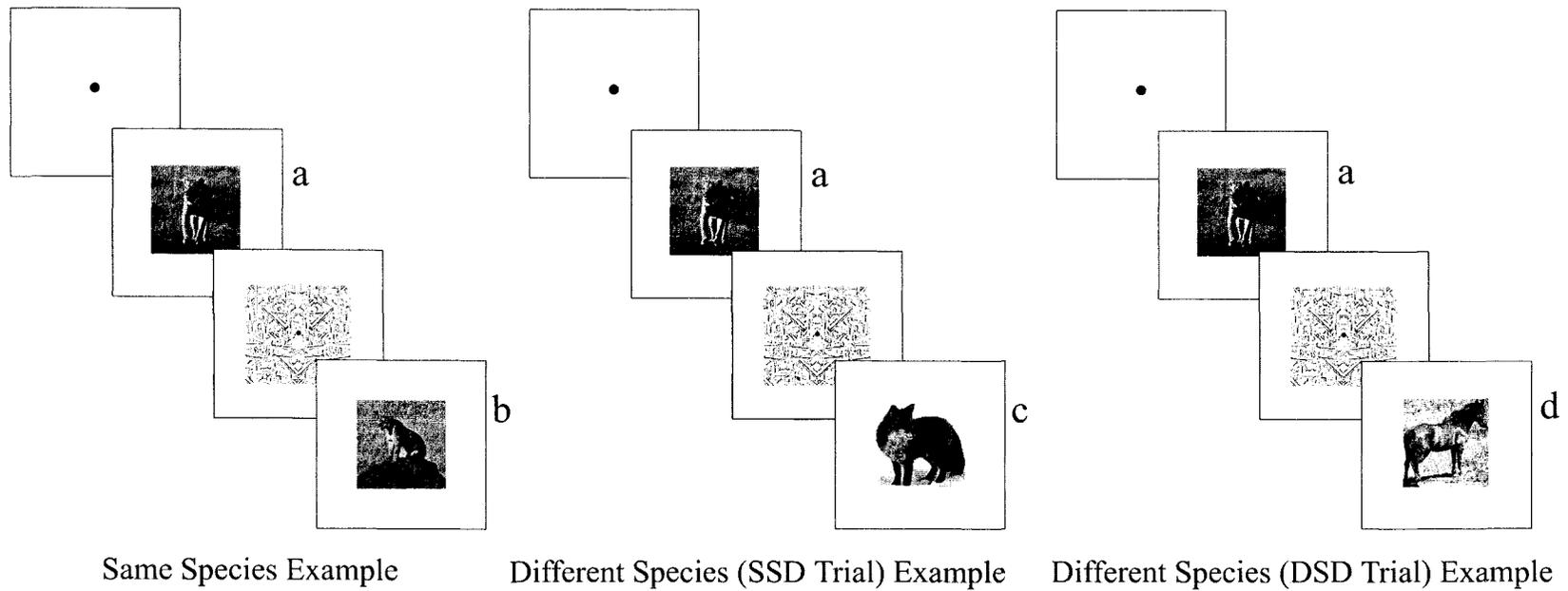


Figure 7. Illustration showing the three different combinations of stimuli that were shown in Experiment 1.

prosopagnosia results from damage to the visual recognition system which mediates visual recognition of any stimulus of a biological nature. Therefore, the biological recognition hypothesis predicts that individuals with prosopagnosia should show equally poor ability to discriminate between animals regardless of type of comparison (i.e., according to the biological recognition hypothesis LB should show equally poor performance on the SSD trials and the DSD trials, and LB's performance on both types of trials should be significantly worse than that of the controls). Conversely, the subordinate-level recognition hypothesis and the expert recognition hypothesis predict that individuals with prosopagnosia should show no significant difference from that of controls in terms of ability to discriminate between animals regardless of type of comparison. According to the subordinate-level recognition hypothesis, prosopagnosia results from damage to the visual recognition system that mediates visual recognition at the subordinate-level. Therefore, according to the subordinate-level recognition hypothesis, because animal discrimination at the species level is a basic-level recognition task, individuals with prosopagnosia should exhibit normal animal discrimination at this level of analysis. Similarly, because animal discrimination at the species level was not an area of particular expertise for LB, according to the expertise recognition hypothesis she should exhibit normal visual discrimination for all non-expertise categories. To recap, the coordinate relations hypothesis predicts that LB should have significantly more difficulty than the controls with the SSD trials but not with the DSD trials. The biological recognition hypothesis predicts that LB should have significantly more difficulty than the controls with both the SSD trials and the DSD trials, (whereas the subordinate-level recognition hypothesis and the expertise recognition hypothesis predict that

LB's performance on both the SSD trials and the DSD trials should not be significantly different from that of the controls).

Method

Participants

The participants for all of the experiments reported here were one individual with prosopagnosia (LB) and a group of neurologically intact controls. The control participants were undergraduate students at Iowa State University who reported normal or corrected to normal vision (8 males (1 left handed) and 8 females (1 left handed) with a mean age of 22.5 years and a range of 21 to 38). LB was a 41-year-old female with prosopagnosia but normal visual acuity in the lower right quadrant of visual space. All participants were naïve to the purpose of the experiment.

Test of Prosognosia. LB and the controls were given a test of famous face recognition constructed for the purpose of verifying the diagnosis of prosopagnosia for LB and to verify that controls show normal face recognition. The test of famous face recognition included identification of 18 grayscale photographs of famous actors, politicians, and athletes, who were chosen to maximize ease of identification. LB's score on the test of famous faces was six correct out of 18 as compared to the controls average mean correct of 16.6 out of 18 confirming the diagnosis of prosopagnosia. The test of famous faces is shown in Appendix A.

Test of Object Agnosia. LB and the controls were given a test of basic-level object recognition constructed for the purpose of verifying that both LB and the controls show normal basic-level object recognition. The test of basic-level object recognition included

identification of 18 grayscale photographs of common objects, which were chosen to maximize ease of identification. The test of basic-level object recognition is shown in Appendix B. LB score on the test of basic-level object recognition was sixteen correct out of 18 (the two errors were most likely due to poor contrast of the items) as compared to the controls average mean correct of 17.9 out of 18 confirming that none of the participants met the criterion for diagnosis of object agnosia.

Apparatus

The experiment was controlled by a 1 Ghz PowerPC Powerbook G4 computer using Superlab Pro software. Participants responded via button press using the built in keyboard that gives ± 0.5 ms response time accuracy. Stimuli were presented on an Apple 15-inch LCD screen with a resolution of 1280 x 854 pixels and a response time of approximately 10 milliseconds.

Stimuli for Experiment 1 consisted of gray scale photographs of 34 animals (17 different species with two exemplars of each). All animals chosen for use in the experiment were ones that share their largest geons and relations with another animal from a different basic-level category (e.g., dog and a coyote share the same three largest geons and relations). The animals chosen for the experiment grouped by geon structural description are as follows: members of the accipitridae family (eagles and hawks), members of the anatidae family (geese and swans), members of the canidae and felidae families (coyotes, dogs, foxes, wolves, bobcats, cats, and female lions), members of the family equidae (donkeys, horses, and mules), and members of the hominidae family (chimpanzees, gorillas, and orangutans). The photographs were chosen so as to maximize the number of visible parts and to be the most prototypical exemplars that could be found. The photos were scanned in such a way

that their maximum extent would fit just inside a 504 X 504 pixel box. Given the conditions of the experiment, the stimuli would fit in a box with 8° x 8° of visual angle. Examples of the stimuli may be seen in Figure 8.

Procedure

Presentation of the stimuli was self-paced. Participants pressed a key on the keyboard to begin each trial. After pressing the key, a fixation cue was presented for 500 msec, followed by presentation of one of the stimuli presented at center of fixation for 500 msec, followed by a pattern mask for 250 msec, followed by a different stimulus which remained on the screen until the subject responded. On half of the trials, the second stimulus was a member of the same species as stimulus one (the “same species” trials). The other 50% of the trials were “different species” trials. For half the “different species” trials, the second animal shared the same structural description as the first and for half it had a different structural description. Special care was taken to ensure that none of the trials resulted in the comparison of a bird to mammal (i.e., a feather to fur switch) so the participant could not use low level texture features to perform the discrimination.

The participant’s task was to indicate via button press whether the two animals were members of the same species as quickly and accurately as possible. Participants were instructed to press the “1” key on the keyboard (which was labeled “same”) with their left hand if the two images were members of the same species. Participants were instructed to press the “0” key on the keyboard (which was labeled “different”) with their right hand if the two images were not members of the same species. To ensure that participants put forth sufficient effort participants received feedback after each trial regarding the accuracy of their response.

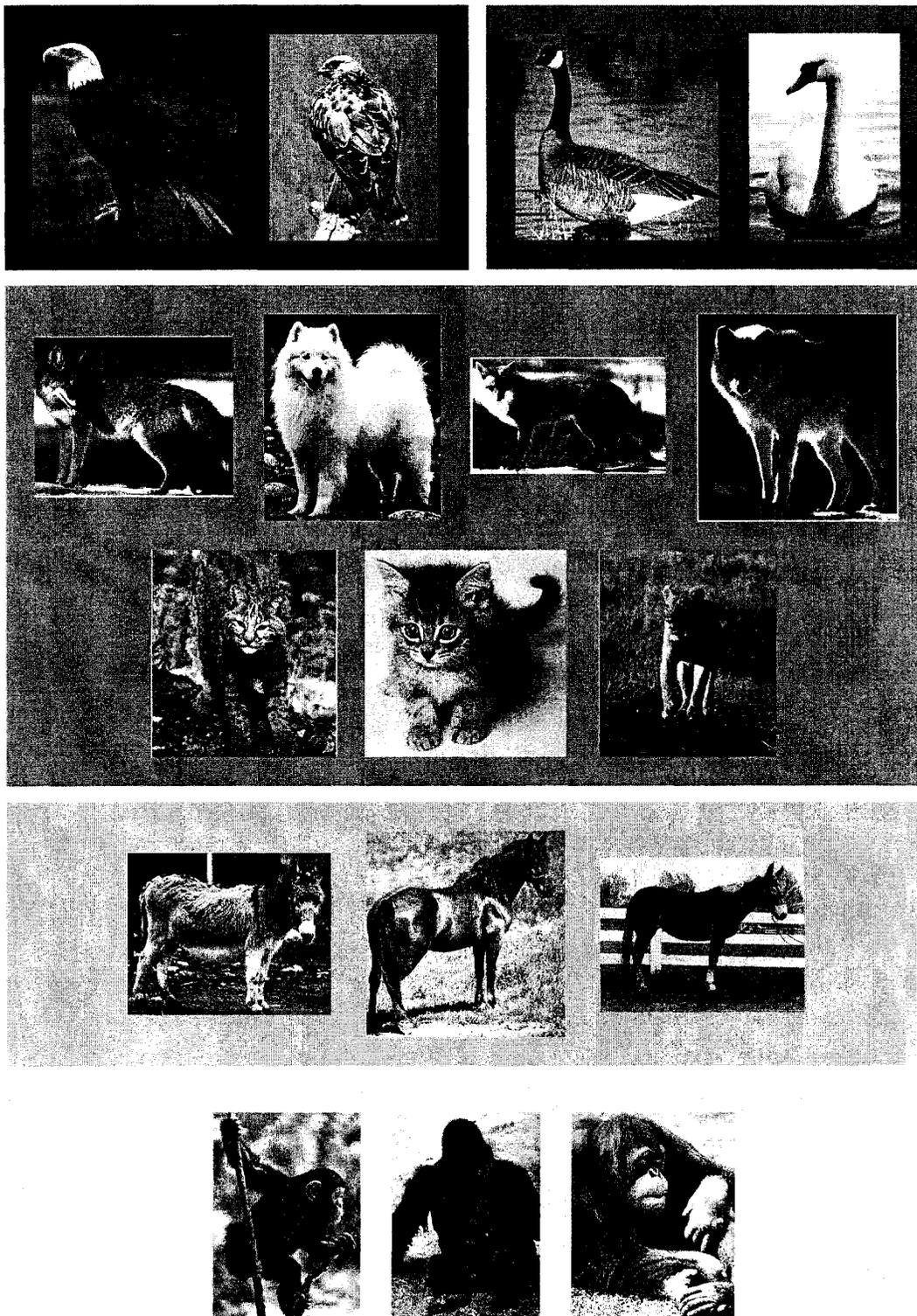


Figure 8. Examples of the 17 different species used in Experiment 1 grouped by geon structural description families.

The experiment consisted of 136 trials. There were 34 animal pictures used during the experiment: two exemplars each of 17 different species. Each animal picture appeared four times as the first picture in a trial for each subject: two trials in which both animals were the same species (but different exemplars), one trial in which the second animal was a different species and had a different structural description than the first (DSD trials), and one trial in which the second animal was a different species, but had the same structural description as the first (SSD trials). The order in which the stimuli were presented was chosen randomly with the constraint that the mean presentation position for the DSD trials equaled that of the SSD trials. All participants were shown the same presentation order. Participants completed 16 practice trials prior to the actual experiment. None of the practice images were used in the experiment proper.

Results

A modified t-test developed for use in neuroscience to compare a single-case to a small group of controls was used to determine if LB's difference in error rate between the SSD trials and the DSD trials differs reliably from the difference in the controls' mean error rate between the SSD trials and the DSD trials while at the same time testing to see if LB showed a deficit for the SSD trials or the DSD trials (Crawford & Howell, 1998). The same analysis was conducted on reaction time data. However, due to general visual problems (specifically right upper quadrantanopia (i.e., blindness in the right upper quadrant of visual field) and left homonymous hemianopia (i.e., blindness in the left half of the visual field)) LB was much slower overall on all the experiments reported here and thus reaction time was not the main dependent variable of interest.

