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**A psychobiological exploration of mental rotation in three
groups of children: Control, learning disabled, and Down
syndrome**

Uecker, Anne Cantalupo, M.S.

The University of Arizona, 1991

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**300 N. Zeeb Rd.
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A PSYCHOBIOLOGICAL EXPLORATION
OF MENTAL ROTATION
IN THREE GROUPS OF CHILDREN:
CONTROL, LEARNING DISABLED, AND DOWN SYNDROME

by
Anne Cantalupo Uecker

A Thesis Submitted to the Faculty of the
DEPARTMENT OF PSYCHOLOGY
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Abstract

The present study investigated anomalous hemispheric processing for language and its impact on spatial task performance. Mental rotation and dichotic listening tasks were administered to three groups of children: control (C), learning disabled (LD), and Down syndrome (DS). Significant differences were found in reaction time and accuracy measures in mental rotation. Although the DS group lacked a systematic reaction time function, all three groups produced similar accuracy functions: each group appeared to demonstrate difficulty at equivalent angular disorientations. Dichotic listening resulted in performance differences only when the DS group was compared to the C and LD groups: discrepant language processing was not demonstrated between the C and LD groups. Conclusions could not be reached regarding the impact of language lateralization on spatial task performance. Inconsistencies of neuropsychological measurements are discussed; the topic of mental rotation is explored in depth. Generalizations regarding performance outcomes are limited to a behavioral level.

A Psychobiological Exploration of Mental Rotation
in Three Groups of Children:

Control, Learning Disabled, and Down Syndrome

This paper is concerned with the development of the ability to perform a spatial task, mental rotation, in three populations of individuals: a control group, a learning disabled (LD) group, and a group of Down syndrome (DS) individuals. It starts by considering several aspects of mental rotation, including its basic nature and importance, its developmental progression, and the importance of the reaction time measure. Also examined is the role of imagery. A discussion of the neural structures involved in imagery and mental rotation along with a consideration of the relevant anatomic features of the LD and DS populations lead to speculations regarding performance on this nonverbal task. Special attention is given to the issue of lateralization. The purpose of the present research is to compare performance of the mental rotation task in three populations possessing aberrant patterns of language lateralization. Performance on a spatial task may be affected by the varying degrees of language lateralization present in our population. Mental rotation and dichotic listening tasks are looked at to observe if a systematic relationship exists between the hemispheric demands of spatial and language skills.

Why Study Mental Rotation?

Why study mental rotation? In particular, why study mental rotation in such designated populations as "normal", "learning disabled" (LD), and "Down syndrome" (DS)? Three important reasons are first, it is an elementary spatial skill separate from language; second, it is a skill that undergoes development early in life; and third, it allows an investigator to infer underlying cognitive processes. In sum, mental rotation allows a glimpse into the broader domain of spatial cognition. Examination of mental rotation in our three populations can be expected to shed light not only on spatial development, but on spatial development in exceptional populations.

Mental rotation is an elementary spatial skill. Lohman (1987) states that the core of spatial ability is the ability to create image-coded memories (Anderson, 1983). Shepard (1975) adds that spatial ability requires the conscious performance of an analog operation (i.e. a transformation or rotation) on these images (Shepard, 1975). Spatial skills and abilities comprise an important domain separate from that of language. Although the difference between spatial analog processing and verbal-sequential processing is a fundamental dichotomy in human cognition (Gazzaniga, 1983), research precedence is often given to language. The task of mental rotation allows an insight into this alternate domain of development, namely spatial cognition. It is important to consider "spatial" or

"nonverbal" aspects of intelligence in such groups as the learning disabled and Down syndrome. Most tests that purport to measure intelligence rely heavily on language and associated verbal skills known to be impaired in these populations. Without a consideration of the contribution of spatial cognition, it is difficult to state with certainty that intelligence and ability level are being adequately measured.

Traditionally, tests of spatial abilities are used only as "performance" or "nonverbal" measures. They are not used to predict success in school, and cannot be correlated to success later in life (Lohman, 1987). Lohman (1987) states that "beyond some minimal level of competence, spatial abilities are simply not that important for success in school or work" (p. 182). Lohman leaves several questions unanswered: what constitutes a minimum level of competence?, when is it accomplished?, and what purpose does it serve in terms of learning and getting around in the world? It is important to define a concept such as "minimum level of competence", but further, it is essential to relate this competence to the individual's overall functioning. Spatial skills, of course, develop early, but the correlation with later development is unknown. It is important to look at the progression of spatial development in normal populations, as well as to look at development in populations where it might be delayed. The notion of a

"minimum level of competence" might mean something different applications in these groups. Clues relating to the emergence of everyday behaviors might be found.

An additional reason for studying spatial cognition is that the strength of spatial ability is correlated with other abilities (Lohman, 1987). Spatial abilities may be useful in predicting how problems are represented and solved. To understand spatial abilities may be to understand the basic underpinnings of human thought. For example, in the observation of spatial cognition, one must attempt to grasp how the external world is represented and manipulated within cognitive structures. An investigation of the underlying neural processes comprising the cognition necessitates the understanding of this representation. In studying spatial concepts, there is potential for insight into abstract concepts that neither children nor adults can put into words. Perception of the spatial environment can be looked at with a more complete perspective. Spatial ability can and should be related to the overall developmental scheme.

Mental rotation is a developmental phenomenon. In fact, there is a consensus that all abilities are developed (Anastasi, 1980); disagreement exists, however, when considering how these abilities are developed. Abilities may develop gradually as new knowledge is gained and previous skills are refined, or new skills may result from

new factual knowledge or cognitive skills that differ from those already in the preexisting behavioral repertoire (Lohman & Nichols, 1990). Thurstone (1955, as cited in Lohman, 1987) states that spatial skills show slow and gradual improvement as the individual progresses through childhood and adolescence. A gradual accretion of spatial skills is developed (Lohman et al., 1990). In performing visuospatial tasks, Kinsbourne (1989) holds a maturational component to be responsible for increased proficiency. Young children may deploy a mixed strategy that involves both sides of the brain. Older children, with a more mature neural apparatus, rely more exclusively on the right hemisphere. Therefore, it may be that as the brain matures, the child's representation of the world matures. He is better able to acquire new skills. If a child makes a "mistake" in a task such as mental rotation, it may be incorrect to say that he has committed a perceptual error, rather it is better to maintain the perspective that the child has made a cognitive decision indicative of his level of development (Schaller & Harris, 1974).

Mental rotation is an interesting phenomenon in and of itself. By definition, mental rotation is a process that utilizes mental imagery, an internal, unobservable psychological phenomenon (Dean & Scherzer, 1982). A landmark experiment conducted in 1971 by Shepard and Metzler revealed the internal processes underlying the solution to

mental rotation. Mental rotation offers a behavioral task that quantifies an internal cognitive process, and allows insight into spatial cognition.

Many authors, most notably Shepard and colleagues (see for example Cooper and Shepard, 1973; Shepard, 1975; Shepard & Cooper, 1982) state that mental rotation is an analog process. In an analog process, an external event is preserved in the internal representation. Mental rotation need not imply that something is physically rotating within a person's brain. However, it is implied that the process of mental rotation has something in common with the actual process of a physical rotation (Shepard, 1975; Shepard, 1978; Shepard & Cooper, 1982, Boff, Kaufman, & Thomas, 1986). Péronnet and Farah (1989) state that mental rotation is one of the clearest cases of an analog cognitive process; one isomorphic with the physical process being represented. The primary evidence for this is that the time needed to complete a mental rotation is linearly related to the number of degrees of rotation (Péronnet & Farah, 1989).

Shepard and Metzler's work (1971) implied that mental rotation is a holistic and continuous process, and that a rotated internal representation must pass through a "trajectory" of intervening states between the beginning and the end of the transformational process. Under these assumptions, increasing reaction times with greater degrees of angular disparity reflect the additional time required to

"rotate" an internal representation. The slope of the reaction time curve is often used to estimate the speed of "mental rotation" (Steiger & Yuillie, 1983). The reaction time paradigm in mental rotation has enjoyed widespread use for almost two decades.

What is Mental Rotation?

Much research exists documenting the fact that mental rotation measures an internal cognitive process. The standard mental rotation task consists of a comparison between two figures: a disoriented stimulus figure and a standard upright figure. A subject is asked to decide whether the two figures are the same or different. Both the accuracy of mental rotation and the reaction time required to make the decision are recorded. The classic mental rotation task upon which a majority of the mental rotation work has been modeled is that of Shepard and Metzler (1971). In their task, subjects are exposed to a representation of a three-dimensional block type structure (see figure 1).

Insert figure 1 about here

Two of these configurations are presented to a subject simultaneously, typically at differing angular orientations. The task of the subject is to decide if the stimulus figures are the same or different. If the blocks are the same, they could be rotated to an identical position. If the blocks

differ, this is due to one of them being a mirror image of the other. Shepard & Metzler (1971) used a reaction time paradigm in which they found a linear increase in reaction time as a function of angular disparity. This major finding made the mental rotation paradigm very popular, and one that has since proved very robust (see for example, Cooper et al., 1973; Shepard et al., 1982). Mental rotation has become a paradigm widely applied in basic research on the formation and manipulation of images (Steiger et al., 1983).

Although variants of the mental rotation task exist, all share the basic theme of comparing two figures to see whether they are the same or different. The basic component to this approach is the measurement of reaction time. The stimulus figures used in mental rotation experiments are unlimited. For example, the range of stimulus figure varies from small people holding such objects as umbrellas, tennis rackets, or baskets, to "L" figures, stick figure type mannequins (Farah & Hammond, 1988), variants of stick figure mannequins, alphanumeric characters (Corballis & Sergent, 1988, 1989), and random geometric shapes (Cooper, 1975; Van Strien & Bouma, 1990). The list goes on. In developmental studies stimuli are used that will have maximal meaning to children. For example, plastic toy airplanes (Foulkes & Hollifield, 1989), numerals (Hatakeyama, 1989), ice cream cones with a bite taken from one side or the other

(Hatakeyama, 1989; Marmor, 1977), panda bears (Marmor, 1975) and Mickey Mouse figures (Dean, Scherzer & Chabaud, 1986) have all been used in studies of mental rotation with children.

The Development of Mental Rotation

It is pertinent to consider the process involved in the development of mental rotation. Piaget and Inhelder (1971) investigated the kinetic imagery components of mental rotation. Historically, mental rotation was measured through drawings and tracings rather than through the measurement of reaction time. Piaget and Inhelder (1971) describe experiments in which the ability of children to represent the 90 degree rotation of a vertical rod to the horizontal position was investigated. It was through drawings that Piaget and Inhelder were able to ascertain that children four to five years of age were able to successfully represent oblique angles only 50% of the time, and that it was not until seven years or after that seventy-five per cent of the subjects were successful. Piaget and Inhelder obtained this same finding when using tracing or gestural imitation as a means of measurement (Piaget & Inhelder, 1971). Piaget and Inhelder stated that young children were not able to perform mental rotation tasks because they lacked a kinetic image. They concluded this from the fact that the child showed the rods position to be at only the initial and terminal positions of the

movement. The rod is shown at no intermediate positions. Piaget and Inhelder (1971) concluded that the anticipation of rotation does not come naturally to the young child.

Due primarily to the predominance of mental rotation studies performed with children using reaction time as a mode of measurement (Childs & Polich, 1979; Kail, Pellegrino, & Carter, 1980; Marmor, 1975, 1977), there is skepticism about using children's drawings as an appropriate method of study (Dean et al., 1982). The reaction time paradigm used with children is based upon the method for studying mental rotation in adults (Cooper et al., 1973; Shepard et al., 1971). Nevertheless, results from both drawing studies (Piaget et al., 1971) and reaction time studies (Foulkes, Sullivan, Hollifield, & Bradley, 1989; Kail et al., 1980; Marmor, 1975, 1977) generally agree that proficiency in mental rotation is developed at around eight years of age (Dean et al., 1982). Dean and his fellow investigators, in contrast to proponents of the reaction time paradigm, state that drawings are valid measures of the quality of anticipatory images.

Discrepancies do exist when considering the age at which mental rotation skills develop. For example, Foulkes and Hollifield (1989) found that children from 5 to 6 years could solve mental rotation problems with the accuracy of adults, but that these children did not reliably employ a mental rotation strategy. Their conclusion was based on an

analysis of reaction time functions. However, Marmor (1975, 1977) found that children as young as four years were proficient at mental rotation, producing reliable linear functions. Rosser, Ensing, and Mazzeo (1985) examined this discrepancy by looking at the role of stimulus salience. Their study indicated that children's ability to perform mental rotation tasks is contingent on the number of orientation cues, provided that the discrimination of a reflection is not required. Similarly, Hatakeyama (1989) concluded that in the situation where pairs of concrete figures containing enough orientation cues are presented, the figures can be readily discriminated. It is not true that 5 year old children cannot execute mental rotation.

Linearity within the Mental Rotation Task

The strength of the mental rotation task is that it provides a reliable and predictable measure: an increase in reaction time occurs as a function of angular disparity. Cooper and Shepard (1973) describe their reaction time graph for mental rotation of asymmetrical alphanumeric characters as follows: "from the symmetry of the curve we see that the increase in reaction time resulting from a given angle of tilt is the same for both clockwise and counterclockwise rotations. However, this increase is not strictly linear but concave upward, with the sharpest increase occurring as we approach the completely inverted angle of 180 degrees..." (p. 102). The symmetric form of this mental rotation

function is similar to the curve obtained in other mental rotation experiments (Childs et al., 1979; Corballis, Macadie, & Beale, 1985; Corballis et al., 1988, 1989). In fact, it is typical for a symmetrical curve to result when figures are disoriented with a range from 0 to 360 degrees. A strictly linear one sided function emerges when the mental rotation task employs disoriented figures from 0 to 180 degrees (Dean et al., 1986; Johnston & Weismer, 1983; Kail, 1986; Shepard et al., 1971).

Linearity is of utmost importance to the mental rotation task: it allows one to infer an underlying analog process. However, the concave manner in which the Cooper and Shepard (1973) function sloped upward marked a departure from linearity. They attempted to explain their concave function with reference to a critical angle where mental rotation of the stimulus figure becomes necessary. In other words, it is not always necessary to fully rotate a stimulus to upright in order to make the same-different discrimination (see also Hock & Tromley, 1978). The imaginal representation of the upright stimulus figure in long term memory is broadly tuned: the figure continues to be recognized in positions that deviate from zero degrees. For example, Cooper and Shepard (1973) suggest that the normal-versus-backward discrimination for alphanumeric characters can be made for characters tilted 60 degrees or more without any need of mental rotation.

Cooper and Shepard (1973) further elaborate on their concept of the critical angle by conjecturing that the reaction time function obtained would be completely flat from 0 degrees out to the critical angle and then should climb linearly from that point to 180 degrees. The more concave function typically obtained could be explained by the critical angle changing from subject to subject, from character to character, and maybe even from trial to trial (Cooper et al., 1973). In a description of the function obtained by Cooper and Shepard (1973), Hock and Tromley (1978) write that "the symmetrical reaction time function indicated that the stimuli were rotated through the minimum angle necessary to reach upright" (p. 529). In an experiment looking at the physiological components of mental rotation, Georgopoulos and colleagues state that this is behaviorally meaningful due to the reduction of computational effort (Georgopoulos, Lurito, Petrides, Schwartz, & Massey, 1989). Similarly, there is a reduction in the computational effort involved in mental rotation that results from not rotating a stimulus figure entirely to the upright.

A stimulus can be perceptually upright even though it is not physically upright or in a normal orientation (Hock & Tromley, 1978). Hock and Tromley propose a model of perceptual uprightness to explain the nonlinearity obtained in the mental rotation function. They hypothesize that

mental rotation would be required only when familiar stimuli are disoriented to the degree that they are no longer perceptually upright. Yuille and Steiger (1982) state that if the stimulus is highly familiar and easily managed in the appropriate (upright orientation), then the mental rotation will be performed more efficiently.

The Rate of Mental Rotation

The rate at which a stimulus figure can be rotated seems to vary from stimulus figure to stimulus figure as well as from experiment to experiment. For example, whereas Shepard and Metzler (1971) estimate a rate of approximately 60 degrees per second, Cooper and Podgorny (1976) estimate a rate of approximately 500 degrees per second! The difference may be due to the nature of the stimulus figures themselves. For example, the former experiment utilized a three-dimensional stimulus figure whereas the latter experiment utilized two-dimensional stimuli. Or, the difference may be in the experimental procedure itself. Experimental conditions vary from research project to research project. It is difficult to determine exactly where the variability lies.

Variability may lie with the individuals performing the mental rotation. The process of the rotation itself may present a problem, as might the process of search, encoding, or comparison (Shepard et al., 1982). Rates of mental rotation also vary as a function of stage of development.

For example, Kail, Pellegrino, and Carter (1980) found mental rotation rates to vary from 8.44 msec/deg for fourth graders to 4.92 msec/deg for college students. In addition, Yuille and Steiger's (1982) research indicates a high degree of variability in the rates of mental rotation. Their research found estimated rates of from 31.8 to 272.3 deg/sec in a training task for an experimental group.

Familiarity of the stimulus figure is another factor that will affect the rate of mental rotation: the more familiar the stimulus figure, the easier it will be to perform the mental rotation. It is fairly common to expect that the rate of mental rotation increases with the complexity of the stimulus figure. Young children may find it particularly difficult to rotate unfamiliar and unnamed stimuli. Proficiency is gained with development (Kail et al., 1980). For example, the study by Kail and his colleagues found that children rotated characters from the primary mental abilities test (PMA) more slowly than alphanumeric characters. Children generally need more time to execute processes than do adults (Kail, 1986).

The Role of Imagery in the Mental Rotation Task

Imagery has maintained a central role in the debate concerning the nature of representational processes since the time of Locke (Steiger et al., 1984). Current opinions of imagery vary: Pylyshyn (1979), for example, questions the meaning and utility of the imagery concept, Piaget &

Inhelder (1971) assign imagery a moderate role, and Shepard (1978) asserts the fundamental importance of imagery in human cognition (Steiger et al., 1983) and everyday life. Imagery has been hypothesized to play a role in many kinds of thinking and problem solving. It might be natural to expect that a loss of imagery would necessarily be accompanied by a variety of other cognitive deficits (Farah, 1984).

Imagery is traditionally associated with nonverbal memory and thought (Paivio and te Linde, 1982), and so is classically associated with the right hemisphere. As in the mental rotation literature, the imagery literature is replete with the issue of propositional representation versus analog representation. Again, the analog side states that representational units and structures are perceptual isomorphs of a physical reality, whereas the propositional side of the debate states that the representations are amodal and structurally descriptive in form. Farah (1985) states that mental rotation studies support an array theory in which a surface image preserves the integrality of shape and orientation information in images: subjects cannot match the shape of an image to a stimulus unless the orientation also matches. Whereas this integrality is a natural consequence of an analog format, there is no reason to expect propositional representations of visual stimuli to represent shape and position information (Farah, 1985).

That imagery is "like" perception has led many philosophers and psychologists to propose that some of the same internal structures and processes underlie both forms of representation (Farah, 1985; Kosslyn, 1980). Mental rotation studies tell us about the functional properties of imagery, but we do not know from these studies what might be happening during visual perception. It is possible that imagery activates a set of analog, functionally spatial representations that are reserved solely for short-term visual memory use (Farah, 1985).

How important is the generation of an image in mental rotation? A related question might be: is visual imagery really visual or is it closely related to perception (Farah, 1988)? Writers like Hebb (1968), Shepard (1978) and Finke (1980) assert that visual representations are activated simultaneously with the perceptual event. Other writers (see for example, Pylyshyn, 1979) assert that the recall of visual information is carried out in systems distinctly different from those used in the actual process of "seeing". Actually, findings in neuropsychology indicate support for the use of visual processing areas of the brain in visual imagery, as well as a sharing between visual and perceptual mechanisms (Farah, 1988). Cerebral blood flow studies have found activation in the posterior areas of the brain including the occipital lobe, the posterior superior parietal cortex, and the posterior inferior temporal area

during a visual imagery task (Roland & Friberg, 1985). These areas are important for higher visual processing and are the same areas that normally show increased blood flow in visual-perceptual tasks. Further, EEG and ERP studies have found imagery activity localized to the occipital areas. For example, in the first 200 ms of stimulus processing, ERP activation was localized at occipital recording sites (Farah, P rronet, Gonon, Giard, 1988). These results are exciting because they convey a clear sense that visual imagery uses the same neural representational machinery as vision. Referring to the Ratcliff (1979) study, Paivio and te Linde (1981) say that the right posterior structures are important for mental transformations requiring the manipulation of a visual image. It is likely that the subject of imagery is very pertinent to the study of mental rotation.

A further issue in regard to mental imagery is how close a resemblance it shares with perceptual representations. Existing evidence suggests that 1) imagery shares modality-specific representations with the visual system, and 2) that imagery shares more abstract, amodal representations of stimuli that preserve the spatial characteristics of visual representations (Farah et al., 1988). Farah argues that a specifically neural characterization of mental imagery is supported by experiments involving the detection of letters after they

were imaged. For example, mental rotation experiments demonstrate that imagery, like visual representation, has an analog spatial format (Farah et al., 1988). Farah and colleagues assert, on the basis of ERP findings, that imagery engages visual representations. This is based on the finding that scalp evoked ERP recordings are maximal over the modality-specific visual regions of the brain during a task in which subjects were asked to image a "t", a "h", or nothing at all. Subsequently, these subjects might be presented with a matching image, a nonmatching image or no image (Farah et al., 1988). That imagery and perception interact at a common locus, and that mental imagery accesses stimulus representations in the visual system proper, is implied. The logical next question might be "what areas in the brain share the responsibility for perceptual processing?". With the answer to this question, a better application of visuospatial processing to imagery (or vice versa) can be accomplished.

The Neural Structures Involved in Imagery

A question most often asked is, "what brain structures are responsible for imagery?". The most popular hypothesis is that these structures are preferentially located in the right hemisphere (e.g. Ley, 1983), and perhaps especially in the parietal or parieto-occipito region of that hemisphere. Paivio and te Linde (1982) state that both hemispheres are capable of generating mental images of meaningful objects

and patterns, but that the right hemisphere most probably has the advantage in the case of faces and geometric forms, and that the left hemisphere has the advantage with verbal material. Another view states that the posterior regions of both hemispheres are crucial sites for imagery (e.g. Bisiach, Capitani, Luzzatti, & Perani, 1981). Recently, Farah (1984) and Farah, Gazzaniga, Holtzman, & Kosslyn (1985) have focused on left hemisphere structures in the generation of multipart images.

Paivio (1988) asserts that all of these interpretations are partially correct. Different cortical and subcortical regions in both cerebral hemispheres carry out different imagery functions. The region most active during an imagery task depends on the criteria used to define imagery as well as the type of task used to tap those functions (Paivio, 1988). A straightforward interpretation of such contrasting observations is that nonverbal representations in the left hemisphere are especially likely to be activated and used when the task entails referential activity, as in object identification by naming, imaging to words, and describing images verbally. The right hemisphere imagery functions are revealed by tasks that require nonverbal associative processing or transformation of nonverbal information with minimal verbal involvement. The functional lateralization of referential imagery to the left may be a neuroanatomical consequence of the left hemisphere specialization for

speech. The right hemisphere predominance in certain nonverbal and image-related tasks may be partly a default consequence of the left hemisphere dominance in language functions (Paivio, 1988). Evidence is stronger that the right hemisphere dominates in tasks that require transformation of images, such as mental rotation, or in tasks that require mental organization of complex visual patterns, as in the case of closure tests.

The parietal lobes, occipital lobes, and temporal lobes have all been implicated in the ability to form visual images. Either the left or the right hemisphere can be held responsible (Farah, 1984). Although a specific locus for imagery has been difficult to pin down, Farah (1984) in a comprehensive review of the literature on mental imagery found a region in the posterior section of the left hemisphere to be critical for the image generation process. Farah (1985) offers further support for the role of the left hemisphere in imagery with the case study of a commissurotomy patient. The patient was presented with a letter classification task known to require imagery. Only the left hemisphere was able to perform the imagery task. Similarly, Ehrlichman and Barrett (1983) reviewed the neuropsychological literature concerned with the laterality of imagery and found that although it is commonly believed that image-generation is a right hemisphere function, this is not supported by the data. Instead, the "right

hemisphere" hypothesis applies to spatial abilities and other higher visual perceptual processing. Farah (1984) further states that these image centers might be located close to the posterior language centers of the left hemisphere. More precise information on more individuals with imagery-depriving lesions is needed before specific localizing information can be obtained.

The Anatomical Substrate of Mental Rotation

Mental rotation involves visuospatial abilities, which typically require the parietal cortex. The range of responsibilities of the parietal cortex can be seen in the variety of visuospatial disorders associated with dysfunction in this brain region. For example, one common result is a distorted concept of the body form and its relationship with the external environment; in addition, it is not uncommon for an individual to lose the ability to accurately identify absolute or relative locations, distances and sizes of objects. Difficulties in precise reaching and pointing to objects in extrapersonal space result, as well as more general errors in spatial orientation. Patients have difficulty in performing reversible operations in space. Dressing or constructional apraxias may be apparent. Neglect, loss of the topographical sense, and perceptual rivalry are also common disorders attributed to the malfunctioning of the parietal lobes (Mountcastle, 1978).

Spatial functions are commonly associated with the posterior parietal cortex. The anterior parietal cortex is thought to be involved in primary somatosensory functions. The anterior parietal lobe is composed of Brodman's areas 1, 2, and 3. The posterior parietal cortex incorporates areas 5, 7, 39, and 40. Areas 5 and 7 are known as the superior parietal lobule, and areas 39 and 40 are known as the inferior parietal lobule (Brodman, 1905, as cited in Hyvärinen, 1982). The particular portions of the posterior parietal cortex thought to be responsible for performing mental rotation are roughly Brodman's areas 7 and 40 in the right cerebral hemisphere (Warrington & Taylor, 1973).

Several studies exist which document the role of the posterior parietal cortex in the mental rotation task (Butters & Barton, 1970; Deutsch, Bourbon, Papanicolaou, & Eisenberg, 1988; Feinberg & Jones, 1985; Ratcliff, 1979). For example, in the 1970 study of Butters and Barton, patients with cerebral damage were tested on their ability to perform reversible operations in space. Parietal lobe damage leads to an inability to imagine differing perspectives in regard to some other person or object. That is, patients with such damage are unable to assume the examiner's perspective through a rotation, in thought or imagery, of themselves or of the examiner (Butters et al., 1970). Butters and Barton make the important note that the posterior parietal cortex is the last cortical region to

fully mature and does not do so until the child is five to eight years of age (Geschwind, 1965). This would imply that the ability to perform the mental rotation task does not develop until this age, which in fact corresponds to the developmental literature.

Research by Ratcliff (1979) supports this proposed role of the posterior parietal region. More specifically, he found that patients with right posterior lesions were more deficient on a mental rotation task than were those individuals with left posterior lesions. Osaka (1984) utilized an electroencephalographic (EEG) measure to look at hemispheric differences in arithmetic and visuospatial tasks. An asymmetry in the right hemisphere was reported for the mental rotation task. A further example of the role of the parietal cortex in mental rotation is provided by Feinberg and Jones (1985) who present a case study of a patient with a right parietal infarction demonstrating a dramatic abnormality in the 180 degree rotation of objects in either the vertical or horizontal plane. A later study (Deutsch et al., 1988) measured regional cerebral blood flow in 19 subjects during visuospatial tasks. An asymmetry was found in the posterior parietal-temporal association areas: mental rotation more reliably activated the right hemisphere than either the judgment of line orientation task or the fragment puzzle task (Deutsch et al., 1988). The preceding studies all suggest that the posterior parietal cortex in

the right hemisphere is involved in mental rotation.

Many spatial abilities are modulated by the posterior parietal cortex. These abilities often have concomitant visual components (Mountcastle, 1978). This seems reasonable due to the many visual properties ascribed to the posterior parietal cortex (see for example Motter, Steinmetz, Duffy, & Mountcastle, 1987; Steinmetz, Motter, Duffy, & Mountcastle, 1987). In the case of spatial dysfunction, seemingly parallel defects occur in the visual field. Mountcastle (1978), however, asserts that the root of the disabilities seems to lie within the perceptual domain. Other researchers disagree. For example, Corballis and McLaren (1982) further implicate the "visuo"perceptual nature of the mental rotation task. They suggest that when an individual is actually engaged in the process of mental rotation, directionally sensitive visual mechanisms which underlie the perception of motion are active. The dichotomy between "spatial" and "visual" tasks introduced by the parietal cortex remains an unresolved issue in perception research.

Visuospatial Perception and the Parietal Cortex

An important remaining avenue to explore in regard to mental rotation and visuospatial processing is that of the parietal cortices' role in vision. Mishkin, Ungerleider, and Macko (1983) present evidence suggesting that two cortical visual pathways lead from the striate cortex.

At one time it was thought that visual mechanisms were contained only within the striate cortex. However, we now know that tissue necessary for vision includes prestriate regions of the occipital lobe, as well as the more anterior regions of the temporal and parietal lobes. The evidence of Mishkin and his colleagues (Mishkin, Lewis, & Ungerleider, 1982; Mishkin & Ungerleider, 1982) further suggests that the visual system is segregated into two higher order visual pathways divided upon the basis of the respective striate destinations of the temporal and parietal lobes. The specialty of the first of these pathways is for "object" vision, and the specialty of the second of these pathways is for "spatial" vision (see also Motter et al., 1987).