Error Data. The error data from the different trials of Experiment 1 can be seen in Figure 9. Mean error rates for the same species trials for the control and for LB were 12.3% and 14.7% respectively. Controls responded same on 51.2% of the trials. LB responded same on 58.1% of the trials. The fact that LB performed better on the same species trials than the coordinate relations theory would predict is likely due to her showing a bias to respond same. Analysis revealed that LB's difference in error rate between the SSD trials and the DSD trials was significantly greater than the difference in the controls' mean error rate between the SSD trials and the DSD trials, $t(15) = 3.48$, $SE = 8.13$, $p < .005$. Further analysis revealed that LB's error rate for the SSD trials was significantly greater than the controls' mean error rate for the SSD trials, $t(15) = 4.53$, $SE = 7.02$, $p < .0005$, whereas LB's error rate for the DSD trials was not significantly different from the controls' mean error rate for the DSD trials, $t(15) = 0.13$, $SE = 4.25$, $p > .45$. That is, just as the coordinate relations hypothesis predicts, LB made significantly more errors than the controls on those trials that required discrimination within a structural description (58.8% for LB compared to 27% for the controls), but LB did not make significantly more errors than the controls on those trials that could be accomplished on the basis of structural descriptions (2.9% for LB compared to 2.4% for the controls). Both LB and the controls made more errors on the SSD trials than on the DSD trials. This finding is consistent with the coordinate relations theory as according to the theory the SSD trials (e.g., discriminating between a horse and a donkey) require participants to utilize the relatively slow and error prone coordinate recognition system to mediate discrimination (e.g., one of the discriminating characteristics of horse and a donkey is the size of the ears in proportion to the rest of the animal) whereas the DSD trials (e.g.,

discriminating between a horse and a gorilla) can be accomplished using the faster structural description system.

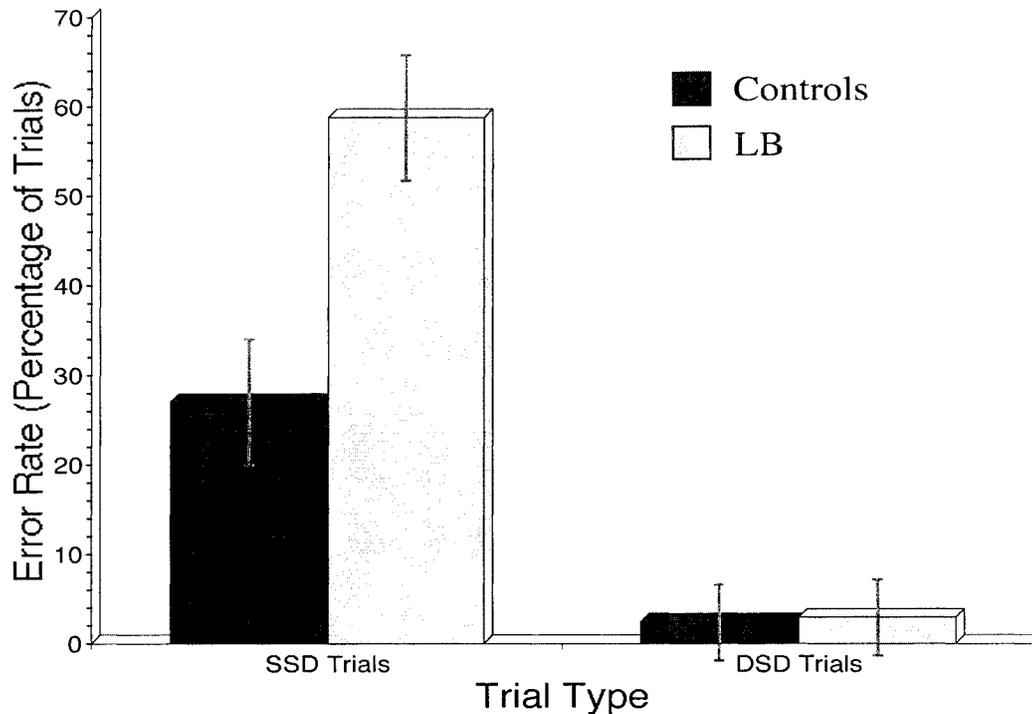


Figure 9. Error rate data from Experiment 1. Error bars represent the average standard error of the mean for the control participants.

Reaction Time Data. Although error rate was the principal dependent measure in these experiments, the response times for the correct trials were analyzed to determine whether the error rate data might be a consequence of speed-accuracy trade-off. The reaction time data from the different trials of Experiment 1 can be seen in Figure 10. Mean reaction times for the same species trials for the control and for LB were 860 msec and 2446 msec respectively. Analysis revealed that although in the direction predicted by the coordinate recognition hypothesis, LB's difference in mean reaction time between the SSD trials and the DSD trials was not significantly greater than the difference in the controls' mean reaction

time between the SSD trials and the DSD trials, $t(15) = 0.51$, $SE = 154$, $p > .60$. Further analysis revealed that, LB's mean reaction time for the SSD trials was significantly greater than the controls' mean reaction for the SSD trials, $t(15) = 9.03$, $SE = 218$, $p < .0001$, also LB's mean reaction time for the DSD trials was significantly greater than the controls' mean reaction time for the DSD trials, $t(15) = 9.17$, $SE = 82$, $p < .0001$. Despite the fact that reaction time was not the principal dependent variable in these studies, note that the pattern of the reaction time data is consistent with that predicted by the coordinate relations hypothesis (and inconsistent with the three other theories) indicating that the error rate results were not a consequence of a speed-accuracy trade-off. LB almost doubled (a 95% increase) her mean reaction time for the SSD trials compared to the DSD trials whereas the controls participants showed only a 25% increase.

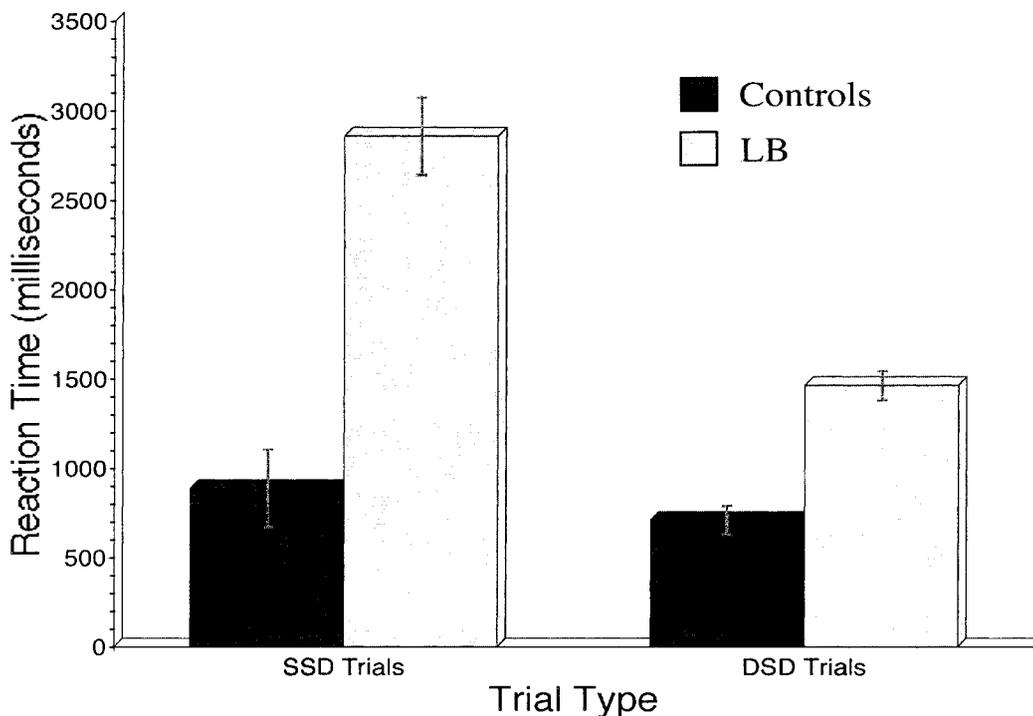


Figure 10. Reaction time data from Experiment 1. Error bars represent the average standard error of the mean for the control participants.

Discussion

The pattern of results from Experiment 1 are precisely the pattern predicted by the coordinate relations hypothesis and cannot be accounted for by the current alternatives to the coordinate relations hypothesis. Just as predicted by coordinate relations hypothesis, LB's visual recognition difficulties relative to that of the controls were on those visual recognition tasks that require the use of coordinate relations (i.e., the SSD trials) and not on those visual recognition tasks that can be performed using a structural description representation (i.e., the DSD trials). Recall that none of the three alternative theories (biological recognition hypothesis, subordinate-level recognition hypothesis, or expert recognition hypothesis) predicts any difference in DSD and SSD trials. The results of Experiment 1 are therefore inconsistent with all the current alternatives to the coordinate relations theory.

EXPERIMENT 2: PHYSICALLY DISCRIMINATING METRIC CHANGED VS. GEON CHANGED OBJECTS

A structural description of an object consists of a specification of the primitive shapes present in the object and the relations among those shapes (coded categorically). Thus, a change in either a) the primitives making up an object or b) a change in the categorical relations among the primitives should theoretically result in a change in the structural description of that object. According to the coordinate relations theory, therefore, the basic-level object recognition system (which coordinate relations theory posits uses a structural description) could be used to detect changes to an object whenever the changes alter either the identity of the primitives or their categorical relations. In contrast, changes to an object that do not alter the identity of its primitive shapes or the categorical relations among the shapes should theoretically not result in a change in the object's structural description. Therefore, according to the coordinate relations theory, the (coordinate) face recognition system would be required to detect changes to an object if the changes do not alter the identity of the primitives or their categorical relations (because such changes would not alter the structural description of the object and thus cannot be detected using the basic-level object recognition system).

Experiment 2 examined the prediction of the coordinate relations theory that changes to the identity of an object's primitives can be detected using the basic-level object recognition system while changes to the primitives that do not alter their identity must be detected using the face recognition system. In the most popular structural description theory of object recognition, Biederman's (1987) Recognition by Components theory, the primitives that are presumed to underlie basic-level recognition are a set of 36 primitive shapes called

geons. Examples of different geons would be "cylinder", "cone", "truncated cone", and "brick" (the reader should examine Biederman, 1987, for a full description of how the 36 geons are derived). A key feature of geons is that they do not alter their identity due to changes in length or size. That is, in the structural descriptions used by Biederman's theory, a long thin "cylinder" and a short squat "cylinder" would both be classified generically as "cylinders". It is because the geons do not alter their identities due to size and length changes that all the differently shaped mugs in Figure 2 would receive exactly the same structural description according to Biederman's theory.

The logic of Experiment 2 can be understood by looking at the tables in Figure 11. Note that tables a and b in Figure 11 differ in the length of the table top, but have exactly the same geons and categorical relations among the geons. Biederman's (1987) theory would therefore predict that tables a and b would activate exactly the same structural description in the basic-level object recognition system. According to coordinate relations theory, therefore, discriminating tables a and b from one another would require use of the face recognition system because they would activate the same description in the basic-level object recognition system. In contrast, Biederman's theory predicts that tables a and c in Figure 11 would activate different structural descriptions because they have a difference in their geons. The table top in table a is a "brick" geon while the table top in table c is a "cylinder" geon. According to coordinate relations theory, therefore, discriminating tables a and c from one another would be performed using the basic-level recognition system because they would activate different structural descriptions in that system. If the coordinate relations theory is correct, a prosopagnosic should be relatively unimpaired at discriminating table a from table c (because the prosopagnosic's intact basic-level object recognition system can be used to

make the discrimination), but should be much worse than a control at discriminating table a from table b (because, according to coordinate relations theory, making such a discrimination would require the face recognition system which is impaired in prosopagnosics).

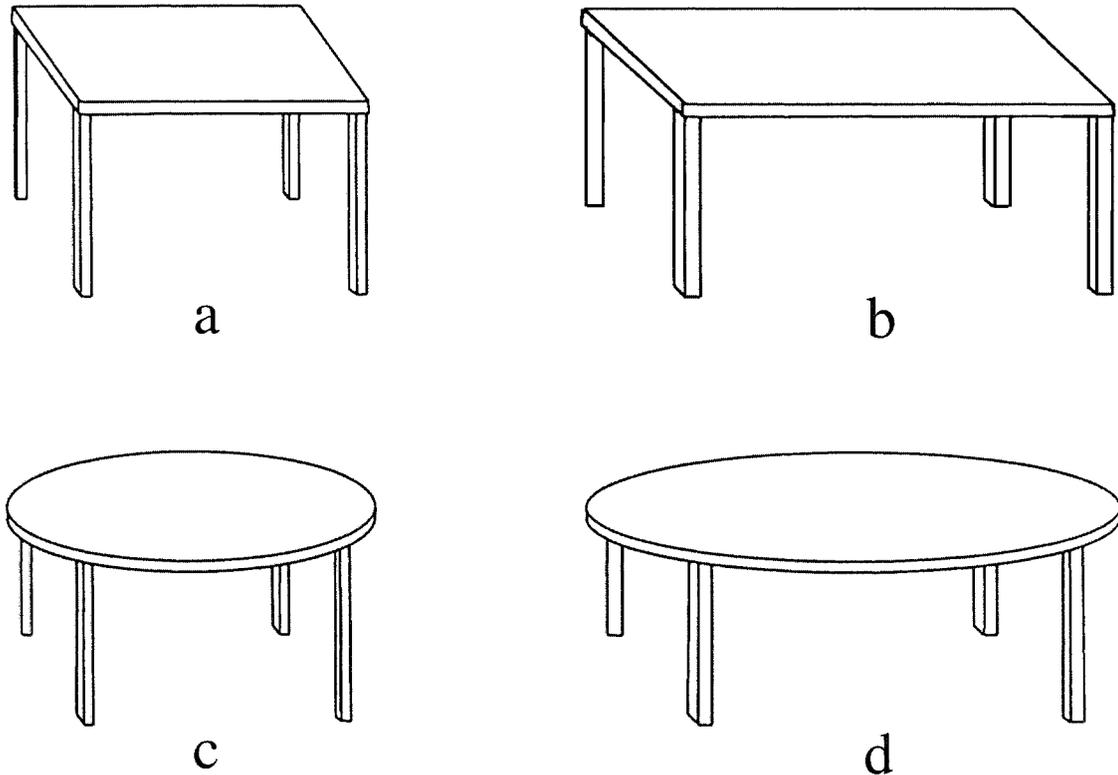


Figure 11. Examples of the different exemplars of objects comprising the basic-level category “table” in Experiment 2. Objects a and b as well as objects c and d share the same geon structural description but have different metric properties whereas objects a and c as well as objects b and d do not share the same geon structural description. For example, the structural description of tables a and b might be four bricks “below” and to the “side-of” a brick, whereas, the structural description of tables c and d might be four bricks “below” and to the “side-of” a cylinder. Examples of metric change trial pairings would be a comparison of tables a and b or a comparison of tables c and d. Examples of geon change trial pairings would be a comparison of tables a and c or tables b and d.