The visual pathway concerned with spatial vision makes its way through a multisynaptic occipitoparietal projection system that follows the course of the longitudinal fasciculus. This pathway interconnects the striate, prestriate, and inferior posterior parietal areas. It is critical for the visual location of objects in space. It is further postulated that links involving the occipitoparietal pathway with the dorsal limbic and the dorsal frontal cortex may involve the cognitive construction of spatial maps and the visual guidance of motor behavior. This pathway, referred to as the dorsal visual pathway, is directed from the striate dorsally into the parietal lobe. In contrast, the ventral system refers to striate pathways leading

ventrally to the temporal lobe (Mishkin et al., 1983). A unique property of the parietal lobe is that it appears to have convergent input from the other sensory modalities. Sensory inputs from different modalities integrate in the parietal cortex to form the beginning processes of thought and cognition (Kolb & Whishaw, 1990).

Farah, Hammond, Levine, and Calvanio (1988) point out similarities in the locations of visual and spatial representations in visual neurophysiology. Although there is now some agreement that images represent some spatial properties of visual stimuli in an analog format, an issue continuing to divide experimenters is whether the nature of images is best characterized as "visual" or "spatial". For example, Kosslyn (1983) states that it seems clear that some of the same mechanisms are involved in both vision and visual imagery. These mechanisms may link to form a basis for visual perception.

Farah (1985) argues that the idea of separate but similar systems for imagery and perception is not implausible. She suggests it is possible that the imagery system evolved partly as a means for the planning of behavior through the simulation of anticipated events. To accomplish its purpose, it is likely that the imagery system mimicks input from the visual system. However, although these systems share similarities, it is not necessary that imagery and perception share components (Farah, 1985). For

example, Anderson (1978, p. 95) states that images are not tied to the visual modality, but seem to be a part of a more general system for representing spatial and continuously variable information. However, tasks such as selective interference provide conflicting evidence (Baddeley and Lieberman, 1980). It has been found that a nonvisual spatial task interfered with an imagery task, but that a nonspatial visual task did not. An underlying link between visual and spatial representation seems to be implied.

Visual and spatial imagery are two distinct types of representation. Anatomic evidence suggests that normal vision involves parallel, independent systems of object (temporal lobe) and spatial (parietal lobe) representations. This evidence makes more plausible the claim of both visual (object) and spatial representations. It seems natural to conclude that the structure of imagery would parallel the two-component structure of vision. (Farah et al., 1988); this is a "levels of perceptual equivalence" view of imagery (Finke, 1980). The functional architecture of vision is such that the visual appearance of objects and their spatial relations are represented separately and independently by two different perceptual systems (Farah et al., 1988); why not imagery? The link between imagery, mental rotation and spatial tasks in general, and vision awaits further exploration. Much remains to be learned.

Hemisphericity in the Mental Rotation Task

Since mental rotation is a visuospatial ability, it is natural to attribute to the right hemisphere the responsibility for performing this task. Though evidence for this has been found in several studies (Deutsch et al., 1988; Feinberg et al., 1985; Osaka, 1984; Ratcliff, 1979), this interpretation is not without its problems. For example, tachistoscopic experiments produce inconsistent results regarding lateralization of the mental rotation task. In several studies with a commissurotomed subject, a left visual field (LVF) advantage has been found for mental rotation (Corballis et al., 1988, 1989). However, in a study by Voyer and Bryden (1990), visual field (VF) activation changed as a function of level of spatial ability. For example, low spatial subjects were found to have a LVF advantage, subjects with medium spatial ability were found to have no VF advantage, and high spatial ability subjects were found to have a right visual field advantage (RVF). Van Strien and Bouma (1990) found an absence of a VF advantage in a mental rotation task where random shapes were used as stimuli. Similarly, Uecker and Obrzut (1990), found no VF effects in a mental rotation task that utilized stick figures as stimuli. Still other studies (Fischer & Pellegrino, 1988; Mehta, Newcombe, & Damasio, 1987) exist in which a left hemisphere superiority in mental rotation has been found.

Language to the left. Spatial ability to the right.

This is how the brain's abilities are commonly divided. An alternative perspective is to consider each hemisphere's capacity for processing opposing modes of information. The left hemisphere is more proficient at the coding of sequential elements; it is better at analytic processing. The right hemisphere excels at processing information that is holistic or configural in nature (Atkinson, Herrnstein, Lindzey, & Luce, 1988). The possibility of different patterns of organization in each hemisphere has previously been raised by Levy (1969) who described the right hemisphere as a holistic, synthetic processor of information in contrast to the logical, analytic processing of the left hemisphere (Lindgren, 1977).

A common debate in the literature is whether mental rotation is a continuous process, or whether it is performed in a holistic manner (Boff et al., 1986). Although anatomical evidence points to a right hemisphere and holistic approach to mental rotation, the neuropsychological approach of tachistoscopic presentations does not. Is it possible to divide the brain's capacities on the basis of analytical versus holistic functions? Perhaps more relevant, is it possible to divide behavioral tasks on this basis? Must spatial tasks be considered solely holistic in order to be performed predominantly by the right hemisphere? Both sequential and holistic components seem natural elements in mental rotation tasks in that "a rotated

internal representation must pass through a 'trajectory' of intervening states between the beginning and the end of the transformational process" (Shepard et al., 1971). Better definitions of the terms "sequential" and "holistic" as applied to mental rotation seem warranted. Agreement between neuropsychological and anatomical measures would help to resolve arguments such as these.

A further confounding factor in regard to hemisphericity in mental rotation experiments is pointed out by DeRenzi (1982). The easier the labelling of a spatial stimulus, the greater the likelihood of some contribution of the left hemisphere (DeRenzi, 1982). Verbal mediation represents a potential confound in information processing and recall, even when geometrical and highly schematic forms are used. Voyer and Bryden (1990), in their finding of different visual field asymmetries with increasing levels of spatial ability, suggest that the right hemisphere is better at processing novel stimuli, while the left hemisphere is better at processing familiar stimuli. However, alphanumeric characters yield a LVF advantage (Corballis et al., 1988, 1989), whereas geometric forms yield no VF advantage at all (Van Strien et al., 1990). More indepth analyses are needed to determine how stimulus figures affect the lateralization of a behavioral task such as mental rotation. Potential factors, including the hemisphericity of the task, stimulus figures (verbal versus nonverbal or

familiar versus nonfamiliar) and processing demands (analytic versus holistic) need to be explored for possible interaction effects.

Language Lateralization, Dichotic Listening, and the Invasion Hypothesis

Although available evidence is far from conclusively establishing the fact that mental rotation is a right hemisphere visuospatial task, many researchers assert that this is indeed the case. Though spatial functions are usually thought to be located in the right hemisphere, and language is typically located in the left hemisphere, aberrant populations exist in which language is located diffusely throughout both the left and right hemispheres. Sometimes cases are found in which language is located unilaterally only in the right hemisphere.

Dichotic listening tasks, commonly used in the neuropsychological assessment of language lateralization, have predominantly found a right ear advantage (REA) indicative of left hemisphere language in the majority of the population. Similarly, a REA is found in LD populations, although the left hemisphere effect is typically less than that of the common majority. In dichotic listening experiments with DS individuals, many studies have found a reversed ear advantage or a left ear advantage (LEA) indicative of right hemisphere specialization for language. These phenomena, as well as the dichotic listening task

itself, will be explored in more detail in a subsequent section.

Sometimes, when verbal processes "invade" the brain space rightfully belonging to nonverbal processes, visuospatial processes are displaced. Both overall ability level and laterality effects for visuospatial skills are reduced. This is referred to as the "invasion" hypothesis (Fairweather, 1980). The invasion hypothesis has been alternatively referred to as the "crowding effect" by earlier authors (Sperry, 1974; Teuber, 1974) and was originally suggested by Levy (1969). Crowding occurs due to the transfer of language to the right hemisphere following early left brain damage (see for example Basser, 1962); verbal and spatial skills become allocated to the same hemisphere. The result is a competition for space in which language has primacy and develops at the expense of typical right hemisphere abilities.

The "crowding effect" hypothesis is not without its problems. For example, DeRenzi (1982) argues that it is difficult to explain the impairment of both verbal and performance IQ due to the relatively low frequency with which speech is actually taken over by the right hemisphere--even in the case of left sided damage. The crowding hypothesis cannot be applied to adults because they do not have transfer of language to the right hemisphere. DeRenzi (1982) further asserts that this explanation may

account for the impairment of performance measures of IQ in only a small minority of children (DeRenzi, 1982). An alternative explanation is offered by Basso, DeRenzi, Faglioni, Scotti, and Spinnler (1973) who argue that the areas of the left hemisphere involved in language overlap with other areas that have roles in nonlanguage types of intellectual performance. Verbal mediation may be a necessary accompaniment of these cognitive operations. Disruption of language might consequently lead to disruption of nonverbal abilities because of structural limitations and not because of the crowding effect.

Although the crowding effect hypothesis has not received unanimous acceptance, it has intrinsic appeal. For example, that there is only so much space in the brain that can be allocated to language and to spatial functions is an interesting idea. That language has priority status may be questionable, although the fact that language represents a prerequisite and primary human ability is unquestionable. It may actually be that language, though not necessary for physical or intellectual survival, is necessary for social interaction. Thus, due to the evolutionary importance of language, developing brain structures give it precedence in an individual's ontogeny. Spatial abilities, though of substantial import to the intellectual domain, can be sacrificed in order to promote language development.

Corballis and Morgan (1978) offer theoretical support

for the invasion hypothesis. They refer to a left-right maturational gradient that would make certain brain structures more susceptible to injury at certain times during development. Specifically, the more immature hemisphere at the time of injury would be particularly susceptible to crowding effects. Since the left hemisphere matures earlier than the right hemisphere (Geschwind & Galaburda, 1985), one might thereby anticipate crowding effects to be more prominent after early left hemisphere injury. Nass and Peterson (1989) present evidence in support of this hypothesis.

Witelson (1976) agrees with Levy's (1969) hypothesis that crowding of language skills into both hemispheres may result in deficient spatial skills. She attempts to apply Levy's reasoning to learning disabled individuals with reading problems. The crowding effect now occurs due to the diverse representation of spatial skills in both hemispheres. Due to nonverbal processes taking up space in the left hemisphere, the result is poor reading, poor spelling, and often deficient oral language. On the basis of tests of dichotomous tactual stimulation, Witelson (1976) states that there is a greater left hemisphere involvement in spatial processing. Further support for diffuse processing of spatial skills comes from a tachistoscopic study in which a lack of visual field differences for spatial stimuli was found in a group of dyslexic boys as

compared to a control group.

The concept of the invasion hypothesis warrants more in-depth exploration. It is possible that language lateralization exerts an influence on the performance of spatial tasks. If this is the case, then individuals with language most strongly lateralized to the left hemisphere will have strong spatial skills; individuals with language more diffusely represented in both hemispheres will have more trouble with spatial tasks; and individuals with "reversed" specialization for language will fare poorly on tasks such as mental rotation. Tenets of the invasion hypothesis can be explored in control, LD, and DS populations. "Crowding" of language is a variable that may explain differential performance in a task such as mental rotation. A further consideration of the anatomical features of the LD and DS brain is necessitated.

Neural Considerations in Regard to Learning Disabilities

In the late 19th century the left angular gyrus was thought to serve as the "visual memory center" for words (Spreeen, Tupper, Risser, Tuokko, & Edgell, 1984); damage in this area was held to be responsible for visual word blindness. Investigations of this region (Brodmann's area 39 in the posterior cortex) may be warranted in the case of both language and spatial abilities, especially in regard to such cases as developmental dyslexia.

The cause of developmental dyslexia is unknown.

Learning disabled individuals comprise a group consisting of various deficits and etiologies. Hier and colleagues (1978) applied the technique of computerized brain tomograms to the brains of 24 dyslexic individuals. In none of these individuals was evidence of brain injury found. However, results did reveal that ten of the dyslexic patients had brains that were wider in the right parietooccipital region than the left, eight patients had brains that were wider on the left, and six patients were found to have brains that were symmetrical. This contrasts to the finding that this area is wider on the left side in the majority of the population. A study by Geschwind and Levitsky (1968) showed that the posterior portion of the temporal lobe, the planum temporale, is larger on the left side in most brains (see also Witelson & Pallie, 1973).

Hier and colleagues speculate that the greater size of the left posterior region may provide a more favorable anatomical substrate for the development of language in most people (Hier et al., 1978). Of interest is the fact that Hier and colleagues found individuals with reversed asymmetry to have a significantly lower verbal IQ (by 12 points) than the other dyslexic subjects. They caution against misinterpreting these results. The incidence of reversed asymmetry in the population is approximately 10 to 12%. Although the reversal of asymmetry may be a risk factor leading to dyslexia, it should not be expected that

these individuals will necessarily have dyslexia or a verbal disability.

CT scans of LD individuals commonly reveal no irregularities (Denckla, LeMay, & Chapman, 1985). However, when irregularities are present they often occur in the form of cerebral asymmetries (i.e. smaller left hemisphere) or in the form of pathology in posterior cortical association areas critical for visual-verbal processing (Bigler, 1989). Kinsbourne (1989) states that the left hemisphere may be structurally compromised in such cases. Geschwind and Galaburda (1985) postulate that abnormalities in LD populations are related to alterations in both cortical and subcortical structures that result from impaired neuronal migration and assembly. At this time, it appears that normal asymmetrical development, with left hemisphere dominance for language and right hemisphere dominance for spatial processing, is somehow arrested in the dyslexic individual (Selz & Wilson, 1989).

In another study, Hynd, Semrud-Clikeman, Lorys, Novey, & Eliopoulos (1990) further examined lateralization patterns in dyslexic brains using magnetic resonance imaging (MRI). Hynd and colleagues found that in 90% of the dyslexics the left hemisphere was less than or equal to the right hemisphere in terms of the length of the planum temporale, a very significant increase over base rates. Dyslexics consistently showed a decrease in the size of regions known

to be implicated in language and in regulation of motor control and attention (left planum, bilateral insular regions, and right anterior region). A deviation in normal patterns of brain development was implied (Hynd et al., 1990). A question remains as to whether or not this leads to deficits in the visuospatial realm (Pirozzolo, 1979); further research into the relationship of the bilateral posterior cortex in the region of the angular gyrus and its relationship to reading and dyslexia is needed (see Golden, 1982) as well as more research into deviations of plana morphology in dyslexics and neurolinguistic functioning (Hynd et al., 1990).

Although anatomically there seems to be support for the view that representation of language in LD may be weaker, more diffuse, or even reversed, neuropsychological studies utilizing the dichotic listening method generally have not substantiated these claims. In fact, dichotic listening studies usually result in a REA or left hemisphere language specialization in LD individuals. For example, Witelson (1976) had no a priori reason to suspect that a REA would not show up in a dichotic listening task administered to LD individuals. Her findings were as expected: an REA was found in her group of LD individuals as well as in the control group of individuals. An interesting finding of her research, however, was that overall accuracy in the identification of the dichotic stimuli (in this case,

digits) was significantly greater in the control group as compared to the LD group. Witelson (1976) indicated that a disorder in left hemisphere functioning might be present.

More recent studies of dichotic listening question the traditional explanation of LD individuals having incomplete or delayed cerebral lateralization (Hynd, Orbrzut, Weed, & Hynd, 1979). Dichotic listening studies, in general, appear to yield inconsistent results. For example, studies exist that do not demonstrate atypical laterality or phonetic processing (for example, Dermody, Mackie, & Katsch, 1983), whereas other studies produce positive evidence. Swanson & Mullen (1983) in an assessment of word recall effects found LD children to have an atypical pattern of left ear (right hemisphere) and both ear advantage for words. However, nondisabled children were found to have a right ear (left hemisphere) advantage for words. These authors maintain that observed asymmetries in dichotic performance do not reflect structural or strategic deficits in a straightforward manner.

Other dichotic listening studies have employed a free recall paradigm as well as dichotic conditions of "directed left" and "directed right" (Obrzut, Conrad, & Boliek, 1989; Obrzut, Conrad, Bryden, & Boliek, 1988; Obrzut, Obrzut, Bryden, & Bartels, 1985). In the free recall paradigm, LD individuals typically demonstrate a REA. Although the REA produced in some cases is weaker, it is also not unusual for

the LD individuals to recall as many or more of the stimuli presented to the right ear than the control individuals. Laterality effects tend to result due to the inability of LD individuals to maintain a REA when attention is directed to the left ear. These results are interpreted to indicate that LD children are not as lateralized for speech discrimination processes, and that they are more susceptible to attentional bias (Obrzut et al., 1985, 1988, 1989).

Neural Considerations in regard to Down Syndrome

Mental retardation has been frequently defined as representing uniform impairment in all domains of cognitive functioning (Bihrlle, Bellugi, Delis, & Marks, 1989). This may be due to pervasive structural anomalies being present throughout diverse brain regions. The DS brain is typically described as round with a shortened frontooccipital diameter and a steeply ascending occiput (Blackwood & Corsellis, 1976; Kemper, 1988; Zellweger, 1977). And although the contribution of the lobes of the brain have not been fully analyzed with respect to the size of the brain (Kemper, 1988), both Benda (1971) and Crome and Stern (1972) have commented on the hypoplasia of the frontal lobes. Crome and Stern (1972) further elaborate on the frontal lobes in relationship with the cerebellar middle lobe. The relationship between these two areas include the fine movement control of hands, fingers, lips, tongue, and vocal cords. Both of these areas are small and incompletely

developed in the newborn infant. In normal infants, these areas grow rapidly. This is evidenced both by neurochemical research as well as by simple observations of behavior. The growth of these areas can be observed neither anatomically nor behaviorally in the DS infant. The growth of these areas is slow and lags behind the progress made by the normal individual. These areas seem to remain incomplete in the DS individual (Crome and Stern, 1972).

Benda (1971) has also noticed a compression of the occipital lobes. Similarly, Benda (1971) has noted the decreased size of the cerebellum and brainstem (Crome, Cowie, & Slater, 1966). These areas often remain hypoplastic throughout life. Hypoplasia is also apparent in the operculum and the superior temporal lobe (Zellweger, 1977). Ross, Galaburda, and Kemper (1984) in an attempt to further study the superior temporal gyrus, encountered a difficulty due to the distorted appearance of the architectonic areas. Rather than cell numbers simply being decreased, these authors speculated upon the absence of a particular cellular element (Ross, Galaburda, & Kemper, 1984). A narrowed superior gyrus is a consistent finding affecting approximately 50% of DS brains (Blackwood et al., 1976; Zellweger, 1977). Further, the narrowed superior temporal gyrus is six-tenths more likely to occur in the left hemisphere (Kemper, 1988).

The layers comprising the cerebral cortex of the DS

brain are less distinguishable than in normals. Areas can display either dense neuronal packing or a lack of neuronal elements. Where neuron packing does occur, the neurons take on an immature appearance. Irregularities in the neuronal population are especially noteworthy in the third cortical layer (Zellweger, 1977). A reduction in the number of neurons was described early in the century by Davidoff (Davidoff, 1928). He noted a reduced number of neurons in the third cortical layer of the temporal, frontal, parietal, and occipital lobes.

More recent studies have directed their attention to the visual cortex (Becker, Armstrong, & Chan, 1986; Takashima, Becker, & Armstrong, & Chan, 1980; Wisniewski, Laure-Kamionowska, & Wisniewski, 1984). Takashima and colleagues (1980) counted the number of dendritic spines and looked at the difference between the spines of normal infants and the spines of the DS infants. In preterm infants, no differences in kind or number could be detected, whereas in the full term infant, there was a slightly reduced number of dendritic spines in the DS infants. The spines were also short and thin. By the time the infants were four months old, dendritic spines were significantly reduced in number as well as being long and thin. Twenty to fifty percent fewer neurons were found in the visual cortex of sixty DS brains aged birth to fourteen years (Wisniewski et al., 1984).

Dichotic listening tests have yielded some very interesting results in DS subjects. For example, they suggest that language is lateralized to the right rather than the left hemisphere in DS individuals. This is suggested by the LEA obtained in dichotic listening tasks with DS individuals (Hartley, 1981, 1982; Pipe, 1983; Zekulin-Hartley, 1983) in contrast to the REA usually found in the normal population (Bryden, 1988). Due to the use of ear advantage as an index of laterality, an early theory prompted by the use of the dichotic listening tests with DS subjects postulated reversed lateralization or asymmetry for brain functions (Hartley, 1981). In other words, left hemisphere functions were subsumed by the right hemisphere in DS individuals, and right hemisphere functions were subsumed by the left hemisphere. Although the finding of an LEA in dichotic listening tasks in DS subjects was confirmed by subsequent researchers (Bowler, Cufflin, & Kierna,, 1985; and Elliott, Weeks, & Elliott, 1987b; Sommers & Starkey, 1977), the idea of a general hemispheric reversal of function has not held up.

Dichotic listening studies have also looked at the ear advantage for environmental sounds. The recognition of environmental sounds is accomplished mainly through the work of the right hemisphere. If the cerebral hemispheres were functionally reversed, a dichotic listening task using environmental sounds would be expected to yield a REA, thus

localizing the identification of environmental sounds in the left hemisphere. In fact, DS subjects showed a strong LEA and therefore right hemisphere superiority for recognition of environmental sounds (Bowler et al., 1985), refuting the idea of a true reversed asymmetry.

Subsequent researchers have explored language lateralization through methods other than that of dichotic listening. For example, finger tapping studies (Elliott, 1985; Elliott, Weeks, & Jones, 1986), a rod orientation task (Elliott, 1986, as cited in Elliott et al., 1987b), a dichotomous stimulation task (Elliott, 1986), and dual task performance focusing on speech production as opposed to speech reception (Elliott, Edwards, Weeks, Lindley, & Carnahan, 1987a) have led investigators to propose the idea of a unique pattern of cerebral organization rather than a reversed asymmetry of function in the DS population. While the reception of speech seems to be located in the right hemisphere, Elliott et al. (1987b) propose that speech production is located, as usual, in the left hemisphere. Further studies are needed in order to provide a more clear anatomical base in the study of behavioral relationships. An examination of the validity of these dichotic listening tasks will follow in a further section.

Although the morphology of the DS brain has been examined, little is known about how disturbed neurologic function translates into abnormal behavior. Several authors

(Bellugi, Bihrlle, Jernigan, Trauner, & Doherty, 1990; Bihrlle et al., 1989; Jernigan & Bellugi, 1990; Trauner, Bellugi, & Chase, 1989) have used DS subjects not as a focus for study but as a comparison sample to another group of mentally retarded individuals, William's syndrome. This comparison has led to DS subjects being studied in depth with such techniques as magnetic resonance imaging (MRI), and in terms of intelligence and performance on spatial measures of intelligence. As a result of such concentrated examination, a dissociation in hierarchical spatial visual processing has been found. Spatial abilities are a subject that has undergone little examination in DS subjects; the studies of Bihrlle and her colleagues (1989), as well as the studies of Bellugi and colleagues look at specific aspects of visuospatial functioning. DS individuals were found to be grossly impaired on a battery of visuospatial tasks; however, through a close examination of drawings of the two mentally retarded groups, it was shown that DS individuals were more proficient at the skill of global or gestalt representation of an object. It was found that DS individuals consistently represented the global figure at the expense of the local details of the stimulus (Bellugi et al., 1990). For example in a 1989 study (Bihrlle et al., 1989) two groups of mentally retarded subjects (again William's syndrome [WS] and DS subjects) were asked to replicate a global stimulus form (for example an arrow) that

was comprised of several smaller local stimuli (for example, dashes). In other words, the shape of an arrow was formed from a series of many small orderly dashes. DS individuals ignored the smaller local forms (dashes) and replicated only the overall global form of the arrow in a heavy solid line. This was in exact contrast to the WS subjects who instead produced only a series of dashes, in no particular arrangement. This research suggests that DS individuals were performing in a manner comparable to that predicted for left-hemisphere lesioned patients. In contrast, WS individuals acted as right-hemisphere lesioned individuals should. These results suggest a relationship between language and visuospatial processing (Bihrlé et al., 1989). Patients with left-hemisphere lesions typically depict general configurations with little internal detail.

Measurements of Lateralization using Dichotic Listening

Ear asymmetries in dichotic listening tasks and actual hemispheric specialization for speech or language processing often do not correspond (Satz, 1976, 1977). Although the base rate as determined by response to intracarotid sodium amytal injections for speech or language processing is .95 for right-handed adults, the probability of showing greater accuracy on dichotic listening tests in the right ear is only about .70 for this same group. This probability is even lower in children. Satz calculated that the probability of having left hemisphere speech is .97 given a

REA and still a very high .90 given a LEA. Thus the probability of having right hemisphere speech, even given a left ear advantage, is only .10. (Satz, 1976, 1977). The usefulness of dichotic listening tasks appears to rest on determining the relative degree of hemispheric specialization rather than identifying whether an individual has a left or right hemisphere specialization for processing language. This requires viewing specialization on a continuum instead of in an either-or fashion (Lindgren 1977). For example, in our populations of control, LD, and DS individuals, it might be stated that along a continuum of language lateralization, the majority of the population, represented by the control group in our experiment, has language located most strongly in the left hemisphere; the LD group, although having a left hemispheric propensity for language, has language situated more weakly here, and the DS individuals, although displaying a LEA indicative of right hemisphere language, has an even weaker representation of language in the left hemisphere.

Insert figure 2 about here

Ironically, handedness might be regarded to fall along the same continuum in these populations (see Bishop, 1990; Kinsbourne, 1988). Normal individuals in the general population are predominantly right-handed, LD

populations tend to have a greater number of left-handers, and DS populations tend to have even more left-handers. Handedness, like language, is most appropriately regarded as a continuum ranging from strong right handedness across mixed handedness to strong left handedness (Hardyck & Petrinovich, 1977).

Most investigators have failed to show a relationship between lateral preference and linguistic competence (Satz, 1976; Rourke, Bakker, Fisk, & Strang, 1983). Witelson (1976) states that although there are some studies that attempt to make a case for an abnormality of cerebral dominance, most studies usually involve statistically nonsignificant differences between poor reading and control groups. Most studies in fact support the view that LD children with learning problems have left hemisphere specialization for language. Satz (1976) reviewed much of the literature on dichotic listening experiments with LD individuals and found inconsistent results. Though some studies do indeed fail to find a lack of a significant REA in LD individuals, a good proportion of the studies do find a significant REA. In the meantime, Orton's (1925, 1937) original theory of anomalous dominance in the LD population still awaits the advent of more sophisticated technology in order to be confirmed or disconfirmed. Kinsbourne (1989) states that due to the propensity of dichotic listening studies in LD individuals to find normal laterality, the

possibility that a lack of left-sided language can explain reading disabilities should be ruled out.

Mental Rotation in Exceptional Populations

Although no studies involving mental rotation have been conducted with DS individuals, several studies involving learning disabled individuals have been performed (Corballis et al., 1985; Johnston et al., 1983; Kershner, 1979; Silver & Hagin, 1970; Stanley, Kaplan, & Poole, 1975). Silver et al. (1970) found that dyslexic children were poorer than control children in recognizing pictures of flags in different orientations. However, both Stanley et al. (1975) and Kershner (1979) found no evidence that LD individuals performed deficiently on tasks of mental rotation. Corballis, Macadie, and Beale (1985) raise the question of whether the tasks used in these two experiments actually required mental rotation. Corballis and colleagues also point out that all previous experiments with reading disabled children relied only on accuracy of performance. Corballis et al. (1985), and Johnston et al. (1983) have both attempted to study mental rotation ability in LD populations with the use of the reaction time paradigm. Both control groups and LD groups had a significant linear relationship between the degree of rotation and reaction time. In other words, mental rotation was performed in an analog manner. Johnston and colleagues (1983) found that language disordered children responded significantly more

slowly than control children. The authors point out that since the linear regression equations were equivalent among the groups, spatial transformation processes themselves were not the source of difficulty. In contrast, Corballis et al. (1985) found that the reading disabled group and the control group did not differ significantly from each other in terms of either errors or in mean reaction time. A highly significant effect for orientation did occur, but the interaction between groups and orientation did not approach significance. Corballis et al. (1985) concluded that reading disabled children were at the same stage of development with respect to mental rotation as were the normal controls, even though the reading disabled individuals lagged by 3.6 years with respect to reading.

Mental Rotation and Dichotic Listening in a Control Group, a Learning Disabled Group, and a Down Syndrome Group

The mental rotation task considered in this paper employed a stick figure which could be holding a ball in either his right or left hand.

Insert figure 3 about here

Though the stimulus figure is common, the present experiment departs from the typical mental rotation experiment in that it asks the subject to make a decision about the side of the stimulus figure holding a ball. The subject is not asked to

make a distinction between left or right; instead, his task is to press a button that corresponds to the side on which the man is holding the ball after mentally rotating the stick figure to the upright position. It is anticipated that this task will yield the typical mental rotation function. As with other mental rotation experiments, this experiment is designed to look at both correct and incorrect mental rotations as well as reaction times in performing the mental rotation.

Due to the possible effect of a critical angle, it might be expected that nonlinearity of the beginning characters will occur. This may be due to the fact that stick figures have a uniquely defined and well-learned upright orientation. A pertinent question in this regard might be to consider when perceptual uprightness would cease to occur (refer to figures 4 and 5). From an inspection of these figures it would appear that the angles of 0, 45, and 315 degrees all have an inherent perceptual upright whose discrimination does not require a mental rotation. The angles of 90 and 270 degrees seem to be a dividing point where at least some degree of mental rotation is required. And if one is to assume that mental rotation is the strategy being used, then the angles of 135, 180, and 225 degrees require mental rotation. Results will be examined for the effect of a critical angle. If a critical angle of perceptual uprightness is inherent in the stick figure

stimulus, the resulting reaction time function should be concave and symmetrical. A remaining question to be addressed in regard to the obtained reaction time function will be whether or not it is the same for all three of our populations.