Participants in Experiment 2 performed physical discriminations using line drawings of inanimate objects (see Figure 11). During each trial of the experiment, participants were presented with a pair of objects (that belonged to the same basic-level category) separated by a pattern mask, and their task for each trial was to decide if the pair of objects were physically identical. On the trials in which the objects were not physically identical, some of the objects could be discriminated from one another using structural description representations (e.g., tables a and c or tables b and d in Figure 11) (hereafter these trials will be known as geon changed trials) whereas some of the objects could not be discriminated from one another using structural description representations (e.g., tables a and b or tables c and d in Figure 11) (hereafter these trials will be known as metric changed trials). The objects that could be discriminated from one another using structural description representations differed from one another on the basis of one geon, but the aspect ratio of the corresponding geons did not differ. The objects that could not be discriminated from one another using structural description representations share a common structural description, but the aspect ratio of one of the geons was different.

The coordinate relations hypothesis predicts that discriminating between two objects that share a common structural description (i.e., the metric change trials) should be significantly more difficult for individuals with prosopagnosia than for controls, because according to the coordinate relations hypothesis, prosopagnosia results from damage to a coordinate recognition system that is used to make distinctions among objects sharing the same structural description. However, according to the coordinate relations hypothesis, distinguishing between two objects with different structural descriptions (i.e., the geon change trials) should be relatively simple for individuals with prosopagnosia because such a

discrimination can be mediated by the intact basic-level object system. Note that none of the leading alternative to the coordinate relations hypothesis (i.e., the biological recognition hypothesis, the expert recognition hypothesis, or the subordinate-level recognition hypothesis) make such a prediction. Recall that according to the subordinate-level recognition hypothesis the pattern of deficits observed in prosopagnosia result from damage to the visual recognition system that mediates visual recognition tasks that require the viewer to make distinctions among different members of the same basic-level category (e.g., distinguishing between any of the different exemplars of tables in Figure 11). Thus, the subordinate-level recognition hypothesis predicts that individuals with prosopagnosia should show a deficit in their ability to discriminate among members of the same basic-level category (e.g., discriminating between any of the tables in Figure 11) regardless of whether the exemplars being compared share a common structural description. That is, according to the subordinate-level recognition hypothesis, LB should show impairment on both the geon change trials and the metric change trials relative to the controls. Thus, Experiment 2 provides a test of the subordinate-level recognition theory because all the discriminations in Experiment 2 involved discriminations within a basic-level class and therefore are all subordinate-level discriminations.

According to the biological recognition hypothesis, prosopagnosia results from damage to the recognition system that mediates recognition of any biological stimulus. Due to the fact that none of the objects used in Experiment 2 are biological stimuli, the biological recognition hypothesis predicts that LB should not show impairment with either trial type. Similarly, according to the expert recognition hypothesis, prosopagnosia results from damage to the recognition system that mediates recognition of any stimulus within a category of

particular expertise. Due to the fact that neither the geon change trials nor the metric change trials involve stimuli at which any of the participants in the experiment is an expert, the expert recognition hypothesis also predicts that LB should not show impairment with either trial type.

Method

Participants

The participants for Experiment 2 were the same as Experiment 1.

Apparatus

The apparatus for Experiment 2 was the same as Experiment 1. Stimuli for Experiment 2 consisted of line drawings of simple objects taken from the stimulus set used by Cooper and Biederman (1993). Thirty-two basic-level categories were used, none of which were biological stimuli (antenna, axe, barbeque grill, bottle, bell, chair, clock, couch, cup, dust pan, eye glasses, flag, flashlight, glass, hat, ice cream cone, key, lamp, lightbulb, mallet, paintbrush, pipe, saw, screw, shoe, shovel, spatula, spoon, table, teapot, truck, and watch), with four different exemplars from each basic-level object category. Within a set of four exemplars from each basic-level object category, there were two pairs of exemplars that differed from each other by one geon, but the aspect ratio of the corresponding geons did not differ for the objects that comprised that particular pair (see Figure 11, note that objects a and c comprise one pair of geon-changed trials and objects b and d comprise another pair of geon-changed trials). Within a set of four exemplars from each basic-level object category, there were two pairs of exemplars that share a geon structural description, but the aspect ratio of a particular geon common to both objects differ for the two objects (see Figure 11, note that

objects a and b comprise one pair of metric changed trials and objects c and d comprise another pair of metric changed trials). Because the metric changed trials' objects share a common structural description (e.g., the structural description of tables a and b might be four elongated bricks below and to the side-of a flattened brick) discrimination between such objects could not be accomplished on the basis of structural description.

Procedure

Presentation of the stimuli was self-paced. Participants pressed a key on the keyboard to begin each trial. After pressing the key, a fixation cue was presented for 500 msec, followed by presentation of one of the stimuli presented at center of fixation for 500 msec, followed by a pattern mask for 250 msec followed by one of the stimuli of the same basic-level category which remained on the screen until the subject responded. This image was presented at one of four possible locations chosen randomly on any trial (either 1.5° of visual angle above and 1.5° of visual angle to the right, 1.5° visual angle below and 1.5° of visual angle to the right, 1.5° of visual angle below and 1.5° of visual angle to the left, or 1.5° of visual angle above and 1.5° of visual angle to the left) and remained on the screen until the participant made a response with all four locations being used equally often. Differences in the vertical and horizontal position of the stimuli were used to prevent participants from simply using the height or width of the secondary shape as an indicator of whether or not the two stimuli were identical. On half of the trials, the second stimulus was identical to the first stimulus. For the other half of the trials, the stimulus change was equally likely to represent a geon change as it was a metric change (see Figure 12 for illustration showing the three different combinations of stimuli that were shown in Experiment 2).

Task: Indicate via button press if two images are identical.

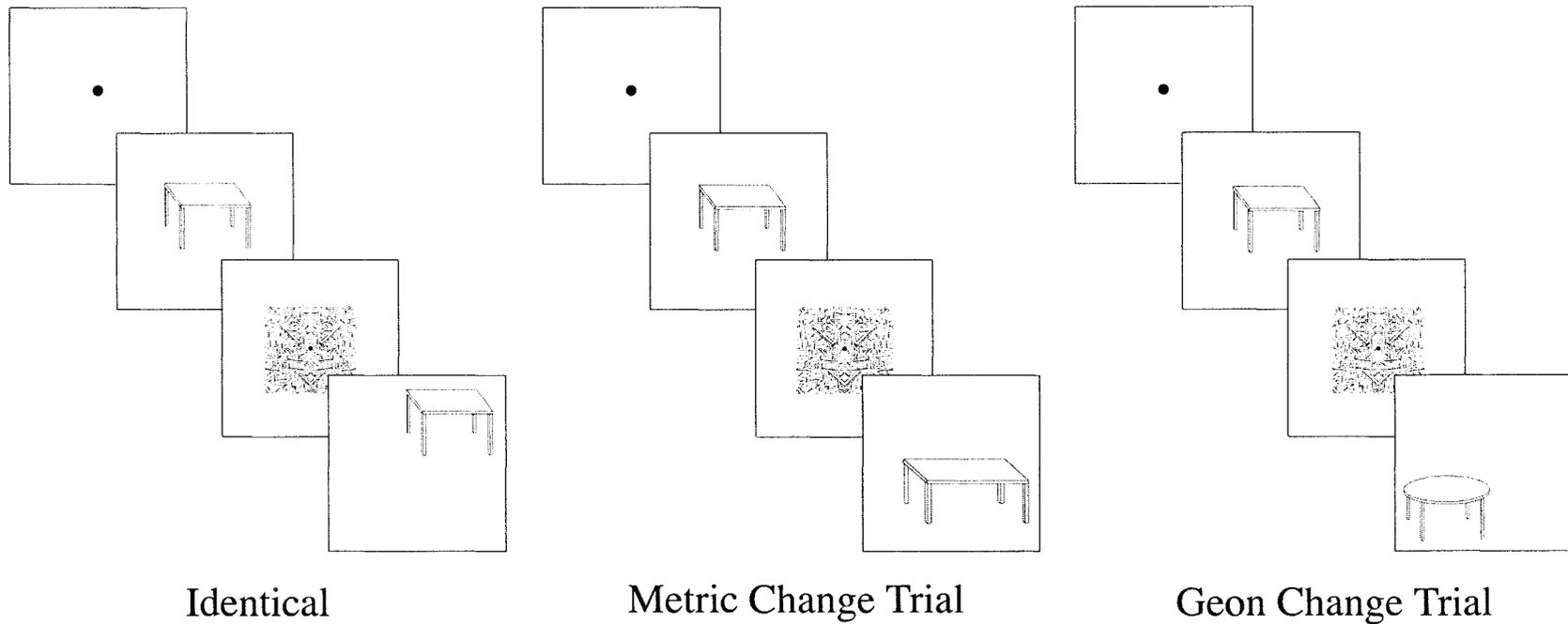


Figure 12. Illustration showing the three different combinations of stimuli that were shown in Experiment 2.

The participant's task was to indicate via button press whether the two stimuli were physically identical to one another as quickly and accurately as possible. Participants were instructed to press the "1" key on the keyboard (which was labeled "same") with their left hand if the two images were physically identical. Participants were instructed to press the "0" key on the keyboard (which was labeled "different") with their right hand if the two images were not physically identical. Note that participants' task in the experiment was *not* to decide whether a metric change or geon change has taken place between the two objects. Participants' task was simply to decide whether the two were physically identical regardless of how they changed. To ensure that participants put forth sufficient effort participants received feedback after each trial regarding the accuracy of their response.

The experiment consisted of 512 trials. Each of the objects appeared four times as the first stimulus for each subject. There were two identical trials, one geon changed trial, and one metric changed trial for each of the 128 objects (32 basic-level category objects x 4 versions of each). The order in which the stimuli were presented was chosen randomly with the constraint that the mean presentation position for the geon changed trials equalled that of the metric changed trials. All participants were shown the same presentation order. Participants completed 16 practice trials prior to the actual experiment. None of the practice images were used in the experiment proper.

Results

A modified t-test developed for use in neuroscience to compare a single-case to a small group of controls was used to determine if LB's difference in error rate between the metric change trials and the geon change trials differs reliably from the difference in the

controls' mean error rate between the metric change trials and the geon change trials while at the same time testing to see if LB showed a deficit for the metric change trials or the geon change trials (Crawford & Howell, 1998). The same analysis was conducted on reaction time data.

Error Data. The error data from the different trials of Experiment 2 can be seen in Figure 13. Mean error rates for the identical trials for the control and for LB were 4.6% and 11% respectively. Controls responded same on 50.8% of the trials. LB responded same on 55% of the trials. The fact that LB performed better on the identical trials than the coordinate relations theory would predict is likely due to her showing a slight bias to respond identical. Analysis revealed that LB's difference in error rate between the metric change trials and the geon change trials was significantly greater than the difference in the controls' mean error rate between the metric change trials and the geon change trials, $t(15) = 4.13$, $SE = 3.94$, $p < .0001$. Further analysis revealed that LB's error rate for the metric change trials was significantly greater than the controls' mean error rate for the metric change trials, $t(15) = 6.82$, $SE = 3.34$, $p < .0001$, whereas, LB's error rate for the geon change trials was not significantly greater than the controls' mean error rate for the geon change trials, $t(15) = 0.72$, $SE = 4.45$, $p > .23$. That is, just as the coordinate relations hypothesis predicts, LB made significantly more errors than the controls on those trials that required metrically precise information (32.8% for LB compared to 10.1% for the controls), but LB did not make significantly more errors than the controls on those trials that could be accomplished on the basis of structural descriptions (9.4% for LB compared to 6.2% for the controls).

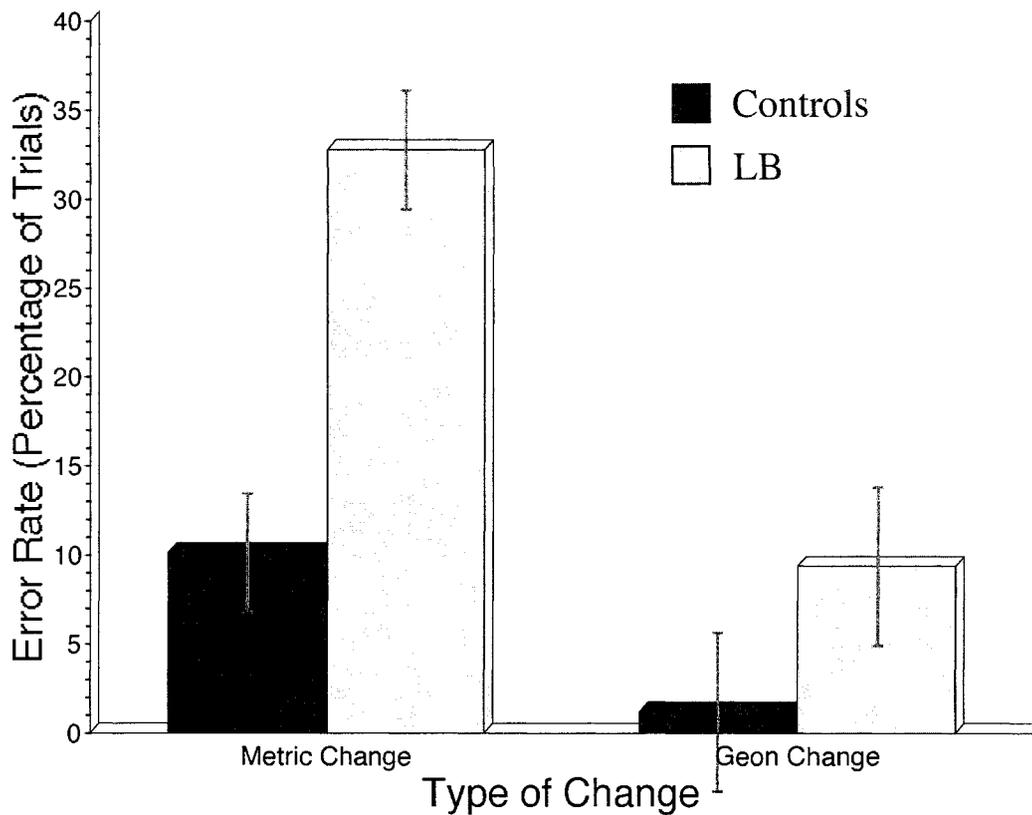


Figure 13. Error rate data from Experiment 2. Error bars represent the average standard error of the mean for the control participants.

Reaction Time Data. Although error rate was the principal dependent measure in these experiments, the response times were analyzed to determine whether the error rate data might be a consequence of speed-accuracy trade-off. The reaction time data from the different trials of Experiment 2 can be seen in Figure 14. Mean reaction times for the identical trials for the control and for LB were 728 msec and 1326 msec respectively. Analysis revealed that LB's difference in mean reaction time between the metric change trials and the geon change trials was significantly greater than the difference in the controls' mean reaction time between the metric change trials and the geon change trials, $t(15) = 2.06$, $SE = 24$, $p < .05$. Further analysis revealed that LB's mean reaction time for the metric

change trials was significantly greater than the controls' mean reaction time for the metric change trials, $t(15) = 10.16$, $SE = 96.90$, $p < .0001$, and, LB's mean reaction time for the geon change trials was significantly greater than the controls' mean reaction time for the geon change trials, $t(15) = 7.13$, $SE = 99.99$, $p < .0001$. That is, LB was significantly slower than the controls on all the trials in the experiment. The reaction time data thus show the same pattern as the error data thus suggesting that the observed pattern in the error data was not due to a speed-accuracy trade-off.

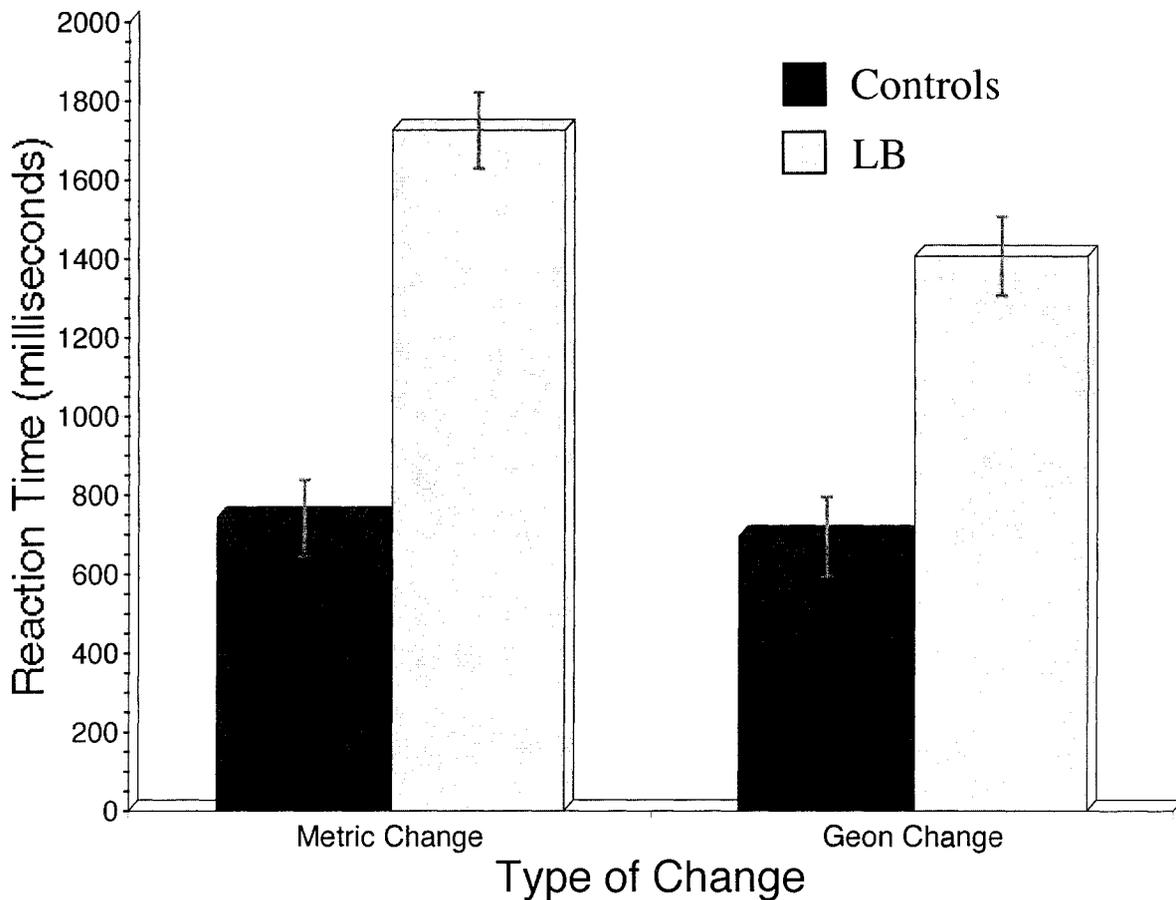


Figure 14. Reaction time data from Experiment 2. Error bars represent the average standard error of the mean for the control participants.

Discussion

The pattern of results from Experiment 2 show that LB had far greater impairment on the metric change trials than the geon change trials relative to the controls. Of the four hypotheses offered to explain the difference between the face recognition system and the basic-level object recognition system, only the coordinate relations hypothesis makes this prediction. Just as the coordinate relations hypothesis predicts, visual recognition tasks that required the use of coordinate relations (the metric change trials) were significantly more difficult for LB than for the controls, whereas, LB performance was close to that of the controls for visual recognition tasks that can be performed using a structural description representation (the geon change trials). As such, the findings of Experiment 2 provide support for the coordinate relations hypothesis and are inconsistent with the leading alternative theories (i.e., the biological recognition hypothesis, the subordinate-level recognition hypothesis, and the expert recognition hypothesis) none of which would have predicted that the metric change trials would be so much more difficult for LB than the geon change trials.

EXPERIMENT 3: PHYSICALLY DISCRIMINATING PURELY METRIC CHANGED
VS. CATEGORICAL CHANGED ABSTRACT LINE DRAWINGS

One of the main problems with most experiments that have attempted to test the biological recognition hypothesis, coordinate relations hypothesis, expert recognition hypothesis, and subordinate-level recognition hypothesis is that the stimuli used cannot be arbitrarily assigned to be in a particular class of objects. That is, real world stimuli are either of a biological nature or of a non-biological nature. And when using real-life stimuli, such as objects and animals, it is very difficult to completely control for differences in previous experience the participants may have with the objects or other variables that might correlate with real world object categories.

The purpose of Experiment 3 was twofold. Recall that a structural description of an object consists of a specification of the primitive shapes presented in the object and the categorical relations among those primitives and that the purpose of Experiment 2 was to determine whether changes in the identity of the geons in an object are easier for prosopagnosics to detect than changes to the parts that do not alter the geon's identities. The first purpose of Experiment 3 was to determine whether changes in the *relations* among the primitives that alter the structural description of the object are easier for prosopagnosics to detect than changes in the relations that do not alter the structural description of the object. The second purpose of Experiment 3 was to test the coordinate relations hypothesis while controlling for other variables that have been theorized to underlie the dissociation in neural visual recognition systems (e.g., biological or non-biological distinction, level of expertise, level of processing) by using nonsense objects (i.e., artificial abstract objects). Experiment 3 utilized abstract nonsense drawings constructed so as to produce two distinct classes of

changes: categorical changes and purely metric changes. The stimuli used in Experiment 3 were constructed from a common set of baseline abstract nonsense line drawings (see Figure 15 for examples of stimuli). Although the categorical changes and purely metric changes were constructed by altering the baseline shapes precisely the same amount metrically, the stimuli were constructed so as to ensure that the structural description of the categorical change shapes differs from that of the baseline shapes but the structural description of the purely metric change shapes maintains the same structural description as that of the baseline shapes. Note that the stimuli were constructed in such a way as to ensure that the only difference between the categorical change stimuli and the purely metric change stimuli was whether or not discrimination between said stimuli and the comparison baseline shape can be accomplished solely via a categorical structural description comparison or whether the comparison would require precise metric information. With stimuli of this nature, the coordinate relations hypothesis predicts that distinguishing a particular baseline shape from its categorical change version would be mediated by the (bilateral) categorical recognition system. In contrast, the coordinate relations theory predicts that distinguishing a particular baseline shape from its purely metric change version would require the use of the coordinate (right hemisphere) recognition system. Thus, the coordinate relations hypothesis predicts that LB should be significantly worse at distinguishing the purely metric change versions from the baseline versions compared to the controls, but should be significantly less impaired for the categorical change versions. The categorical and purely metric changes occurred along three dimensions of relational coding: relative position, relative size, and relative orientation.

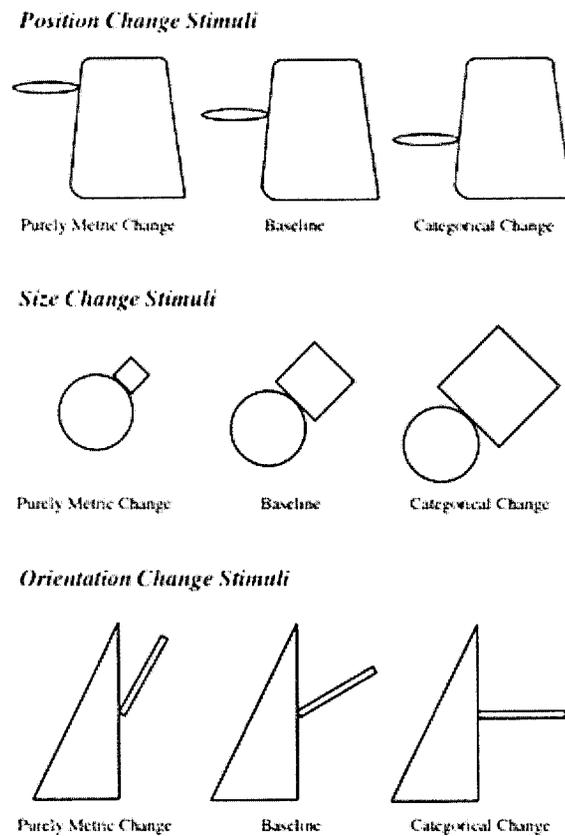


Figure 15. Illustration showing examples of baseline shapes and their corresponding categorical change and purely metric change versions. (Row One: Relative Position Stimuli (structural description of both the baseline and purely metric change version is an ellipse “*above*” and to the “*side-of*” a trapezoid, whereas the structural description of the categorical change version is an ellipse “*below*” and to the “*side-of*” a trapezoid); Row Two: Relative Size (structural description of both the baseline and purely metric change version is a circle “*larger than*” a square, whereas the structural description of the categorical change version is a circle “*smaller than*” a square); and Row Three: (structural description of both the baseline and purely metric change version is a rectangle “*oblique to*” a triangle, whereas the structural description of the categorical change version is rectangle “*perpendicular to*” a triangle). Note that the baseline shapes were modified an equal amount to create both the categorical and purely metric changer versions.

Method

Participants

The participants for Experiment 3 were identical to those of Experiment 1 and Experiment 2.

Apparatus

The apparatus was the same as it was for Experiments 1 and 2. Stimuli for Experiment 3 consisted of black and white line drawings of 108 abstract shapes constructed using Adobe Illustrator 10.0 software. The stimuli were constructed so as to produce 36 baseline nonsense line drawings each comprised of two shapes (a larger, primary shape and a smaller, secondary shape). There were 12 baseline nonsense line drawings for each of the three dimensions (size, position, and orientation). None of the objects resembled any actual object normally encountered in the environment. Each of the 36 baseline nonsense objects was manipulated in such a way as to produce a categorical change version and a purely metric change version (12 baseline objects used to test relative size, 12 baseline objects used to test relative orientation, and 12 baseline objects used to test relative position).

Position Change Stimuli To create the categorical and purely metric changed versions of the relative position stimuli, each secondary shape was moved 1.9 cm up (to create one of the change types) and 1.9 cm down (to create the other change type). (See Figure 16 for examples of the position change stimuli.)