Insert figures 4 and 5 about here

Our goal is not to see whether our task results in a strictly symmetrical linear function, rather we will be interested to observe if the mental rotation at hand is composed of an underlying process performed in a sequential and additive fashion. This would be manifested by an increase in reaction times from 0 to 180 degrees and a corresponding decrease in reaction times from 180 to 360 degrees. The present research entails looking at populations of children at a chronological age at which it can be inferred that the skill of mental rotation will have already developed. It is hypothesized that each of the populations - control, LD, and DS - will be able to perform the mental rotation task in a manner indicative of an underlying analog process. It is further predicted that the control population will be able to perform the task with the most ease, as indicated by quicker reaction times. It is expected that the LD population will perform the mental

rotation task at a level that is slightly less efficient than that of the control population. It is expected that the DS population will also perform the mental rotation task, though a deterioration of the reaction time curve would not be surprising. Reaction times are predicted to vary between the populations as a function of respective developmental levels. The control group should have the quickest reaction time, the LD group should have a reaction time of more intermediate value, and the DS group should have the slowest reaction time.

Finally, the present experiment also examines both language lateralization and spatial processing, representing an attempt to further explore the crowding effect. The brains of our control subjects are assumed to be normally lateralized for both speech and spatial processes. However, the brains of LD individuals are assumed to be less lateralized, at least for speech and perhaps also for spatial processes. The DS brain also is considered with respect to the possibility of reversed asymmetrical representation of language. At the very least, left-hemisphere damage is a good possibility in this population. It is thought that due to the "invasion" of language into the "spatial" territories of LD and DS individuals, performance on a spatial task will deteriorate. Language lateralization, in the present experiment, is measured by a simple free recall task of

dichotic listening, and spatial processing is assessed with the mental rotation task. It is hypothesized that language lateralization as measured in the three groups of individuals will fall along a continuum: the control group will be most strongly lateralized for language, the LD group will have language less well represented in the left hemisphere, and the DS group will have language located primarily in the right hemisphere. These findings will be evaluated on the basis of the strength of the REA found in each population. In addition, performance on the dichotic listening task will be compared to performance on mental rotation. It is hypothesized that mental rotation will be performed most efficiently by the control group; the LD group should have more difficulty with this task; and the DS group should experience the most difficulty. In other words, it is hypothesized that performance in both dichotic listening and mental rotation studies will fall along similar continuums. Results will be evaluated with consideration of how "lateralization" affects performance. Normal individuals with more solidly lateralized skills should perform each task most efficiently, and task performance will vary as a function of laterality for each subject.

Method

Subjects

The sixty-six elementary school children participating

in the study were chosen from the general Tucson, Arizona area. The subject population consisted of three groups of individuals: a control group (C), a learning disabled group (LD), and a Down syndrome (DS) group. The control group was comprised of 25 elementary school-aged children who were being educated in the regular classroom. The mean age was 9.2 (S.D. = 1.37). The mean mental age as measured by the Peabody Picture Vocabulary Test was 11.20 with a S.D. of 2.35. There were 15 males and 10 females in this group. The learning disabled (LD) group was chosen from a school population including only those individuals who were being educated in a special setting for learning disabled individuals. Although in the regular school environment, these children were educated in self-contained learning-disabled classrooms. They had been identified on the basis of tests conducted by their respective school districts. The learning disabled group was comprised of 27 individuals with a mean age of 10.38 (S.D. = 1.08). Mean mental age was 7.48 (S.D. = 1.66). There were 9 females and 18 males in this group. The Down Syndrome (DS) group was comprised of 13 individuals selected for inclusion on the basis of mental retardation resulting from trisomy-21. An average chronological age of 8.37 (S.D. = 1.93) was calculated for this group. The average mental age was 3.05 (S.D. = 1.13). There were 3 females and 10 males in this group. The mean laterality index calculated by using the

Oldfield Handedness Inventory (Oldfield, 1971) was .98 for the control group, .96 for the LD group, and .87 for the DS group.

Several control and LD individuals were not included in the final analysis of the results because they were left-handed, or in the case of two LD individuals, due to multiple classification into special educational categories in addition to learning disabled. Results of 22 controls and 24 LD individuals were analyzed. In the case of the DS group, several individuals were unable to perform the task. Results of 5 DS subjects in the dichotic listening task, and 10 DS subjects in the mental rotation task were analyzed.

Apparatus

Mental Rotation

The overall set up for the mental rotation experiment was simple. Equipment for the mental rotation task consisted of a 15 x 15 x 15 inch black wooden box. The

Insert figure 6 about here

apparatus was located on a table in front of the subject. The front of the box was covered by an opaque piece of plexiglas that could be easily removed and replaced by the experimenter. This manipulation was necessary in order to allow the subject the opportunity to practice the task. When in place, the opaque plexiglas cover prevented the

subject from viewing the inside of the box. When the cover was not in place, the inside of the box and the mental rotation wheel could be viewed and manipulated.

Insert Figure 7 about here

The mental rotation wheel had a diameter of 12 inches and could be revolved or rotated around its center both from the inside and the outside of the box. The subject could revolve the wheel by reaching into the box. The experimenter was able to revolve the position of the stimulus figure through the use of a 360 degree wheel attached to the outside back of the box (refer to figure 6). Also visible inside the box were four 4 watt lightbulbs located in the upper and lower left and right corners of the mental rotation wheel. They served to illuminate the mental rotation wheel when the opaque cover was in place. A 6 voltage battery was located behind the mental rotation wheel, out of sight of the subject. This battery supplied the power to the lightbulbs and to a reaction clock timer located on a control box at the back of the box. In addition, the control box contained a switch to signal the start of the experiment (the lights inside the box were turned on), and was connected to the subject's response box (refer to figure 7). Two buttons on the response box enabled the subject to select the side on which the stimulus

figure held a ball; the control box contained lights indicating the subject's response.

The stimulus was a stick figure 5 inches high and 1 1/2 inches wide (at its widest point) with a ball in either his left or right hand (refer to figure 3). It was contained on a rectangular piece of white poster board that measured 6 1/2 x 1 3/4 inches, and was loosely affixed to the mental rotation wheel with two nails. The figure could be easily removed and replaced, and could be rotated securely throughout the 0 to 360 degree positions.

Dichotic Listening

The dichotic listening task used a two-channel tape recorder to dichotically present the auditory stimuli. Two sets of headphones were used: one each for the experimenter and the subject. The dichotic listening tape, consisting of the consonant-vowel (CV) syllables "ga", "pa", "ta", "ba", "da", and "ka", was prepared by the Kresge Research Laboratories in St. Louis, Missouri. Volume was maintained at a constant level for all subjects.

Procedure

Subjects were tested individually by the experimenter who was seated across the table. The experimenter started by gathering and recording information regarding age, gender, and group placement (C, LD, or DS). The Oldfield Handedness Inventory (1971) was administered. Seven items, including writing one's name, drawing a picture (circle),

cutting a piece of paper, brushing one's teeth, eating with a spoon, and removing a lid from a container formed the basis for determining handedness. The laterality index was obtained from this measure.

Mental Rotation

Training. Before beginning the mental rotation task, each subject underwent a period of training during which it was demonstrated that he/she was capable of understanding and performing the task. During this time, the mental rotation box was open, and the plexiglas cover placed to the side. To begin, the experimenter showed the subject the stimulus figure, which at this point was not attached to the mental rotation wheel. The experimenter asked the subject, "What is this?". Most subjects recognized the stimulus as a stick figure. If the subject did not respond to the experimenter's initial question, the experimenter said, "This is a stick figure.". This received general acknowledgement and no disagreement from any of the subjects. After this introduction of the stick figure, the experimenter mounted it onto the mental rotation wheel in an upright position. The training task of the subject was to press the response button that reflected his/her decision regarding the question "What side is the stimulus figure holding the ball on?". The terms "left" and "right" were not mentioned in the explanation of the task, instead the experimenter focused on which side the ball was on. That

subjects generally knew immediately which side of the stimulus figure the ball was on could be inferred from the fact that they were immediately able to press the correct button without any mistakes. Subjects had to respond correctly on both the right and left sides before going on to the next step in the training procedure. No control or LD children had any problems with this initial task, although three of the DS subjects were unable to press the correct response button. In each of these cases, the subjects did not generally attempt to press any button. These subjects did not continue to participate in the experiment.

After determining that the subjects understood the task instruction of "Press the button that is on the same side as the ball.", the experimenter moved on to the next phase of the training. Each subject performed physical rotations on the mental rotation wheel. Physical rotations were accomplished by the subject first watching the experimenter rotate the mental rotation wheel and stimulus figure and then the subject rotating the wheel and stimulus figure back to upright. For example, the stimulus figure's starting position could be zero degrees. The experimenter would reach into the box and rotate the wheel to 90 degrees. The subject would be instructed to reach into the box, to physically rotate the stimulus figure to the upright position, and then to press the decision button that

corresponded to the side on which the man was holding the ball. In this way, a physical simulation of the mental rotation process was conducted. It was characteristic to repeat this training trial at the 270 degree position, and then also at the 180 degree position. A fourth physical rotation practice was begun at random degree positions. These degree positions illustrated that the man could be presented almost anywhere on the circle. In addition to the position of the stimulus figure changing, the side the man was holding the ball on varied. Each subject was successfully able to complete four physical rotations before moving on to the next step in the training procedure. In this phase, each subject was told that they were now going to have to do a "mental" rotation. Each subject was provided with examples at approximately the 90 and 270 degree positions on the wheel. Subjects demonstrated the ability to understand what it was they had to do in order to mentally rotate the stimulus figure. Emphasis was not given to mental rotation practice during training but rather to 1) the subjects knowing which button to press when the figure is in the upright position, 2) the subjects being able to perform a physical rotation of the stimulus and respond accordingly, and 3) the subjects being able to demonstrate their understanding of what mental rotation is after a brief demonstration. Being able to respond correctly when the figure was at upright as well as performing the analog task

of physical rotation were the prerequisites for the subject to continue the task.

Experimentation. During the mental rotation task itself, the opaque plexiglas cover was on the front of the mental rotation viewbox. This allowed the experimenter to position the stimulus figure at the various orientations around the circle without the subject's being able to see inside of the box. Orientation positions of the stimulus figure varied by 45 degree increments around the circle, and included 0, 45, 90, 135, 180, 225, 270 and 315 degrees. The stimulus figure was presented a total of 32 times, four at each degree orientation, twice with the ball on the left, twice on the right. Stimuli were presented in a pre-set pseudo-random order. The experimenter recorded whether the response was correct or incorrect as well as marking down the reaction time for each of the responses.

Dichotic Listening

The dichotic listening task was performed after the conclusion of the mental rotation task. The experimenter explained to the subject that he/she was now going to listen to a tape through a pair of headphones. On the tape would be a man's voice saying one of the following syllables, "ga", "pa", "ka", "ta", "ba", or "da". These CV syllables were presented to the subject both verbally and nonverbally via small cue cards. The subject was told that the speaker on the tape would be saying one of these syllables to the

right ear and the other to the left ear. The task of the subject was to report which of the syllables he was able to hear best. The experimenter took away the cues and began the tape. The subject responded to what he heard, and the experimenter recorded each of the subjects' responses.

Results

Mental Rotation

Reaction time.

The general linear model was used to analyze both reaction times and correct responses in the mental rotation task. Mean correct reaction times were 3.11 (S.D. = 2.89) for the control group, 4.31 (S.D. = 3.95) for the LD group, and 5.32 (S.D. = 3.32) for the DS group. When all of the reaction time data was pooled, a significant difference in mean correct reaction times occurred only between the control and DS groups, [$F(1, 53) = 13.06, p < .0007$]. In separate analyses, however, overall mean correct reaction times were found to be significantly different between the control group and the LD group, [$F(1, 44) = 8.17, p < .0065$], between the control and DS group, [$F(1, 30) = 14.33, P < .0007$], but not between the LD and DS group. In the earlier analysis, the inclusion of the DS data obscured the difference between the control and LD groups. These results were confirmed by a Tukey's post hoc analysis where significant differences ($p < .05$) were found between these same groups. There was no significant difference in the

reaction time measure between the LD and DS group. Figure 8 depicts the actual and predicted reaction times obtained by each group; figure 9 illustrates the dispersion of reaction times.

Insert figures 8 and 9 about here

Further analyses were conducted in order to look for differences between the C and LD groups in mean correct reaction times at specific angular orientations. The DS group was not included in these analyses due to a lack of systematic reaction times. Mean correct reaction times are listed in table 1; statistical differences between the groups are listed in table 2. Conclusions regarding these values follow in the discussion section.

Insert tables 1 and 2 about here

It is characteristic for mental rotation functions to show a linear relationship between angular disparity and reaction time. There was a significant linear effect in the correct reaction times [$F(1, 53) = 40.88, p < .0001$]. This linear effect did not differ between the control and LD groups, however the linear effect in the DS group was significantly different from that of the control group, [$F(1, 53) = 8.49, p < .0052$]. In other words, although

control and LD groups demonstrated a similar strategy in the mental rotation task; the DS group did not. In addition to the linear effect, it might be expected that the inclusion of perceptually upright stimuli would introduce a curve in the otherwise straight-line function. Correct reaction times were analyzed to test this hypothesis. There was a significant quadratic component in the reaction times [$F(1, 53) = 16.61, p < .0002$]; this quadratic effect did not differ between control and LD groups, but it was significantly different between control and DS groups, $F(1, 53) = 5.21, p < .0266$. This again indicates a similar performance strategy in control and LD groups, but not in the DS group.

The side of the stick figure which held the ball was also looked at as a main effect. Mean correct reaction times for the right side were 2.92 (S.D. = 1.79) (C), 3.91 (S.D. = 2.58) (LD), and 5.32 (S.D. = 3.32) (DS); mean correct reaction times for the left side were 3.11 (S.D. = 2.89) (C), 4.31 (S.D. = 3.95) (LD), and 5.32 (S.D. = 3.32) (DS). When all of the data was pooled together, side was significant [$F(1, 53) = 4.37, p < .0413$]. A significant difference also resulted when comparing only the control and LD groups, [$F(1, 44) = 4.21, p < .0462$]. All groups were able to respond more quickly when the ball was held on the right side. Analyses conducted separately for the right and left side data were not discrepant from analyses of overall

reaction time.