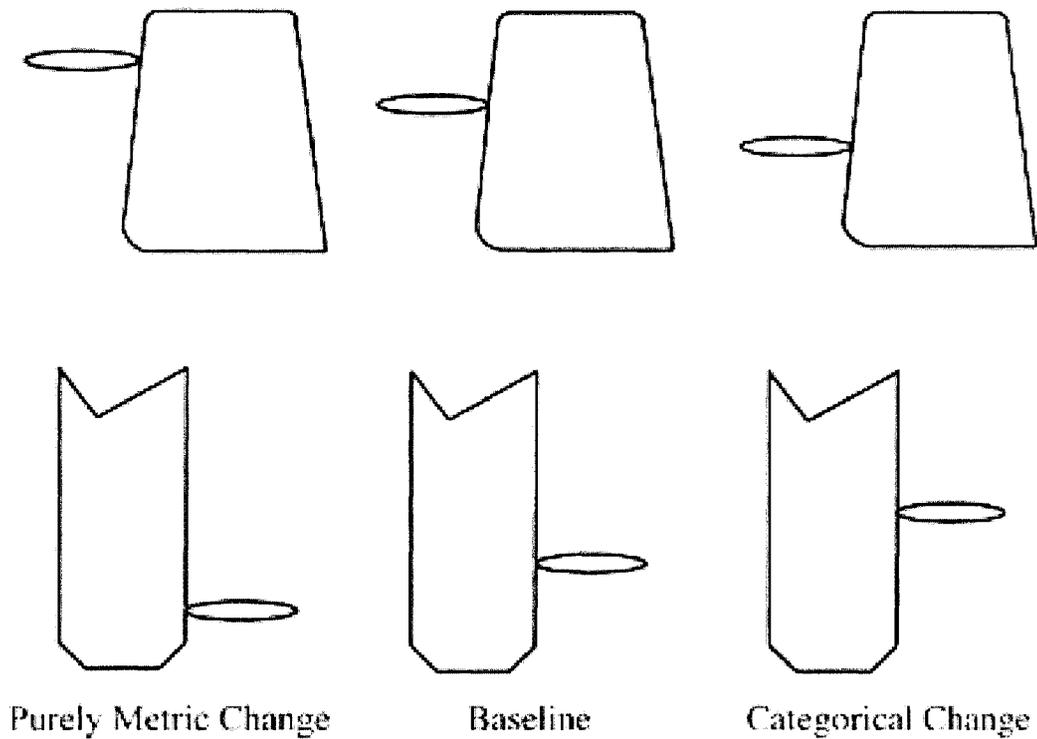


Figure 16. Illustration showing examples of baseline shapes and their corresponding categorical change and purely metric change versions of the position change stimuli. Row One: the structural description of both the baseline and purely metric change version (in terms of relative position) might be an ellipse “*above*” and to the “side-of” a trapezoid, whereas a structural description of the categorical change version (in terms of relative position) might be an ellipse “*below*” and to the “side-of” a trapezoid. Row Two: the structural description of both the baseline and purely metric change version (in terms of relative position) might be an ellipse “*below*” and to the “side-of” a polygon, whereas a structural description of the categorical change version (in terms of relative position) might be an ellipse “*above*” and to the “side-of” a polygon.

Size Change Stimuli To create the categorical change version of the relative size objects, the secondary shapes area was increased by 25% (to create one of the change types)

and decreased by 25% (to create the other change type). (See Figure 17 for examples of the size change stimuli.)

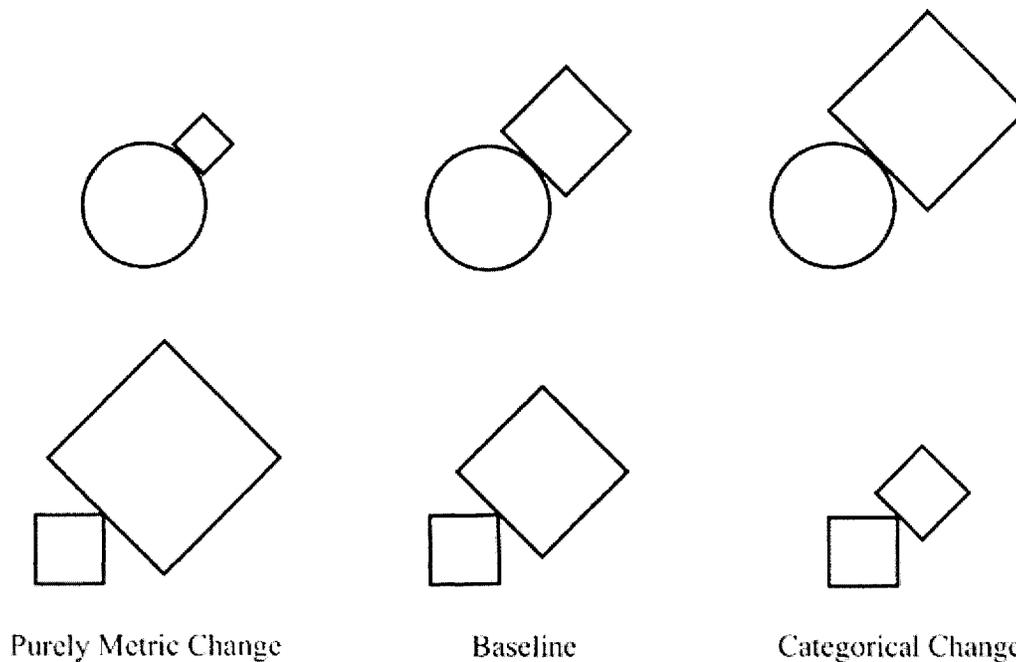


Figure 17. Illustration showing examples of baseline shapes and their corresponding categorical change and purely metric change versions of the size change stimuli.

Row One: the structural description of both the baseline and purely metric change versions (in terms of relative size) might be a circle “*larger than*” a square, whereas the structural description of the categorical change version (in terms of relative size) might be a circle “*smaller than*” a square. Row Two: the structural description of both the baseline and purely metric change version (in terms of relative size) might be a square “*smaller than*” a diamond, whereas the structural description of the categorical change version (in terms of relative size) might be a square “*equal to*” a diamond.

Orientation Change Stimuli Similarly, to create the categorical change version of the relative orientation of the relative orientation objects, the secondary shape was rotated 30°

clockwise (to create one of the versions) and 30° counter-clockwise (to create the other). All stimuli for Experiment 3 were sized so as to ensure their maximum extent fits into a 300 x 300 pixel box. (See Figure 18 for examples of orientation change stimuli.)

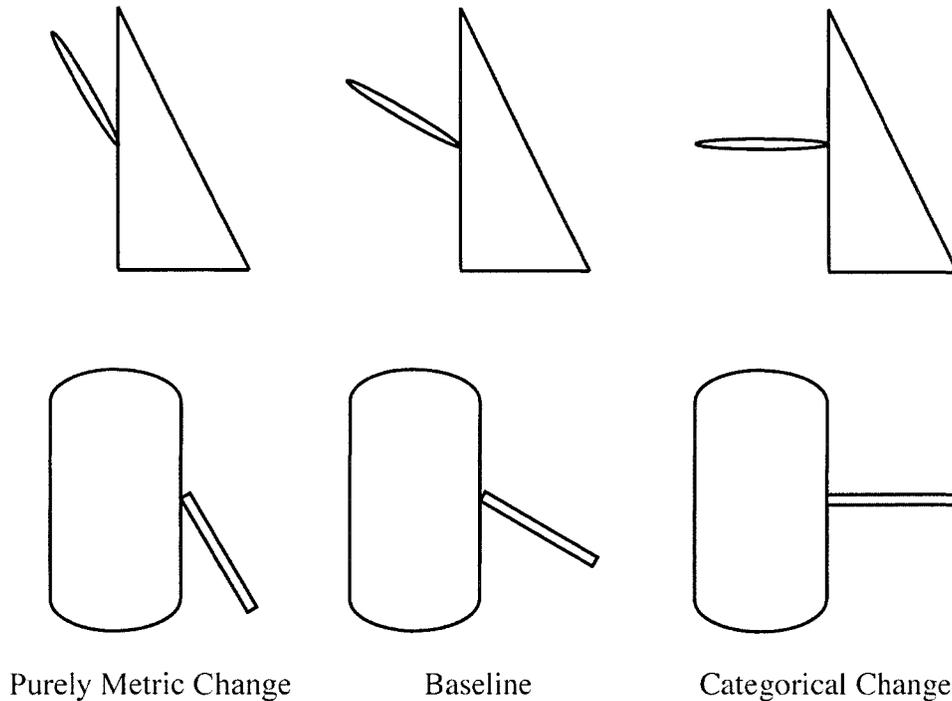


Figure 18. Illustration showing examples of baseline shapes and their corresponding categorical change and purely metric change versions of the orientation change stimuli. Row One: the structural description of both the baseline and purely metric change versions (in terms of relative orientation) might be an ellipse “*oblique to*” a triangle, whereas the structural description of the categorical change version (in terms of relative size) might be an ellipse “*perpendicular to*” a triangle. Row Two: the structural description of both the baseline and purely metric change version (in terms of relative orientation) might be a rectangle “*oblique to*” an ellipse, whereas the structural description of the categorical change version (in terms of relative orientation) might be a rectangle “*perpendicular to*” an ellipse.

Procedure

Presentation of the stimuli was self-paced. Participants pressed one key to begin each trial (participants were instructed to press whatever key was the correct response on the last trial in order to begin the next trial). After pressing one of the keys, a fixation cue was presented on the computer screen for 500 msec, followed by presentation of the first stimulus (one of the baseline shapes) in central fixation for 1000 msec, followed by a pattern mask for 500 msec. The pattern mask was a collection of random lines and served to eliminate any possible after-image from the first stimulus. The pattern mask was followed by presentation of the second stimulus (either an identical image, the purely metric change version of the object, or the categorical change version of the object) until participant response via key press. The second stimulus was randomly presented to one of four possible lateralized positions: 1.5° of visual angle up and 1.5° of visual angle to the right, 1.5° of visual angle down and 1.5° of visual angle to the right, 1.5° of visual angle down and 1.5° of visual angle to the left, or 1.5° of visual angle up and 1.5° of visual angle to the left with all four positions being chosen equally often. Differences in the vertical and horizontal position of the stimuli were used to prevent participants from simply using the height or width of the secondary shape as an indicator of whether or not the two stimuli were identical (i.e., the subject had to compute the relationship between the two parts of the objects in order to complete the task).

The participant's task was to decide whether the second image presented is identical to the first image presented. Participants were instructed to press the "1" key on the keyboard (which was labeled "same") with their left hand if the two images were identical and to push the "0" key on the keyboard (which was labeled "different") with their right hand if the two images were not identical. To ensure that participants put forth sufficient effort

participants received feedback after each trial regarding the accuracy of their response. Note that the participants' task was *not* to decide whether a purely metric or categorical change has taken place between the two objects. The participants' task was simply to decide whether the two objects were physically identical regardless of how they changed.

Experiment 3 consisted of 576 trials. Each of the 36 baseline objects served as the initial stimulus for 16 trials (2 identical trials, 1 categorical change version, and 1 purely metric change version x 4 presentation positions). The order in which the stimuli were presented was chosen randomly with all participants being shown the same presentation order. Participants completed 16 practice trials prior to the actual experiment. None of the practice images were used in the experiment proper.

Results

A modified t-test developed for use in neuroscience to compare a single-case to a small group of controls was used to determine if LB's difference in error rate between the purely metric change trials and the categorical change trials differs reliably from the difference in the controls' mean error rate between the purely metric change trials and the categorical change trials while at the same time testing to see if LB showed a deficit for the purely metric change trials or the categorical trials (Crawford & Howell, 1998). The same analysis was conducted on reaction time data.

Error Data – Three Dimensions Combined. Mean error rates for the identical trials for the control and for LB were 3.5% and 6.8% respectively. Controls responded same on 51.7% of the trials. LB responded same on 53.7% of the trials. The fact that LB performed better on the identical trials than the coordinate relations theory would predict is likely due to

her showing a bias to respond identical. Analysis revealed that LB's difference in error rate between the purely metric change trials and the categorical change trials was significantly greater than the difference in the controls' mean error rate between the purely metric change trials and the categorical change trials, $t(15) = 1.87$, $SE = 4.04$, $p < .05$. Further analysis revealed that LB's error rate for the purely metric change trials was significantly greater than the controls' mean error rate for the purely metric change trials, $t(15) = 2.71$, $SE = 6.61$, $p < .01$, whereas, LB's error rate for the categorical change trials was not significantly different from the controls' mean error rate for the categorical change trials, $t(15) = 0.24$, $SE = 4.63$, $p > .40$. That is, just as the coordinate relations hypothesis predicts, LB made significantly more errors than the controls on those trials that required metrically precise information (28.4% for LB compared to 8.5% for the controls), but LB did not make significantly more errors than the controls on those trials that could be accomplished on the basis of structural descriptions (6.3% for LB compared to 5.1% for the controls).

Reaction Time Data – Three Dimensions Combined. Although error rate was the principal dependent measure in these experiments, the response times were analyzed to determine whether the error rate data might be a consequence of speed-accuracy trade-off. Mean reaction times for the identical trials for the control and for LB were 866 msec and 1569 msec respectively. Analysis revealed that LB's difference in mean reaction time between all the purely metric change trials and all the categorical change trials (regardless of dimension) was significantly greater than the difference in the controls' mean reaction time between the purely metric change trials and the categorical change trials, $t(15) = 2.22$, $SE = 34$, $p < .05$. Further analysis revealed that LB's mean reaction time for the purely metric change trials was significantly greater than the controls' mean reaction time for the

purely metric change trials, $t(15) = 7.12$, $SE = 154$, $p < .0001$. Analysis also revealed that LB's mean reaction time for the categorical change trials was significantly greater than the controls' mean reaction time for the categorical change trials, $t(15) = 3.87$, $SE = 141$, $p < .001$. Although analysis revealed that LB was significantly slower than the controls on all trial types, LB's difference in mean reaction time between all the purely metric change trials and all the categorical change trials (regardless of dimension) was significantly greater than the difference in the controls' mean reaction time between the purely metric change trials and the categorical change trials. Note that the pattern of reaction time data is the same as for the errors, meaning that the error rate data is not a consequence of speed-accuracy trade-off.

Error Data – Position Change Trials. Mean error rates for the identical trials for the control and for LB were 6.2% and 8% respectively. Controls responded same on 48.1% of the trials. LB responded same on 53.3% of the trials. The fact that LB performed better on the identical trials than the coordinate relations theory would predict is likely due to her showing a bias to respond identical. The error data from Experiment 3's position change trials can be seen in panel 1 of Figure 19. Analysis revealed that LB's difference in error rate between the purely metric position change trials and the categorical position change trials was significantly greater than the difference in the controls' mean error rate between the purely metric position change trials and the categorical position changed trials, $t(15) = 4.27$, $SE = 3.90$, $p < .05$. Further analysis revealed that LB's error rate for the purely metric position change trials was significantly greater than the controls' mean error rate for the purely metric position change trials, $t(15) = 2.71$, $SE = 3.69$, $p < .01$, whereas, LB's error rate for the categorical position change trials was not significantly different from the controls'

mean error rate for the categorical position change trials, $t(15) = 0.24$, $SE = 2.11$, $p > .40$. That is, just as the coordinate relations hypothesis predicts, LB made significantly more errors than the controls on those trials that required metrically precise information (27% for LB compared to 3.2% for the controls), but LB did not make significantly more errors than the controls on those trials that could be accomplished on the basis of structural descriptions (2.1% for LB compared to 1.7% for the controls).