An analysis of the resulting reaction time function was also performed; reaction times were analyzed to determine if the resulting sides of the reaction time graph were symmetrical around the midpoint. Values of 0 to 180 were tested against values of 180 to 360. Although the two sides of this function were found to differ significantly, $[F (1, 53) = 4.20, p < .0454]$, a significant difference occurred in the quadratic component $[F (1, 46) = 7.17, p < .0103]$, rather than in the linear component (n.s.). The resulting quadratic function was not found to significantly differ between the control and LD groups, though there was a significant difference when the control group was compared with the DS group, $[F (1, 46) = 5.53, p < .0230]$. In more specific analyses between the control and LD groups, nonsignificant results were obtained when comparing the sides of the function: reaction times of 0 to 180 degrees were equivalent to those of from 180 to 360 degrees. Each half of the reaction time function can be characterized as quadratic; a significant difference was apparent in the quadratic component $[F (1, 39) = 12.26, p < .0012]$, however it was the same for both groups. This means that the two sides of the function differed in the same way between the groups. Differences in the linear effect of the symmetrical function were found when comparing the control group to the DS group, $[F (1,30) = 4.57, p < .0408]$. Also, the quadratic

effect of the DS group was significantly different than both the control, [$F(1, 27) = 9.71, p < .0043$] and the LD group [$F(1, 26) = 4.89, p < .0360$]. In sum, although analyses of the resulting shape of the reaction time function demonstrated control and LD groups to have similar strategies, the DS group was found to perform in a different manner.

Accuracy.

The average number correct for the control, LD, and DS groups was respectively 90.06 (S.D. = 16.30), 79.43 (S.D. = 20.37), and 55.94 (S.D. = 8.89). Analyses of response accuracy demonstrate a significant difference when comparing the three groups (control, LD, and DS), [$F(2, 53) = 13.42, p < .0001$] with orientation as a significant main effect, [$F(7, 371) = 11.59, P < .0001$]. When separate group analyses were run, a significant difference emerged between the control and the DS group, [$F(1, 30) = 38.17, p < .0001$] with orientation as a main effect, [$F(7, 210) = 4.48, p < .0001$], and between the LD and DS group, [$F(1, 32) = 12.15, p < .0014$] with orientation again a significant main effect, [$F(7, 224) = 6.31, p < .0001$]. A comparison of the accuracy of responses between the control and LD group demonstrated only marginal significance, [$F(1, 44) = 3.81, p < .0574$]. Orientation remained a significant main effect, [$F(7, 308) = 16.99, p < .0001$]. Analyses of response accuracy on specific angular orientations were also carried

out (see table 3). The mean number of correct responses comprising the basis of this analysis are shown in table 4.

 Insert tables 3 and 4 about here

Also, a graphical depiction of the mean number of correct responses reflective of decreasing accuracy with increasing angular disparity is shown in figure 10.

 Insert figure 10 about here

Due to the absence of a group by orientation interaction, the accuracy function produced by each of the groups is essentially the same: each group appears to have difficulty at the same orientations. The accuracy function was similar to the reaction time function producing significant linear [$F(1, 53) = 27.89, p < .0001$] and quadratic effects [$F(1, 53) = 11.00, P < .0016$]. No interactions were present, and so these effects were the same for each group. The two halves of the function (0 to 180 degrees and 180 to 360 degrees) differed significantly [$F(1, 53) = 6.05, p < .01$], but in the same way in C, LD, and DS groups.

Further analyses of correct responses were conducted regarding the side of the stick figure holding the ball. When the stick figure was holding the ball on the right

side, there was a significant difference between all the groups, [F (2,53) = 16.84, $p < .0001$] and also between orientations, [F (7, 371) = 7.81, $p < .0001$]. When the figure was holding the ball on the left side, the same effects emerged. Both the group effect, [F (2,53) = 5.81, $p < .0052$] and the degree of stimulus disorientation, [F (7, 371) = 6.10, $p < .0001$] manifested significant differences. When the control and LD groups were compared, side was not a significant factor. Orientation, however, remained a significant effect both when the figure was holding the ball on the right side, [F (7, 308) = 9.58, $p < .0001$] and when the figure was holding the ball on the left side, [F (7, 308) = 10.19, $p < .0001$]. When the DS group was compared with the control group, significant differences were apparent on the right side, [F (1,30) = 39.76, $p < .0001$], and on the left side, [F (1,30) = 12.30, $p < .0014$]. Orientation remained an effect only for the right side [F (7,210) = 3.63, $p < .0010$]; it was not significant for the left side. When the LD group was compared to the DS group, only the right side distinguished the groups, [F (1, 32) = 15.85, $p < .0004$]. The orientation main effect was significant [F (7, 224) = 4.61, $p < .0001$]. There was not a significant difference between the LD and DS group when looking at the left side. Orientation remained a significant main effect, however, [F (7, 224) = 3.31, $p < .0023$].

Dichotic Listening

In the dichotic listening task, results were analyzed in a 3 x 2 (group x ear) repeated measures ANOVA. Both the control and LD groups were found to have a significant right ear effect: control, [F (1, 21) = 25.45, p < .0001], and LD [F (1, 23) = 26.53, p < .0001]. Mean number of right and left ear responses are presented in table 5.

 Insert table 5 about here

A significant difference was not found when comparing the magnitude of the right ear response between the control and LD populations. No ear advantage was found in the DS population.

Discussion

Reaction Time Analyses

Reaction times differed between all the groups: control and LD, LD and DS, and control and DS. The hypothesis of the hierarchical arrangement of reaction times is confirmed. The control group, as evidenced by fast reaction times, demonstrates the most efficiency in the performance of the mental rotation task, followed by the LD group, and then the DS group.

Systematic and essentially parallel reaction time functions were obtained from both control and LD groups; slopes do not differ and so these groups appear to solve the

mental rotation task with a similar strategy. Both linear and quadratic effects were statistically significant. The linear effect reflects the fact that angular disparity and reaction times increased concurrently. The quadratic effect most likely reflects the inclusion of perceptually upright stimuli not needing rotation. Systematic increases in reaction time do not occur until the stimuli are sufficiently disoriented; the reaction time function is essentially flat until the angular disparity exceeds 90 degrees (refer to figure 8). Differing intercepts between the groups indicate that the task is solved at different speeds, in agreement with earlier research (Johnston et al., 1983). For example, on the basis of equivalent linear regression equations between control and LD individuals, Johnston and colleagues (1983) concluded that spatial transformation processes themselves were not the source of difficulty: both groups perform mental rotation in the manner dictated by the literature, however LD individuals take longer to solve the task. The function of the DS group did not parallel that of the control or LD groups; its slope was significantly different. Difficulty with spatial transformation processes is indicated.

Changes in reaction time occur as a function of angular disparity, indicating an analog function. The reaction time function for the DS group, however, does not reveal any particular strategy in the performance of mental rotation;

their performance appears to be irregular. Although each group demonstrates considerable variability of reaction times, the variation in C and LD groups is systematic, predictable, and occurs as a function of stimulus disorientation. The DS group, on the other hand, produced reaction times unrelated to the degree of angular disparity. Their strategy was clearly different from that of the C and LD groups. For example, after stimulus presentation, C and LD groups processed and solved the task; the DS group, in contrast, appeared to use the time not to solve the problem, but rather to look at the task, look at the response buttons, look at and wonder about the lights in the box, and in some cases, make a comment regarding judgment to the examiner. Attentional resources are better allocated in C and LD groups (see Kail, 1986); mental effort and attention were more directly focused on the mental rotation task. The DS group demonstrated curiosity about the testing apparatus and environment; their attention was not fully focused on the task. Mental rotation may require more mental effort than the DS subjects can muster. As a consequence, performance in this group of individuals deteriorates (Kail, 1986).

The strategy utilized by the control and LD groups is consistent with the previous mental rotation literature (see for example, Shepard et al., 1971): a linear function occurs due to reaction times increasing as the stimulus moves away

from upright. Further, a symmetrical function emerges as the stimulus figure passes through the 180 degree mark and the degree of angular disparity again decreases; reaction times correspondingly decrease. The resulting reaction time function parallels the results of other studies when mental rotation involves projecting an image through a 0 to 360 degree trajectory (Childs et al., 1979; Corballis et al., 1988, 1989).

The DS reaction time function is different. Systematic changes in reaction time were not observed, suggesting that this group had problems with the mental rotation task itself. Although children as young as four years old have been known to demonstrate proficiency on the mental rotation task (Marmor, 1975, 1977), DS children were unable to perform in a competent manner. However, many investigators have suggested that the ability to perform mental rotation does not actually develop until seven years of age (Piaget et al., 1971; Kail et al., 1980; Foulkes et al., 1989). Though our mental rotation task was designed to be less difficult than the standard same-different mirror image task, our task demands may still have exceeded the capabilities of the DS individuals. Further analysis of the results should enable us to determine if each group performs the rotation, and how they do it.

Accuracy Analyses

In terms of correct responses, there were essentially

parallel functions for each of the three experimental groups; that is, an inverted reaction time function. The peak of the function, though still occurring at 180 degrees, is no longer a pinnacle, but is now a depression. Whereas reaction times increase and decrease in a systematic fashion with changes in the angular disparity, the reverse occurs with the correct response function (compare figure 8 to figure 10). Accuracy decreases with increasing angular disparity and increases with decreasing disparity. An inverted accuracy function is rarely reported in mental rotation literature, probably due to the reliance in mental rotation studies on reaction time data. Though some studies (see for example Childs et al., 1979; Kail et al., 1980) mention that accuracy declines as the degree of rotation increases, this finding is not elaborated upon. Jolicoeur and Landau (1984) on the other hand, rely on accuracy data to make the claim "that changes in orientation can have a systematic effect on the identification of simple patterns" (p. 87). Increases in errors occur as the stimulus departs from upright.

Yuille and Steiger (1982) state that mental rotation is faster when an external stimulus is compared with a well-learned memory representation. Perhaps this is also the case with the ability to make a correct decision. A stimulus presented in a disoriented position does not have a well-learned memory representation unless it can be

manipulated and recognized in imagery. A task analysis for imagery offered by Farah and her colleagues (1985) included 1) recognizing an uppercase letter, 2) associating a lowercase form with the corresponding uppercase letter, 3) generating an image of the lowercase form, 4) classifying the image as to its height, and 5) responding. The task analysis for our experiment includes first the presentation of the stick figure. During this presentation, the subject encodes the figure, taking special note of the side containing the ball. Although a stick figure is a fairly common form, it cannot be assumed that all subjects have an equal degree of familiarity with it. Representations of this figure in memory may not be as strong in the DS group as in the control group. Second, the subject must understand that the task requires a mental rotation. It is during this step that an image needs to be generated. Encoding the stimulus and forming a short-term memory representation most likely places differential processing demands on each of our groups. Third, the subject must perform the mental rotation. The figure must be rotated through space to a position that permits a judgment about which side the ball is on. If we assume the figure is rotated as a whole, the ball's position must be preserved throughout the rotation. Mental rotation thus imposes additional attentional requirements upon the subject. Fourth, the subject must make a decision regarding

which side the ball is on. The decision demands that the figure be rotated to the upright position. The figure may be in this position either physically (as in the case of the stimulus presentation at 0 degrees) or imaginally (after a mental rotation). In sum, this mental rotation task entails stimulus encoding, image generation, rotation, and a decision. A problem may occur at any of these steps.

It is typical for mental rotation studies to administer the experimental task only to those subjects who have demonstrated a certain level of proficiency during training procedures. For example, Marmor (1975, 1977) required her subjects to respond correctly to either ten out of ten training trials, or 20 out of 24 total trials. Similarly, Childs and Polich (1979) continued training until each subject was able to errorlessly complete two successive blocks of eight trials. Furthermore, it is not uncommon for subjects to be eliminated after testing procedures are completed due to an inability to perform a task at a certain level (for example, Foulkes et al., 1989). This procedure, though a common practice, may obscure important group differences by overestimating the group's performance capacity. For example, Marmor (1975) excluded six five-year old children during testing. This number represented 23% of the total number of five-year olds she looked at. In a subsequent study, Marmor (1977) excluded six four-year olds, which was 20% of the total. Rather than being concerned

with developing "age-norms", it might be more relevant to try to further establish developmental parameters for the task of mental rotation.

The task of mental rotation is comprised of several different levels. A stimulus positioned at zero degrees does not require a difficult decision. The decision becomes more difficult as angular disparity increases. Individual performance will vary as a function of development. Several studies report that reaction times differ between groups of differing developmental levels (Kail et al., 1980). It would be informative to conduct a study comparing error rates and patterns of errors. Although reaction times reveal the underlying cognitive process, error patterns have the potential to reveal more about how and when mental rotation abilities are developed.

Mental Rotation Ability

Early in development, mental rotation does not occur at all. As the child grows, he begins to be able to rotate stimuli, but he often makes mistakes. Some of his responses are random: performing a task such as mental rotation lacks meaning. As the child begins to become more concerned with his performance, error rates decrease and a systematic reaction time function begins to develop. The present task allows a brief glimpse of developmental processes involved in mental rotation for two reasons: 1) differences in the number of errors occurs as a function of developmental

level, and 2) a regular pattern of errors is a consistent result between the groups. Observations of error responses prior to the development of a systematic accuracy function promises to yield important information regarding spatial development and attention.

The traditional mental rotation finding indicates a mature functional capacity for representing kinetic stimuli. In our groups, arrested development in mental rotation is evident in the DS population. Due to the difficulty of the task, mental rotation may not be meaningful to these subjects; as a consequence, a lack of motivation in the form of performance deterioration becomes apparent. Both the C and LD groups have a reason to perform mental rotation; they are more eager to demonstrate proficiency, and so the task has meaning. Both groups are able to represent a stimulus in imagery: a functional maturity has been obtained. Performance proficiency, however, differs between these groups. The LD group is consistently slower and less accurate in mental rotation. They are not at the same developmental level as the C group. It is presumed, however, that development of mental rotation has followed a similar progression. It is possible that, given time, the LD group will gain efficiency in the task. In conclusion, the DS group, as indicated by low but regularly occurring accuracy, is at a beginning stage of mental rotation; lack of attention to the task prevents a more mature performance.

C and LD groups both perform mental rotation in a mature manner, though circumstances dictate that LD individuals perform less competently.

Reaction time results indicate similar functions only for the control and LD groups. The function for the DS group reflects this group's difficulty in performing the task with a consistent strategy. In contrast, in terms of response accuracy all groups produced a similar function. When looking at the accuracy function, it is tempting to state that the performance of the DS group is the same (or comparable) to that of the C and LD groups. It appears as though each group had the least amount of difficulty with the upright figure, and increasing difficulties became evident with greater degrees of angular disparity. The conclusion might be that regardless of the strategies employed, all groups had comparable difficulties at the same angles. This interpretation becomes difficult when viewing the fact that the percentage correct in the DS group is rarely above chance. It is remarkable, however, that despite the low level of overall accuracy in the DS group, a regular pattern of responses was obtained with respect to the accuracy function. This finding may require additional research regarding the development of mental rotation abilities.

A Critical Angle in Mental Rotation?