Reaction Time Data – Position Change Trials. Mean reaction times for the identical trials for the control and for LB were 872 msec and 1569 msec respectively. The reaction time data from Experiment 3's position change trials can be seen in panel 1 of Figure 20. Analysis revealed that LB's difference in mean reaction time between the purely metric position change trials and the categorical position change trials was significantly greater than the difference in the controls' mean reaction time between the purely metric position change trials and the categorical position change trials, $t(15) = 3.56$, $SE = 45$, $p < .005$. Further analysis revealed that LB's mean reaction time for the purely metric position change trials was significantly greater than the controls' mean reaction time for the purely metric position change trials, $t(15) = 9.41$, $SE = 119$, $p < .0001$. Further analysis also revealed that LB's mean reaction time for the categorical position change trials was significantly greater than the controls' mean reaction time for the categorical position change trials, $t(15) = 4.17$, $SE = 131$, $p < .0005$. That is, LB was significantly slower than the controls on all trials regardless of type. Despite the fact that reaction time was not the principal dependent variable in these studies, note that the pattern of the reaction time data is consistent with that predicted by the coordinate relations hypothesis (and inconsistent with the three other theories). LB showed a 43% increase in her mean reaction time for the purely metric

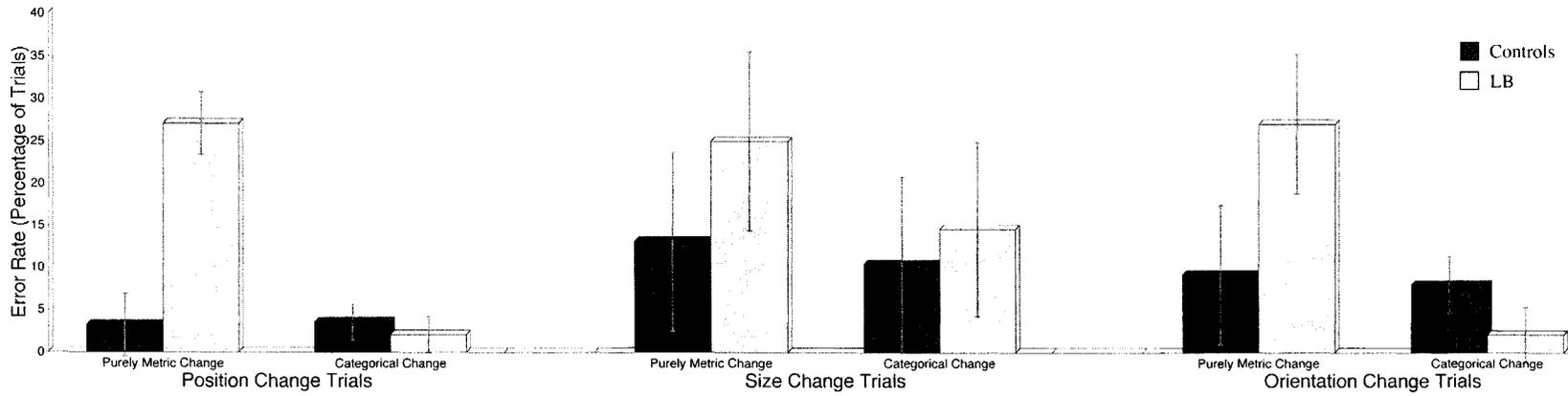


Figure 19. Error rate data from Experiment 3. Error bars represent the average standard error of the mean for the control subjects.

position change trials compared to the categorical position change trials whereas the controls participants showed less than a 1% increase. Note that the pattern of reaction time data is exactly the same as for the errors, meaning that the error rate data is not a consequence of speed-accuracy trade-off.

Error Data – Size Change Trials. Mean error rates for the identical trials for the control and for LB were 2.1% and 6.1% respectively. Controls responded same on 54.8% of the trials. LB responded same on 54.3% of the trials. The fact that LB performed better on the identical trials than the coordinate relations theory would predict is likely due in part to her showing a bias to respond identical. The error data from Experiment 3's size change trials can be seen in panel 2 of Figure 19. Analysis revealed that although in the predicted direction LB's difference in error rate between the purely metric size change trials and the categorical size change trials was not significantly greater than the difference in the controls' mean error rate between the purely metric size change trials and the categorical size changed trials, $t(15) = 0.49$, $SE = 7.75$, $p > .60$. Further analysis revealed that LB's error rate for the purely metric size change trials was not significantly greater than the controls' mean error rate for the purely metric size change trials, $t(15) = 1.12$, $SE = 10.62$, $p > .13$, similarly LB's error rate for the categorical size change trials was not significantly different from the controls' mean error rate for the categorical size change trials, $t(15) = 0.40$, $SE = 10.34$, $p > .34$. Although, these comparisons did not reach significance, note that the pattern is completely consistent with the pattern predicted by the coordinate relations hypothesis (25% for LB compared to 13.1% for the controls for the purely metric size change trials and 14.5% for LB compared to 10.4% for the controls for the categorical size change trials).

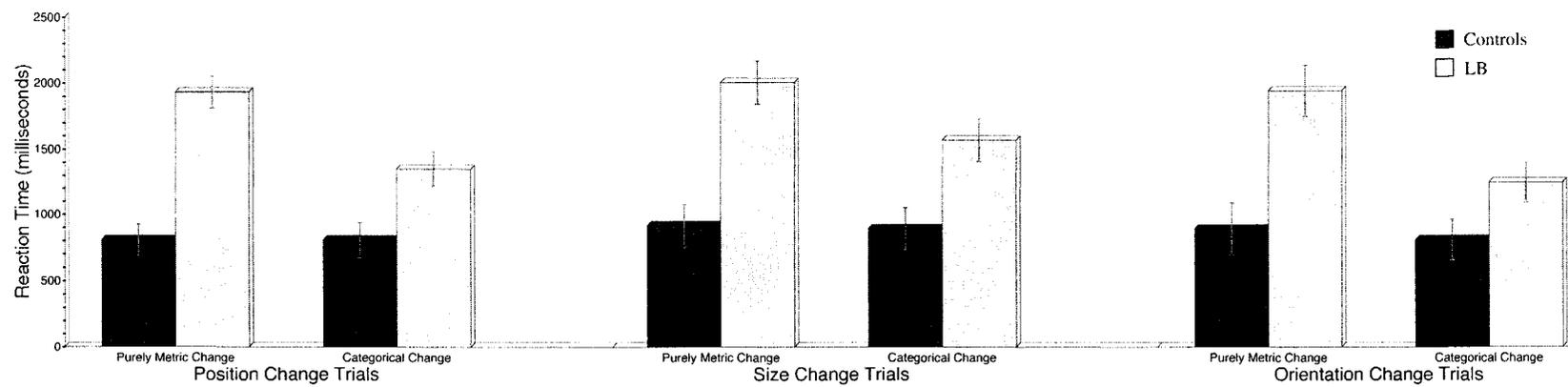


Figure 20. Reaction time data from Experiment 3. Error bars represent the average standard error of the mean for the control subjects.

Reaction Time Data – Size Change Trials. Mean reaction times for the identical trials for the control and for LB were 864 msec and 1642 msec respectively. The reaction time data from Experiment 3's size change trials can be seen in panel 2 of Figure 20. Analysis revealed that LB's difference in mean reaction time between the purely metric size change trials and the categorical size change trials was significantly greater than the difference in the controls' mean reaction time between the purely metric size change trials and the categorical size change trials, $t(15) = 2.39$, $SE = 60$, $p < .05$. Further analysis revealed that LB's mean reaction time for the purely metric size change trials was significantly greater than the controls' mean reaction time for the purely metric size change trials, $t(15) = 7.74$, $SE = 162$, $p < .0001$. Further analysis also revealed that LB's mean reaction time for the categorical size change trials was significantly greater than the controls' mean reaction time for the categorical size change trials, $t(15) = 4.22$, $SE = 161$, $p < .001$. That is, LB was significantly slower than the controls on all trials of the experiment likely as a result of her visual field deficit. Despite the fact that reaction time was not the principal dependent variable in these studies, note that the pattern of the reaction time data is consistent with that predicted by the coordinate relations hypothesis. That is, LB showed a 28% increase in her mean reaction time for the purely metric size change trials compared to the categorical size change trials whereas the controls participants showed only a 2% increase. Note that the pattern of reaction time data is exactly the same as for the errors, meaning that the error rate data is not a consequence of speed-accuracy trade-off.

Error Data – Orientation Change Trials. Mean error rates for the identical trials for the control and for LB were 2.1% and 6.4% respectively. Controls responded same on 52.3% of the trials. LB responded same on 53.5% of the trials. The fact that LB performed

better on the identical trials than the coordinate relations theory would predict is likely due to her showing a bias to respond identical. The error data from Experiment 3's orientation change trials can be seen in panel 3 of Figure 19. Analysis revealed that LB's difference in error rate between the purely metric orientation change trials and the categorical orientation change trials was significantly greater than the difference in the controls' mean error rate between the purely metric orientation change trials and the categorical orientation changed trials, $t(15) = 1.84$, $SE = 6.20$, $p < .05$. Further analysis revealed that LB's error rate for the purely metric orientation change trials was significantly greater than the controls' mean error rate for the purely metric orientation change trials, $t(15) = 2.17$, $SE = 8.25$, $p < .05$, whereas, LB's error rate for the categorical orientation change trials was not significantly different from the controls' mean error rate for the categorical orientation change trials, $t(15) = -0.37$, $SE = 3.30$, $p > .35$. That is, just as the coordinate relations hypothesis predicts, LB made significantly more errors than the controls on those orientation change trials that required metrically precise information (25% for LB compared to 9.2% for the controls), but LB did not make significantly more errors than the controls on those orientation change trials that could be accomplished on the basis of structural descriptions (2.1% for LB compared to 3.3% for the controls).

Reaction Time Data – Orientation Change Trials. Mean reaction times for the identical trials for the control and for LB were 862 msec and 1447 msec respectively. The reaction time data from Experiment 3's orientation change trials can be seen in panel 3 of Figure 20. Analysis revealed that LB's difference in mean reaction time between the purely metric orientation change trials and the categorical orientation change trials was significantly

greater than the difference in the controls' mean reaction time between the purely metric orientation change trials and the categorical orientation change trials, $t(15) = 1.82$, $SE = 78$, $p < .05$. Further analysis revealed that LB's mean reaction time for the purely metric orientation change trials was significantly greater than the controls' mean reaction time for the purely metric orientation change trials, $t(15) = 5.40$, $SE = 195$, $p < .0001$. Further analysis also revealed that LB's mean reaction time for the categorical orientation change trials was significantly greater than the controls' mean reaction time for the categorical orientation change trials, $t(15) = 2.88$, $SE = 153$, $p < .01$. Again, LB was significantly slower than the controls on all trials. Despite the fact that reaction time was not the principal dependent variable in these studies, note that the pattern of the reaction time data is the same as the pattern of the error rate data consistent with that predicted by the coordinate relations hypothesis (and inconsistent with the three other theories). LB showed a 43% increase in her mean reaction time for the purely metric orientation change trials compared to the categorical orientation change trials whereas the controls participants showed less than a 1% increase. Note that the pattern of reaction time data is exactly the same as for the errors, meaning that the error rate data is not a consequence of speed-accuracy trade-off.

Discussion

The pattern of results from Experiment 3 closely matches the pattern predicted by the coordinate relations hypothesis and cannot be accounted for by the current alternatives to the coordinate relations hypothesis for all three dimensions (position, size, and orientation) of change, with all three dimensions showing the same pattern. Just as the coordinate relations hypothesis predicted, visual recognition tasks that required the use of coordinate relations

were significantly more difficult for LB than for the controls, whereas LB's performance was close to that of the controls for visual recognition tasks that can be performed using a structural description representation. As such, the findings of Experiment 3 provide very strong support for the coordinate relations hypothesis and are inconsistent with the leading alternative theories (i.e., the biological recognition hypothesis, the subordinate-level recognition hypothesis, and the expert recognition hypothesis).

Notice that the only difference between the purely metric change trials and the categorical change trials was whether the visual recognition task could be accomplished on a structural description basis. If the visual recognition tasks could be accomplished on a structural description basis (i.e., the categorical change trials), then LB's performance was very close to that of the controls. However, for the visual recognition tasks that required discrimination within a structural description (i.e., the purely metric change trials), then LB's performance was significantly worse than that of the controls. Note that: a) the subject's task was just to determine whether the stimuli were physically identical without regard to the type of change that occurred, b) no subject reported even being aware of the difference between the purely metric change and the categorical change trials and yet, c) changing a dimension the same amount metrically but in such a way that the structural description changes makes a dramatic difference in how easy the task is for LB.

EXPERIMENT 4: KOSSLYN (1987) METRIC TASK VS. CATEGORICAL TASK

In contrast to the categorical/coordinate relations distinction for coding the spatial positions of the primitives in an object representation being discussed previously in this dissertation, Kosslyn (1987) proposed a similar categorical/coordinate distinction in a very different domain. Kosslyn's theory stated that making categorical judgments about the positions of two *different* objects (such as determining if one object is "near or far" to another or "above or below" another) is lateralized to the left hemisphere of the brain, and that making judgments about exact distances between two different objects (such as determining if one object is within 3 mm of another) is lateralized to the right hemisphere of the brain. Typically, a reliable right hemisphere advantage is found when participants are asked to judge exact distances between different objects, and either a left hemisphere advantage or no laterality effect is found when participants are asked to perform categorical judgment tasks between objects (Cowin & Hellige, 1994; Hellige & Michimata, 1989; Kosslyn, Chabris, Marsolek, & Koenig, 1992; Kosslyn, Koenig, Barrett, Cave, Tang, & Gabrielli, 1989; Kosslyn, Thompson, Gitelman, & Alpert, 1998; Rybash & Hoyer, 1992; and Sergent, 1991).