The angles of 0, 45, 90, 270, and 315 degrees were

discussed above as potentially occurring before the appearance of the critical angle (refer to figure 3), the angle at which a rotation is required in order to make the required decision (Cooper et al., 1973). Between group analyses were performed comparing perceptually upright stimuli to those stimuli requiring mental rotation for their solution. Due to the 90 and 270 degree angles being a dividing point between upright and rotated stimuli, two "upright" variables of 0, 45, 90, 270, and 315 degree angles or 0, 45, and 315 degree angles and two "rotated" variables of 135, 180, and 225 degrees or 90, 135, 180, 225, or 270 degrees were used in the analysis (refer to table 3). The purpose was to look for where each group had specific difficulties. When looking at the data for all the groups, significant differences occurred between both upright and rotated variables. This was also the case when C and DS groups were compared. When C and LD groups were compared, there was no difference between the upright variables, but a nearly significant difference ($p < .07$) occurred with comparisons of the rotated variables. When LD and DS groups were compared, they were significantly different ($p < .01$) at the upright angles, but not at the rotated angles of 135, 180, and 225 degrees. However, when the angles of 90 and 270 degrees were included as "rotated" angles, a significant difference was obtained ($p < .05$). In sum, C and LD groups "solve" upright angles equally, but when the rotation

problem becomes more difficult, the groups tend to perform differently. LD and DS groups differ significantly in solving upright problems, suggesting the difficulty that the DS group has with the task itself, but when the mental rotation gets more difficult, there are no significant performance differences.

Reaction time comparisons at "upright" and "rotated" angles were also performed in an attempt to define specific task difficulties. Only the C and LD groups were considered due to the lack of a systematic reaction time function in the DS group. Significant differences were found between the upright and the rotated angles ($p < .05$), however, when the 90 degree angle was included as an "upright" angle, "rotated" angles only tended toward being different ($p < .07$). The C group was more efficient at mental rotation no matter what the angle.

A further examination of the critical angle is warranted. Cooper and Shepard (1973) initially postulated the existence of a critical angle on the basis of the symmetrical mental rotation function sloping upward in a concave manner. They postulated that it was only after the stimulus figure was disoriented to a certain degree that mental rotation became necessary or critical to the solution. When we look at the mean reaction times, the concept of a critical angle is supported. The resulting function takes on a concave shape, especially apparent on

the left side of the graph with the angles of 0, 45, and 90 degrees. In the control group less than one-tenth of a second separates the decision time between the 0 and 90 degree angles. There is an almost flat slope connecting these points, much as Cooper and Shepard (1973) might predict. In the LD group, the difference between these angles is only five-tenths of a second. On the right side of the graph values from 180 to 315 degrees are plotted. The concave linear function is no longer so apparent, as reflected by a significant difference in the quadratic component of the two sides of the reaction time function. Although the reason for this discrepancy is unclear, several possibilities exist: 1) 225, 270, and 315 degree angles were presented on the left side of a revolving rotation wheel. The subjects, who were all right-handed, may have had more ease with figures presented on the right side of the rotation wheel. 2) To reach upright in the shortest possible distance angles of 0, 45, 90, and 135 degrees require a counterclockwise rotation. The angles of 225, 270, and 315 degrees require a clockwise rotation. The 180 degree position is equidistant from 0 degrees and so can be rotated in either direction. It is quite likely that the counterclockwise rotation is executed more quickly by right handers, reflecting the left-right direction of handwriting and reading.

The original hypothesis of a critical angle (Cooper et

al., 1973) and a perceptual upright (Hock et al., 1978) appear to be supported by the reaction times found in this experiment with the stick figure. Other figures, such as abstract geometric figures, may not support the concept of a perceptual upright. Perceptual uprightness may be more apparent in this experiment because the subject only needs to make a decision regarding side. Mirror-image discriminations of more complex figures may not yield such an obvious concave function. Corballis and Sergent (1989), in their tests of mental rotation in a commissurotomed subject, found another problem in the absence of an apparent upright: the right hemisphere was unable to perform a mental rotation. Although a perceptual uprightness may be apparent for figures such as stick figures and alphanumeric characters (Cooper et al., 1973), further experiments need to be conducted in order to determine whether this concept is valid over all stimulus figures. In addition, "uprightness" needs to be explored in relation to hemisphericity. It is likely that perceptual uprightness may change due to the familiarity or verbal codability of a stimulus. Perhaps perceptual uprightness is more broadly tuned (i.e. + 60 degrees from absolute upright) for stimuli taxing left hemispheric identification processes, but more narrowly tuned (i.e. + 15 degrees from absolute upright) when the stimuli are unfamiliar, abstract, and taxing right hemisphere identification processes. The examination of

perceptual uprightness may also yield potentially important information about the development of kinetic imagery in children.

Surprisingly, when we look at the accuracy of responses, the concept of a critical angle is again supported, especially for the angles of 0, 45, and 90 degrees in the control and DS groups (refer to figure 9). Evidence of the LD groups' difficulty at the 90 and 270 degree angles is present; the C group also appears to have a little trouble at 270 degrees as compared to the 315 degree position. It is apparent that when mental rotation is performed correctly, reaction times remain consistent at the "upright" angles.

Dichotic Listening

In the dichotic listening task, competing stimuli are presented simultaneously, and the subject must discriminate between them. The dichotic listening task can result in an overall ear advantage of 100%. This score is dependent upon how many CV syllables are correctly identified. In the present task, C and LD groups had a significant right ear advantage, while the DS group was found to have no advantage.

Although dichotic listening is often thought of as a quick assessment device, it is a task lacking in neuropsychological validity; it does not produce reliable group differences, and often yields inconclusive results

regarding language lateralization. In the present experiment, control and LD individuals have almost identical performance on the dichotic listening task. Similar findings were obtained by Orbzut, Conrad, & Boliek (1989) and Orbzut, Conrad, Bryden, & Boliek (1988). These authors further explore how attentional factors differentiate the groups (see also Obrzut, Hynd, Obrzut, & Pirozzolo, 1981).

Interpreting the results of dichotic listening studies is difficult. The LD population is a diverse and heterogeneous group; clear distinguishing features between its various subgroups have yet to be established. Labels such as dyslexia (Hier et al., 1978; Hynd et al., 1990), reading disabled (Corballis et al., 1985; Orbzut et al., 1989) and simply "LD" (Johnston et al., 1983; Orbzut et al., 1988) fail to clarify the experimental findings. The LD population in this study included individuals being educated in self-contained classrooms, who can be regarded as having academic problems severe enough to keep them from learning in the mainstreamed classroom. A majority of the LD individuals studied had problems in the language domain; more specific deficits included auditory memory, auditory closure, visual memory, and visual closure. It is likely that problems such as group heterogeneity and inadequacy of the measurement device contribute to inconsistent results.

On the basis of dichotic listening tasks alone, one may conclude that LD individuals do not suffer from a lack of

hemispheric asymmetry for language. This is a problem when viewed in the light of conflicting anatomical findings. For example, Hynd et al. (1990) found that 90% of dyslexic individuals have a reversed pattern of anatomical asymmetry in the language areas. An accurate test of neuropsychological functioning would be expected to yield results that agree with this finding as well as those findings of other higher level anatomical studies (for example, Hier et al. 1978; Geschwind et al., 1985). Hynd and colleagues (1990) caution that many studies are not selective in choosing a homogenous group of subjects.

The dichotic listening task may be inappropriate to administer to DS subjects without thorough information regarding audioperceptual deficits. DS individuals characteristically demonstrate language problems, hearing and processing difficulties and articulation problems. Deficiencies in the left temporal cortex (see Kemper, 1988) may be responsible for some of the difficulty experienced by DS subjects: left temporal damage commonly leads to poor performance on the dichotic task. These subjects may be unable to distinguish between the CV elements (see Kolb et al., 1990). Of interest is how the typical DS individual phonemically discriminates and then produces the morphemic elements of language. A goal for future studies is to establish an association between performance on dichotic listening tasks, language behavior, and temporal lobe

damage. In order to better understand the whats and hows of language processing several components of dichotic listening should be varied: stimuli, stimulus presentations, and response requirements are three potential candidates.

Although dichotic listening can and should be viewed as a valuable neuropsychological device, caution should be used in its administration and especially in the drawing of conclusions. Research efforts in the future need to focus on refinements of the procedure in order to establish convergent validity with such techniques as sodium amytal testing, lesion studies, and the more sophisticated computer imaging procedures. In this way, the neuropsychological usefulness of dichotic listening can be further established. A strength to build on with the dichotic listening procedure may be the fact that this task is sensitive to damage in the language areas of the temporal cortex. This task can be used not only to find out about language lateralization, but also to more appropriately find out about language processing. Teaching and communication efforts in those populations where damage is indicated might be more effectively directed.

Inconsistent Neuropsychological Findings

The present experiment has looked at performance on a test of language lateralization and a test of spatial processing with the purpose of assessing the potential effect of crowding on brain structures. Our results do not

permit a clear conclusion regarding either lateralization of language or hemisphericity of the mental rotation task. For example, although mental rotation has been found through anatomic studies to be a right hemisphere task, tachistoscope studies disagree. Tachistoscopic studies have alternately found left visual field advantages, right visual field advantages, and no visual field advantages in mental rotation. Tachistoscopic studies, like dichotic listening studies of language lateralization, produce inconsistent results. Tachistoscopic findings can be regarded as a neuropsychological measurement, and like dichotic listening measures, agreement is lacking when comparisons are made with more sophisticated techniques. The findings of dichotic listening and tachistoscope studies do not even correlate with each other (Kolb et al., 1990). It is difficult to trust the findings gained through these instruments when they lack consistency with each other as well as with the more severe tests of anatomical functioning (ie. lesion studies, cerebral blood flow).

As anatomic techniques become more refined, it is likely that neuropsychological procedures will also follow suit. In order to draw clear and accurate conclusions, we need to use tests that produce consistent results. Although conclusions can be reached regarding the mental rotation task, these conclusions must necessarily be limited to behavioral indices. It is not possible to generalize our

findings to make more global statements about the brain and hemispheric functioning within our populations. Conclusions from the dichotic listening task must be limited to conclusions regarding the dichotic listening procedure itself. In the past, many researchers have been content to form an opinion regarding language lateralization in LD individuals on the basis of dichotic listening results, this may be a mistake. Orton's original theory of deficient left hemisphere language lateralization (1925, 1937) has generated countless volumes of speculation and theorizing; his idea has been substantiated by anatomical work. Rather than throwing away a half-century old theory, it is a good idea to instead work on refining the more recently established dichotic listening technique.

Analog Processing: A Legitimate Neural Assumption?

Since mental rotation and spatial development are the primary topics of interest to this thesis, conclusions about this task need to be drawn. Of primary importance is whether or not mental rotation is performed in an analog fashion in our populations. The reaction time functions of the control and LD populations have shown this to be the case. The finding of a linear function in mental rotation studies is often taken as indicating that an underlying analog process is being performed (Cooper et al., 1973; Farah et al., 1988; Shepard et al., 1982; Shepard et al., 1971). However, a theme running throughout this paper has

been to take issue with research that infers too much about underlying cognitive structures. Does the linear function obtained in mental rotation experiments produce real evidence that an analog process is being performed? On the basis of reaction time findings alone, a conclusive assertion of underlying neural structures mimicking physical structures cannot be made. Fortunately, physiological research has been conducted using mental rotation; neural evidence in favor of analog processing has been produced.

Georgopoulos and colleagues have conducted a series of studies which attempt to explain a behavioral outcome by looking at cell populations (Georgopoulos, Crutcher, & Schwartz, 1989a; Georgopoulos, Kettner, & Schwartz, 1988; Georgopoulos, Lurito, Petrides, Schwartz, & Massey, 1989b; Georgopoulos & Massey, 1987; Kalaska, Caminiti, & Georgopoulos, 1983). They specifically study the direction of aimed arm movements (see for example, Georgopoulos, 1986).

In a behavioral study, Georgopoulos and Massey (1987) asked human subjects to "capture" a light located in the center of a two-dimensional planar working surface within a circle attached to a manipulandum allowing free and almost frictionless movement over that surface. After a period of five seconds or less, the center light was turned off and another light was turned on at another position on the circle's periphery. "Stimulus direction" was defined to

be the vector formed from the center light to the second stimulus. The position of the second stimulus varied from trial to trial. The subject's task was to either move directly toward the stimulus at a zero-degree angle, or to depart from the stimulus at a prespecified angle (i.e., 5, 10, 15, 35 etc. degrees). The subject's actual angular departure was calculated by measuring the angle formed by the vector of stimulus direction and the vector of actual movement. Reaction time was taken as the time between the onset of the peripheral light and the exit of the manipulandum from the center window. Georgopoulos and Massey found that reaction times increased with angle in a linear fashion. They propose that the performance of the task may involve "an internal rotation of an image of the movement vector" (p. 365). In other words, a mental rotation is performed in several steps: 1) the subject imagines the movement vector from the center point to the stimulus, 2) he imaginably rotates the vector to the angle of amplitude required, and 3) he performs a movement toward the periphery of the circle. Subsequent studies attempt to detect the neuronal population vector in mental rotation tasks.

In studies of neuronal populations in rhesus monkeys (Georgopoulos et al., 1988; 1989a), the direction of the population vector was close to the direction of movement. The population vector is comprised of many cells, each

possessing unique directional preferences. Each cell "votes" to determine the direction of the population vector. Georgopoulos and colleagues (1989b) trained rhesus monkeys to capture a center light with a manipulandum, and then move the manipulandum toward a peripheral light. Monkeys were tested with both delay and nondelay conditions. Changes in the activity of the cell populations were evident during the delay period. A directional measure of the population activity showed that the population vector anticipated the movement direction.

Georgopoulos, Lurito, Petrides, Schwartz, & Massey (1989b) more directly investigated the mental rotation hypothesis, which would predict that a population vector "rotate" in the motor cortex. The task required that a monkey move either toward a light (direct trial) or in a direction that was perpendicular to and counterclockwise from the direction of the light (rotation trial). This task was similar to that performed by human subjects (see Georgopoulos et al., 1987). The neuronal population vector was calculated every 10 ms. In the direct trials, the population vector pointed in the direction of movement. However, in the rotation trials the population vector rotated counterclockwise from the direction of the stimulus to the direction of movement. Visualization of mental rotation in a motor cortex neuronal population was accomplished. As suggested for in the earlier study

(Georgopoulos et al., 1987), the subject, in this case a rhesus monkey, performed "mental rotation" by rotating an imagined vector to the required angle (90 degrees), and then moving. Georgopoulos et al., (1989b) note "The rotation of the neuronal population vector is of particular interest because there was no a priori reason for it to rotate at all." (p. 235).

Mental rotation of this sort in neural structures has yet to be demonstrated in a Shepard and Metzler (1971) type task. The research of Georgopoulos and colleagues facilitate speculation about what may be occurring. In fact, reaching behavior itself is commonly affected by parietal cortex damage, although a relationship with imagery has not been demonstrated. Important developmental issues need further research.