In all the research done to test Kosslyn's (1987) theory, participants were explicitly asked to make either a categorical or a purely metric judgment with a common group of stimuli. In other words, it was a change in the *task* that caused hemispheric differences in all the previous experiments, not a change in the *stimuli*. Further, all the experiments designed to test Kosslyn's theory examined the relations between different objects rather than the coding of the relations of the parts within a single object representation. Experiments 1 – 3 of the current paper also concern categorical vs. coordinate coding, but not between different objects as in the previous studies designed to test Kosslyn's distinction, but rather as a means

of coding the position of the primitives within an object representation. For example, in Experiment 3, the relationships of the primitives within a *single object* were changed so that they either did or did not cross a category boundary, and the subject's task always remained the same: to decide whether two shapes are physically identical (i.e., unlike Kosslyn's tasks, participants were never required to make an explicit categorical or coordinate judgment and indeed were likely unaware of the differences between the two type of changes). One possibility is that the same neural mechanisms that underlie Kosslyn's computation of the relations between different objects may also serve to compute the relations of the primitives in the representation used to recognize individual objects. The purpose of Experiment 4 was to compare LB's and the controls' performance on a Kosslyn-task in which the stimuli stay the same but the task changes with the hope of shedding some light as to whether the same neural mechanisms that underlie Kosslyn's computation of the relations between different objects also serve to compute the spatial positions of the primitives within an object representation.

One piece of evidence suggesting that the mechanism underlying the performance in a Kosslyn metric vs. categorical judgment task is the same mechanism that is used to compute relations during object recognition is data from laterality experiments. Typically, a reliable right hemisphere advantage is found when participants are asked to judge exact distances between different objects, and either a left hemisphere advantage or no laterality effect is found when participants are asked to perform categorical judgments between different objects (Cowin & Hellige, 1994; Hellige & Michimata, 1989; Kosslyn, Chabris, Marsolek, & Koenig, 1992; Kosslyn, Koenig, Barrett, Cave, Tang, & Gabrielli, 1989; Kosslyn, Thompson, Gitelman, & Alpert, 1998; Rybash & Hoyer, 1992; Sergent, 1991;

Wilkinson & Donnelly, 1999). The same pattern of laterality effects is found for face versus object recognition, with face recognition showing a right hemisphere advantage (e.g., Hillger & Koenig, 1991; Leehey, Carey, Diamond, & Cahn, 1978; Levine, Banich, & Koch-Weser, 1988; Rhodes, 1993; see Davidoff, 1982, and Ellis, 1983, for reviews) and object recognition showing either a left hemisphere advantage or no laterality effect (e.g., Biederman & Cooper, 1991; Levine & Banich, 1982; Young, Bion, & Ellis, 1980).

The purpose of Experiment 4 was to see if LB would show deficits on a Kosslyn metric judgment task but not on a Kosslyn categorical judgment task similar to the pattern of deficits displayed in Experiments 1-3. If the same neural mechanisms underlie metric relations between different objects that serve to compute the metric relations of the primitives within an object representation, then LB should show a significant deficit on a Kosslyn metric judgment task but not on a Kosslyn categorical judgment task relative to the controls. If a neurologically distinct mechanism mediates computations of metric relations between different objects than the mechanism that mediates computation of metric relations of the primitives within a single object, then LB should show no deficit on either a Kosslyn metric judgment task or a Kosslyn categorical judgment task relative to the controls.

Method

Participants

The participants for Experiment 4 were identical to that of Experiments 1, 2, and 3.

Apparatus

The apparatus for Experiment 4 was the same as Experiments 1, 2, and 3. Stimuli for Experiment 4 consisted of black and white line drawings of eight stimuli each comprised of a

line and a dot constructed using Adobe Illustrator 10.0 software. The dot was directly above or below a horizontal line at one of eight possible locations (see Figure 21 for illustration).

Stimuli and tasks were identical to the stimuli and tasks used by Sergent (1991).

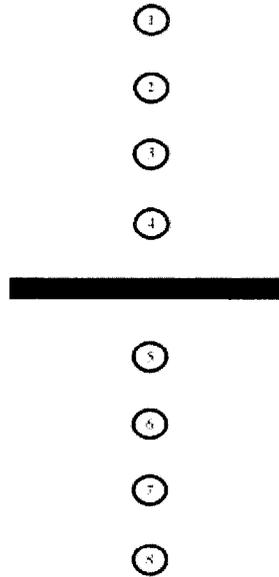


Figure 21. Illustration showing possible position of the dot relative to the horizontal line. Note that stimuli were sized so that positions 1, 2, 7, and 8 were farther than two cm from the line, and positions 3, 4, 5, and 6 were less than 2 cm from the line.

Procedure

Presentation of the stimuli was self-paced. Participants pressed one key to begin each trial (participants were instructed to press whatever key was the correct response on the last trial in order to begin the next trial). After pressing one of the keys, a fixation cue was presented on the computer screen for 500 msec, followed by presentation of one of the eight stimuli in central fixation until participant response. The participant's task for the first block of trials (384 trials) was to determine if the dot was within two cm of the line. The participants were informed to press the "z" key (which was labeled "more/above") with their

left hand if the dot was farther than two cm from the line and to press the “m” key (which was labeled “less/below”) with their right hand if the dot was less than two cm from the line (i.e., a metric task). The participant’s task for the second block of trials (384 trials) was to determine if the dot was above or below the line (i.e., a categorical task). The participants were informed to press the “z” key with their left hand if the dot was above the line and to press the “m” key with their right hand if the dot was below the line (i.e., a categorical task). The presentation order of the stimuli was randomized with all participants seeing the same presentation order. To ensure that participants put forth sufficient effort participants received feedback after each trial regarding the accuracy of their response. Prior to each block of trials participants completed 16 practice trials identical to that of the actual experiment.

Results

A modified t-test developed for use in neuroscience to compare a single-case to a small group of controls was used to determine if LB’s difference in error rate between the metric task trials and the categorical task trials differs reliably from the difference in the controls’ mean error rate between the metric task trials and the categorical task trials while at the same time testing to see if LB showed a deficit for the metric task trials or the categorical task trials (Crawford & Howell, 1998). The same analysis was conducted on reaction time data.

Error Data. The error data from Experiment 4 can be seen in Figure 22. Analysis revealed that LB’s difference in error rate between the metric task trials and the categorical task trials was significantly greater than the difference in the controls’ mean error rate between the metric task trials and the categorical task trials, $t(15) = 4.88$, $SE = 0.83$,

$p < .0005$. Further analysis revealed that LB's error rate for the metric task trials was significantly greater than the controls' mean error rate for the metric task trials, $t(15) = 6.01$, $SE = 1.23$, $p < .0001$, whereas, LB's error rate for the categorical task trials was not significantly greater than the controls' mean error rate for the categorical task trials, $t(15) = -0.79$, $SE = 0.44$, $p > .20$. That is, LB was significantly worse than the controls on those trials that required metrically precise information (9.24% for LB compared to 1.74% for controls) but was not significantly worse than the controls on those trials that could be accomplished on the basis of categorical changes. In fact, LB made fewer errors than controls on the categorical task trials, although this difference did not reach significance (0% for LB compared to 0.35% for controls).

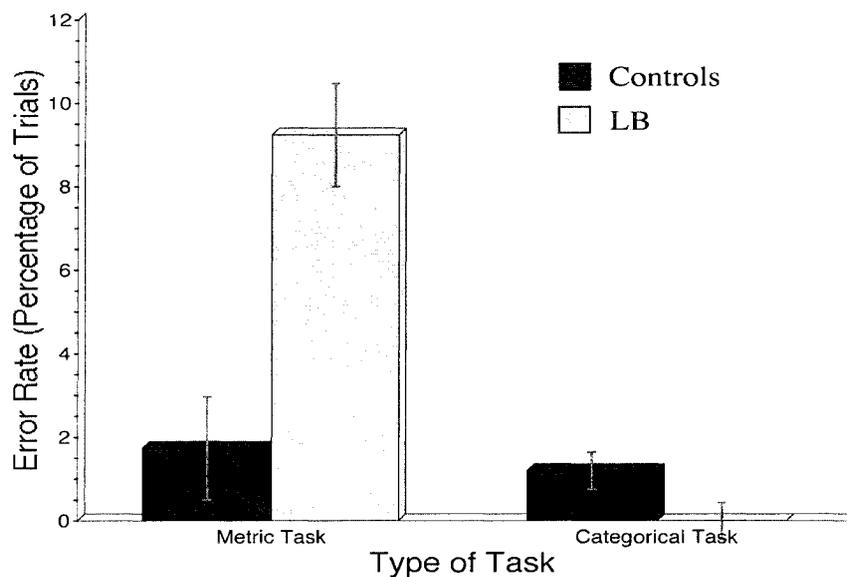


Figure 22. Error rate data from Experiment 4. Error bars represent the average standard error of the mean for the control participants.

Reaction Time Data. Although error rate was the principal dependent measure in these experiments, the response times were analyzed to determine whether the error rate data

might be a consequence of speed-accuracy trade-off. The reaction time data from Experiment 4 can be seen in Figure 23. Analysis revealed that LB's difference in mean reaction time between the metric task trials and the categorical task trials was not significantly greater than the difference in the controls' mean reaction time between the metric task trials and the categorical task trials, $t(15) = 0.14$, $SE = 55$, $p > .89$. Further analysis revealed that although in the same direction as the error rates, LB's mean reaction time for the metric task trials was significantly greater than the controls' mean reaction time for the metric task trials, $t(15) = 4.16$, $SE = 134$, $p < .0005$. Analysis also revealed that LB's mean reaction time for the categorical task trials was significantly different from the controls' mean reaction time for the categorical task trials, $t(15) = 89$, $SE = 89$, $p < .0005$. Thus, the reaction time data do not suggest that the pattern in the error rate data was a consequence of speed-accuracy trade-off.

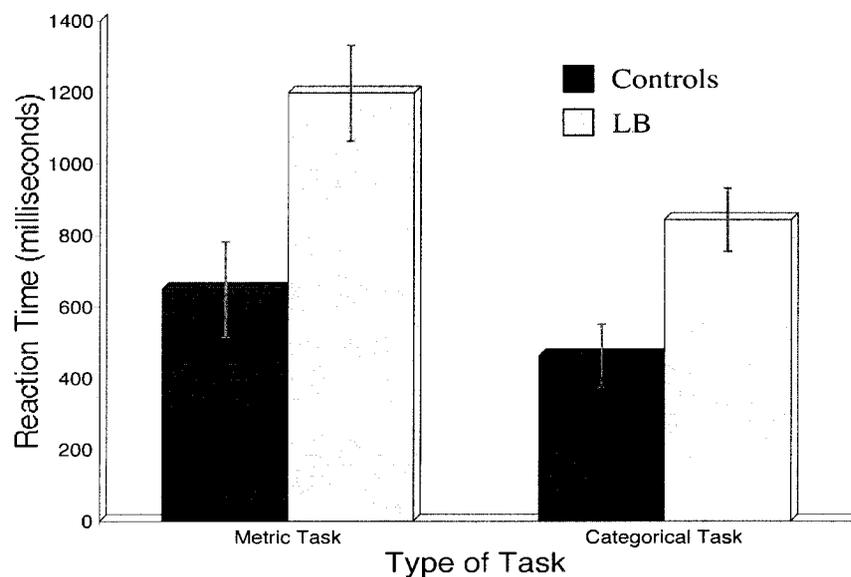


Figure 23. Reaction time data from Experiment 4. Error bars represent average standard error of the mean for the control participants.

Discussion

As was the case with Experiments 1, 2, and 3, in Experiment 4 LB had significantly more difficulty with the coordinate task relative to the categorical task compared to the controls. The finding that LB had significantly more difficulty with coordinate tasks in Experiment 4 and the coordinate trials in Experiments 1, 2, and 3 suggest that the same neural mechanism may mediate coordinate tasks regardless of whether the visual recognition task involves judging the distance between two objects or computing the coordinates of the primitives during a shape recognition task. It is of course possible that LB's difficulties arise from damage to two separate coordinate systems (one that computes the positions of primitives in the representation used for recognition and another that is used to calculate the distances between two different objects), but it is much more parsimonious to posit that both sets of difficulties are due to the loss of a single mechanism for computing distances that mediates both types of tasks. The results also suggest that the right hemisphere advantage found for face recognition may be a consequence of the fact that the representation used for face recognition requires a computation of exact distances and the visual hardware necessary for computing exact distances resides in the right cerebral hemisphere.

GENERAL DISCUSSION

The purpose of this dissertation was to provide a direct test of whether prosopagnosia results from damage to the coordinate recognition system and to test the coordinate recognition hypothesis against the biological recognition hypothesis, the subordinate-level recognition hypothesis, and the expert recognition hypothesis. According to the coordinate relations hypothesis, prosopagnosia results from damage to the coordinate recognition system, which is required for any task that cannot be performed using a structural description representation. Therefore, the theory predicts that any recognition tasks that require discriminating stimuli that share a structural description should be difficult for individuals with prosopagnosia. However, according to the coordinate relations hypothesis, individuals with prosopagnosia should be relatively unimpaired at visual recognition tasks that can be performed using a structural description representation.

In Experiment 1 participants performed an animal discrimination task that fell into two categories: discriminating between two animals species that have different structural descriptions (e.g., discriminating between a dog and a gorilla), and discriminating between two animals species that share a common structural description (e.g., discriminating between a dog and a coyote). The results from Experiment 1 demonstrated that LB made significantly more errors than the controls on those trials that required discrimination within a structural description, but LB did not make significantly more errors than the controls on those trials that could be accomplished on the basis of structural descriptions.

Recall that a structural description of an object consists of a specification of the primitive shapes presented in the object and the relations among those primitives. The purpose of Experiment 2 was to determine whether changes in the identity of the geons in an

object (e.g., distinguishing between a small cylinder topped table and a small brick topped table) are easier for prosopagnosics to detect than changes to the parts that do not alter the geon's identity (e.g., distinguishing between a small cylinder topped table and large cylinder topped table) among stimuli that are all members of the same basic-level class. The results from Experiment 2 demonstrated that LB was easily able to detect changes of the primitives that altered the geon's identity, but LB was severely impaired relative to the controls at detecting changes of the primitives that did not alter the geon's identity.

The purpose of Experiment 3 was to determine whether changes in the relations among the primitives that alter the structural description of the object are easier for prosopagnosics to detect than changes in the relations that do not alter the structural description of the object. In Experiment 3 participants made a physical discrimination between pairs of nonsense objects that were constructed so as to produce two types of changes: purely metric changes (i.e., changes that did not alter the structural description of the object), and categorical changes (i.e., changes that did alter the structural description of the object). The results from Experiment 3 demonstrated that visual recognition tasks that required the use of coordinate relations were significantly more difficult for LB than for the controls, whereas, LB's performance was close to that of the controls for visual recognition tasks that can be performed using a structural description representation.

The purpose of Experiment 4 was to compare LB's and the controls' performance on a Kosslyn (1987) task experiment in which participants were required to make categorical or coordinate judgments about the location of two objects and the stimuli remained the same across tasks. In Experiment 4 LB had significantly more difficulty with the coordinate task trials relative to the categorical tasks compared to the controls. Such findings indicate that

the same neural mechanism may mediate coordinate tasks regardless of whether the visual recognition task involves coding the position of the primitives in the representation used for object recognition or judging the spatial distance between two different objects. These findings provide yet another line of evidence suggesting that what is damaged in individuals with prosopagnosia is the neural structures that code precise metric information.

The coordinate relations hypothesis correctly predicted the results of all of the experiments. That is, just as predicted by coordinate relations hypothesis, LB made significantly more errors than the controls on those trials that required discrimination within a structural description, but LB did not make significantly more errors than the controls on those trials that could be accomplished on the basis of structural descriptions. This is precisely the pattern predicted by the coordinate relations hypothesis.

The pattern of results obtained in Experiments 1 – 4 are incongruent with the current leading alternatives to the coordinate relations hypothesis (i.e., the biological recognition hypothesis, the subordinate-level recognition hypothesis, and the expert recognition hypothesis), none of which would have predicted a difference in discriminations within a structural description and discriminations between different structural descriptions. The position advanced in this paper is not that the nature of the stimulus (e.g., whether it is biological in nature, or the level of categorization, or the level of perceptual expertise) is uncorrelated with whether a visual recognition task is mediated via the neural subsystem that mediates face recognition system. Rather, the position advanced in this paper is that these factors (i.e., the nature of the stimulus, the level of categorization, and the level of perceptual expertise) are neither necessary nor sufficient factors to determine whether a recognition task is mediated by the neural subsystem that mediates face recognition. The position advanced

in this paper is that the critical factor that determines which neural subsystem mediates a given visual recognition task is whether the computational demands of the task are better solved using a coordinate relations representation or a structural description representation. If a given visual recognition task cannot be solved using a structural description representation (e.g., distinguishing between two objects that share the same categorical structural descriptions), then the task must be solved using the coordinate recognition system. If a given visual recognition task can be solved using a structural description representation (e.g., distinguishing between two objects with different categorical structural descriptions), then (due to the computational advantages of the categorical recognition system over the coordinate recognition system discussed previously) the task will be solved using the categorical recognition system.

Note that the biggest advantage that the coordinate relations hypothesis has over the alternative explanations is that it alone offers an explanation regarding how shape representations might differ for the two visual recognition systems. According to the coordinate relations hypothesis, in a coordinate representation the precise distance of each primitive from a fixed reference point or set of fixed reference points is represented, whereas, in a categorical recognition representation the positions of the primitives are specified categorically and relative to the other primitives in the object (i.e., precise locations of the primitives are not specified).

Can Differences in Task Difficulty Explain the Results?

One possible criticism of the conclusions reached by this paper is that perhaps all of the results can be explained by positing that prosopagnosics have great difficulty with any

tasks that neurologically intact individuals find relatively difficult. Note that the controls also made more errors on the metric tasks than they did on the categorical tasks in all the experiments. Thus, perhaps tasks that are a little more difficult for the controls simply become massively more difficult for the prosopagnosic. While this is a legitimate concern, note that only the coordinate relations theory predicts that the metric tasks should be more difficult than the categorical tasks for both prosopagnosics and controls. The metric tasks should be a little more difficult for the controls because they require the controls to use their (less efficient) coordinate recognition system and extremely difficult for the prosopagnosic because her coordinate system is damaged. However, note that the categorical size change comparison in Experiment 3 for the controls was harder than the metric comparison for LB in Experiment 4 (mean error rates of 10.4% and 9.74% respectively). If task difficulty explained all the results, then LB should have shown a deficit for the categorical size change comparisons in Experiment 3 equal to that of her deficit for the metric task trials in Experiment 4, but this was not the case. Also, LB shows a deficit for coordinate recognition system tasks even when the metric change trials were not significantly more difficult than the geon change trials for the controls (e.g., in Experiment 2 and Experiment 3). Thus, the results cannot be explained by positing that prosopagnosics have great difficulty with any tasks that neurologically intact individuals find relatively difficult.

What is Going On with Expertise?

Note that in its current form the coordinate relations theory does not provide an account of the expertise effects that have been observed. For example, the coordinate relations theory does not explain why dog experts show inversion effects for dogs similar to

those found for faces (Diamond & Carey, 1986). Also, the coordinate relations theory does not explain why fMRI studies show that perceptual expertise recruits regions similar to those used in face recognition (Gauthier et al., 2000; Gauthier et al., 1999).

The following is a speculative account for how the coordinate relations theory could explain expertise effects. Expertise might reflect refinement of the coordinate representation for a class of stimuli. For example, a dog expert's coordinate representation system may become more fine grained as the person gains expertise making the individual more sensitive to the features that allow discriminations between dog species. Note that the coordinate relations theory predicts expertise effects should only occur with visual discriminations that occur within a structural description (i.e., only tasks that require the use of the coordinate recognition system). This explains why letters do not show expertise effects although most individuals have substantial expertise with letters. This account of expertise effects has no empirical support at present. However, please note that expertise recognition hypothesis (i.e., that the face recognition system is only used for tasks in which the subject has expertise) cannot account for any of the results of any of the experiments reported in this dissertation.

Implications for Visual Representations

Modern theories of object recognition for the most part can be divided into two groups on the basis of how the primitives of an object are represented and how the relations among the primitives are coded: structural description theories (*parts-based*) and template theories (*holistic*). Structural description theories (e.g., Biederman, 1987; Hummel & Biederman, 1992) posit that objects are represented as a collection of simple volumetric

primitives (e.g., geons) that correspond roughly to the parts of the object, and that the locations of these visual primitives are specified using primitive-to-primitive, categorical relation such as “above”, “below”, and “side-of”. In contrast to structural description theories, template theories (e.g., Bulthoff & Edelman, 1992; Edelman & Weinshall, 1991; Ullman, 1989) typically do not break an object down into its parts, but rather rely on simpler primitives such as edges or pixels, and in template theories the precise location of the primitives are coded via primitive-to-reference point coordinate relations. Over the years there has been great debate over whether human visual abilities are better explained by parts-based or holistic theories, with some camps falling on either side and some camps positing both parts-based and holistic representations (see Hummel, 2000 for a review).

Experiments 2 and 3 provide some of the best evidence ever offered in support of the existence of parts-based representations. Recall that Experiment 2 found that changes to the parts of an object that result in changes in their geons are easier for LB to detect than changes to the parts of an object that do not alter their geon’s identities. Experiment 3 found that changes to the relations among the parts of an object that result in changes to the structural description of the object are much easier for LB to detect than metrically equivalent changes in the relations among the parts of an object that do not alter the object’s structural description. The only difference between the geon change trials and the metric change trials of Experiment 2 was whether the change to the part of an object changed the geon’s identity, and the only difference between the categorical change trials and the purely metric change trials was whether the changes to the relations among the parts of an object alters the structural description of the object. Thus the results of Experiments 2 and 3 are very difficult to explain unless there is a representation at some point in the visual system that explicitly

codes the parts of an object and their categorical relations to one another. In other words, parts-based structural description representations must be used by the human visual system for some tasks.

These results suggest that prosopagnosia represents a damaged coordinate representation system but an intact parts-based representation system. Thus investigations of prosopagnosia can be used to investigate the nature of this parts-based structural description representation system. For example, Biederman's (1987) Recognition by Components theory posits that the primitives that are presumed to underlie basic-level recognition are a set of 36 primitive shapes called geons. Biederman's 36 geons are posited based solely on computational advantages provided by the various geon attributes (e.g., straight vs. curved axis, shape of the cross-section, parallel vs. non-parallel sides, etc.) (see Biederman, 1987 for full details) and have not been empirically tested. If prosopagnosia represents a damaged coordinate relations system but an intact parts-based system, then by investigating the nature of prosopagnosics intact visual abilities one can investigate the nature of the parts-based structure.

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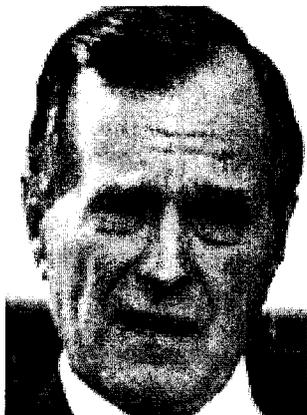
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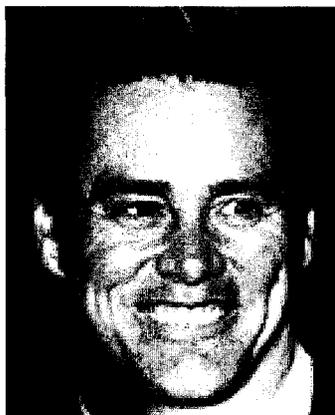
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APPENDIX A. TEST OF PROSOPAGNOSIA



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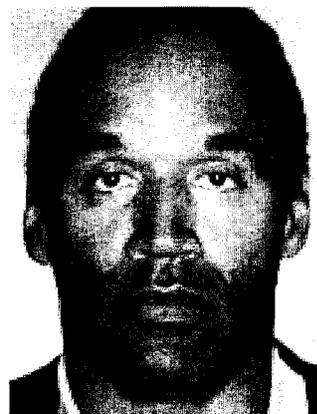
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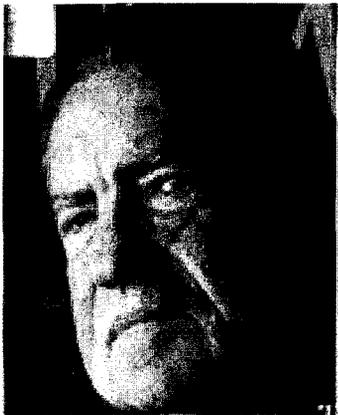
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Test of Prosopagnosia Key:

- 1) George Bush Sr., 2) Jim Carey, 3) Prince Charles, 4) Madonna, 5) Marilyn Monroe,
- 6) Oprah Winfrey, 7) John F. Kennedy Jr., 8) Tom Cruise, 9) O.J. Simpson, 10) Bill Clinton,
- 11) Elvis Presley, 12) Harrison Ford, 13) Mel Gibson, 14) Michael Jackson, 15) Brad Pitt,
- 16) Richard Nixon, 17) John Wayne, and 18) Ronald Reagan.

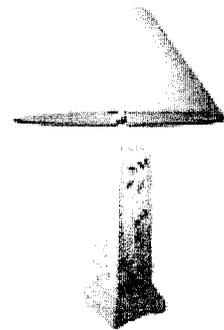
APPENDIX B. TEST OF OBJECT AGNOSIA



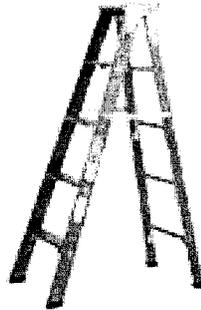
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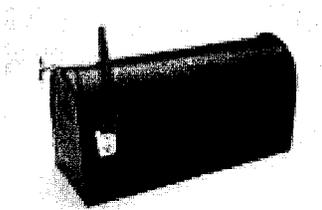
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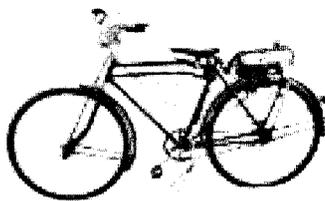
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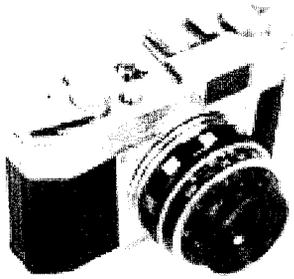
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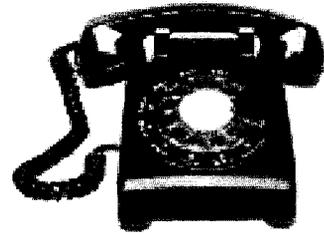
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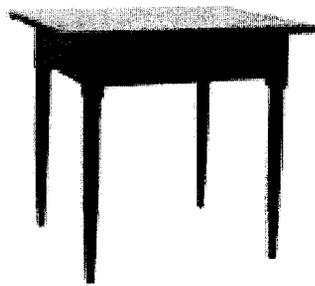
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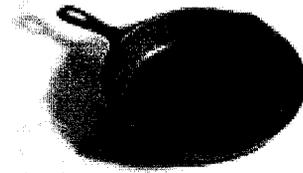
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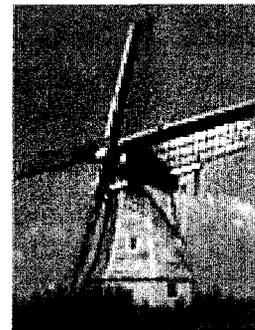
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Test of Object Agnosia Key:

- 1) Airplane, 2) Eyeglasses, 3) Lamp, 4) Ladder, 5) Mailbox, 6) Piano, 7) Bicycle, 8) Gun,
- 9) Car, 10) Camera, 11) Chair, 12) Telephone, 13) Boot, 14) Table, 15) Frying Pan,
- 16) Tennis Racket, 17) Umbrella, and 18) Windmill.