Conclusion

Mental rotation presents itself as an ideal task to pursue. Our original reasons for studying this task included the fact that it is a spatial task, has a developmental time-course, and is an interesting process in and of itself. In addition, physiological proof exists supporting the view that "mental rotation" occurs in underlying cognitive structures. Interesting questions regarding the population vector arise, for example, "When in development do neuronal populations become activated?", "Does imagery play a part in reaching?", and "What is the

association between the imagery of anticipated movement and the imagery involved in later developing tasks such as mental rotation?". With the answer to these questions the role of mental rotation in everyday behavior can be more easily addressed. A developmental approach to cell physiology and the population vector might provide enlightening information.

Mental rotation, regarded at a purely behavioral level, is a task involving spatial processing. Performance on a mental rotation task differentiated between our three groups of subjects. Although an original purpose of this research was to investigate how varying degrees of language lateralization effect performance on a spatial task, we have fallen short of this goal. Whether diffuse or reversed language representation impinges upon the ability to perform a spatial task is at present unresolved. More sophisticated techniques are needed to assess whether "crowding effects" have an impact on intelligence. Anatomical aspects of mental rotation in regard to analog processing, hemispheric functioning, visuospatial perception, and visual and spatial imagery have also been considered. Relevant applications to our populations include delineating behavioral areas where DS individuals are capable of performing analog operations. In addition, one might explore the contribution of spatial skills on developing intelligence. Much research remains to be completed. Neuropsychological procedures need

improvement in order to reach agreement with sophisticated anatomical techniques. Visuospatial functioning needs to be explored with respect to defining the neural areas responsible for their underpinning; an understanding of the development of visual and spatial imagery may lead to greater awareness of individual differences in the performance of perceptual skills.

In conclusion, mental rotation offers a complex task that can be studied at a variety of different levels. Importantly, it represents a coming together of behavioral, cognitive, neuropsychological, and neurophysiological endeavors. As such, it is likely that mental rotation will continue to offer potential insights into how the brain represents the external environment.

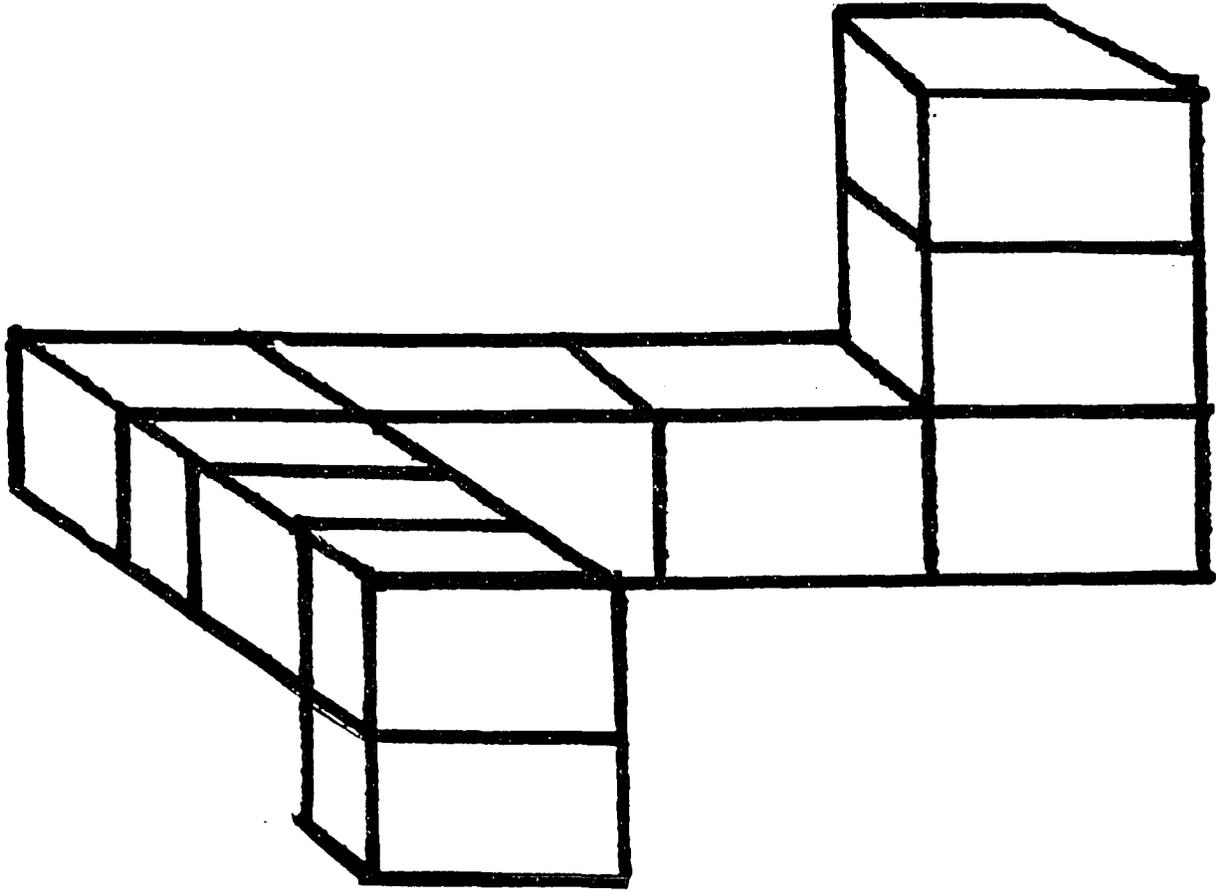


Figure 1. Mental rotation stimulus used by Shepard and Metzler (1971).

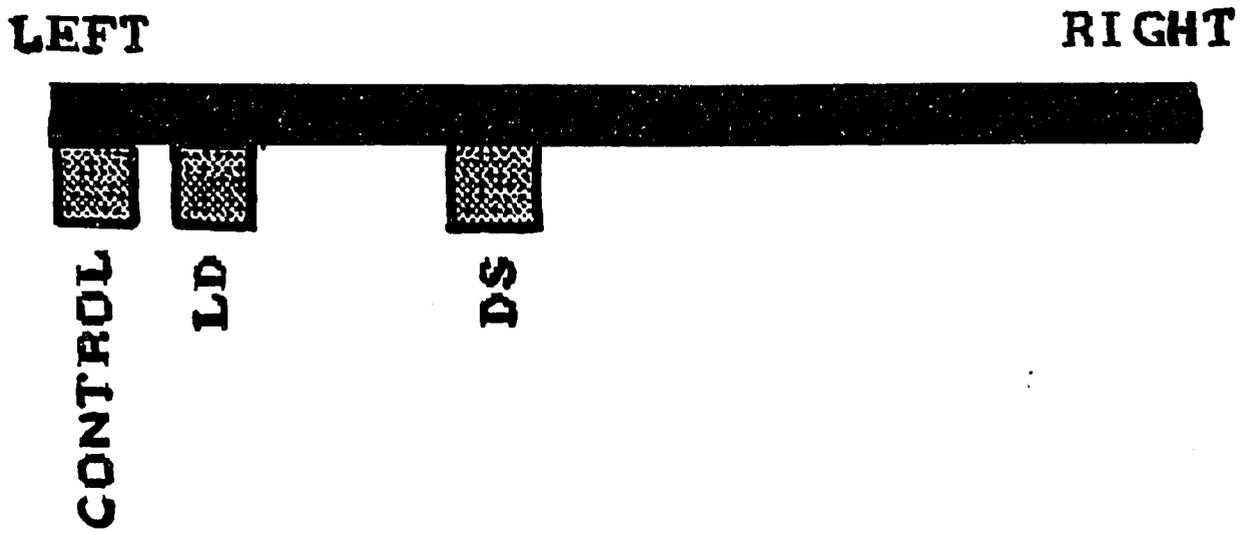


Figure 2. Speech representation in the hemispheres of the brain.

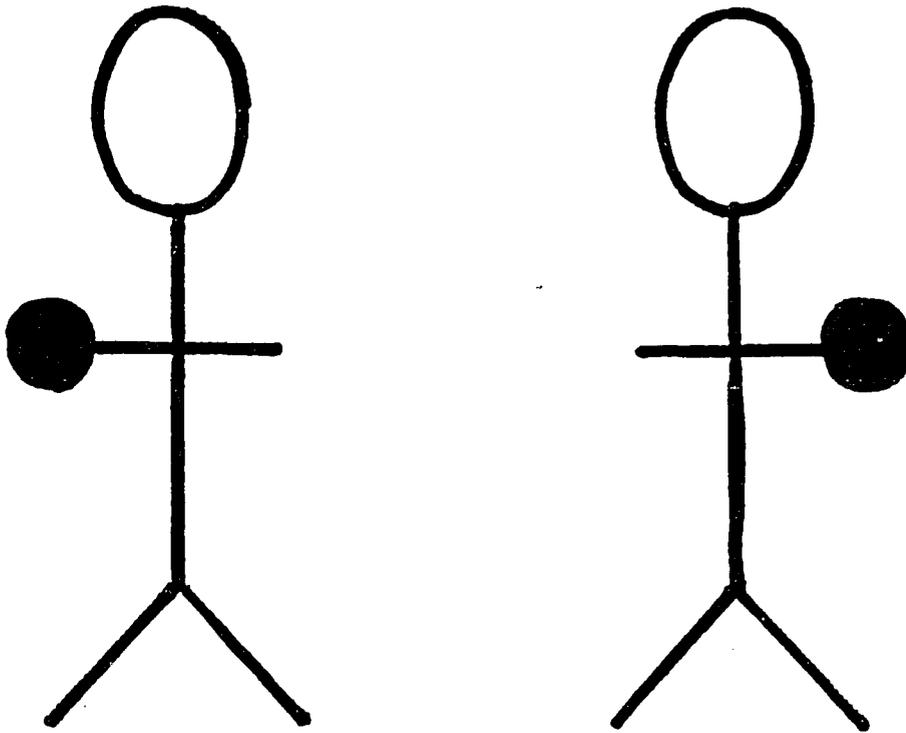


Figure 3. Stick figure stimuli used in the present mental rotation task.

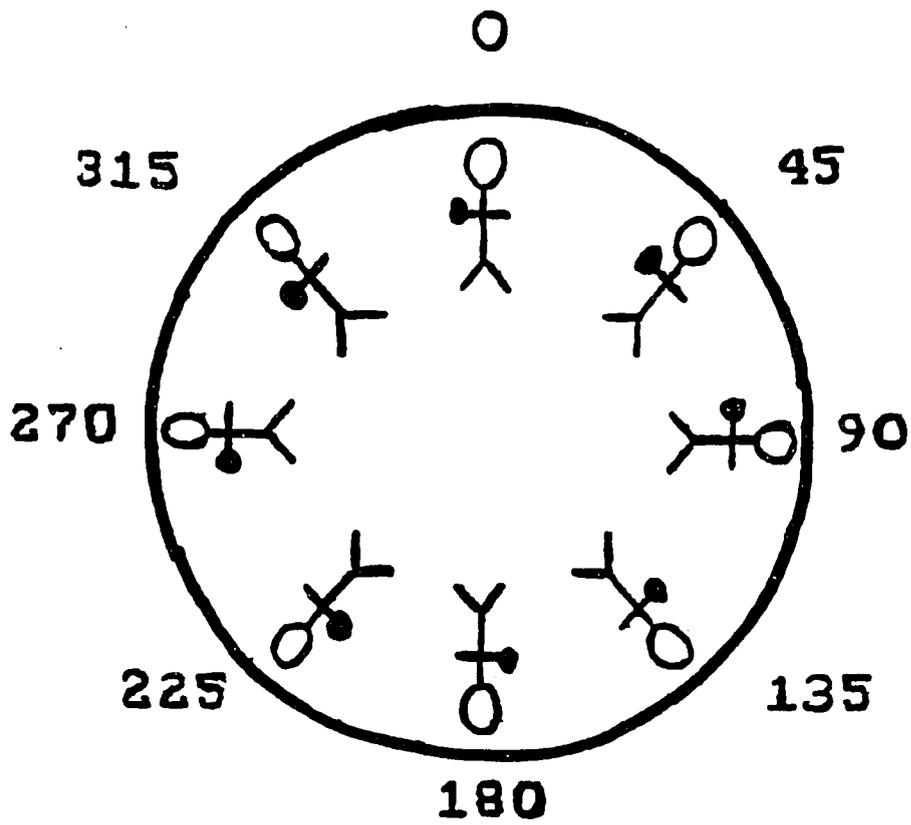


Figure 4. Stick figure stimuli at all possible angle presentations.

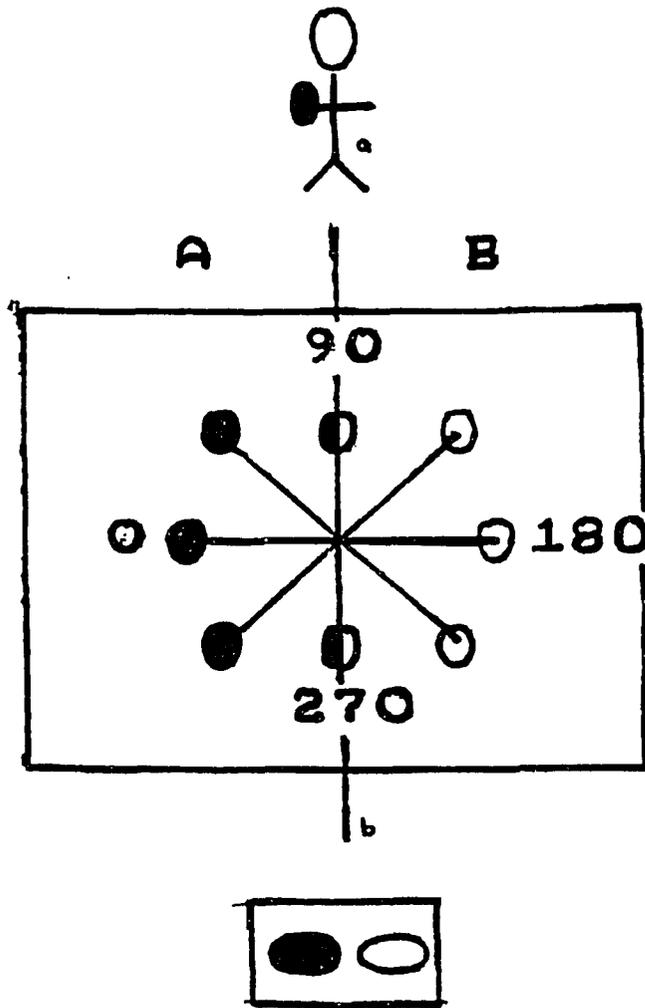


Figure 5. The position of the ball at all possible angular disorientations: examination for perceptually upright positions. a. upright stimulus, 0 degrees. b. rotation vertical used as an indicator of perceptual uprightness. A. filled in circles indicate correct response. B. open circles indicate incorrect response.

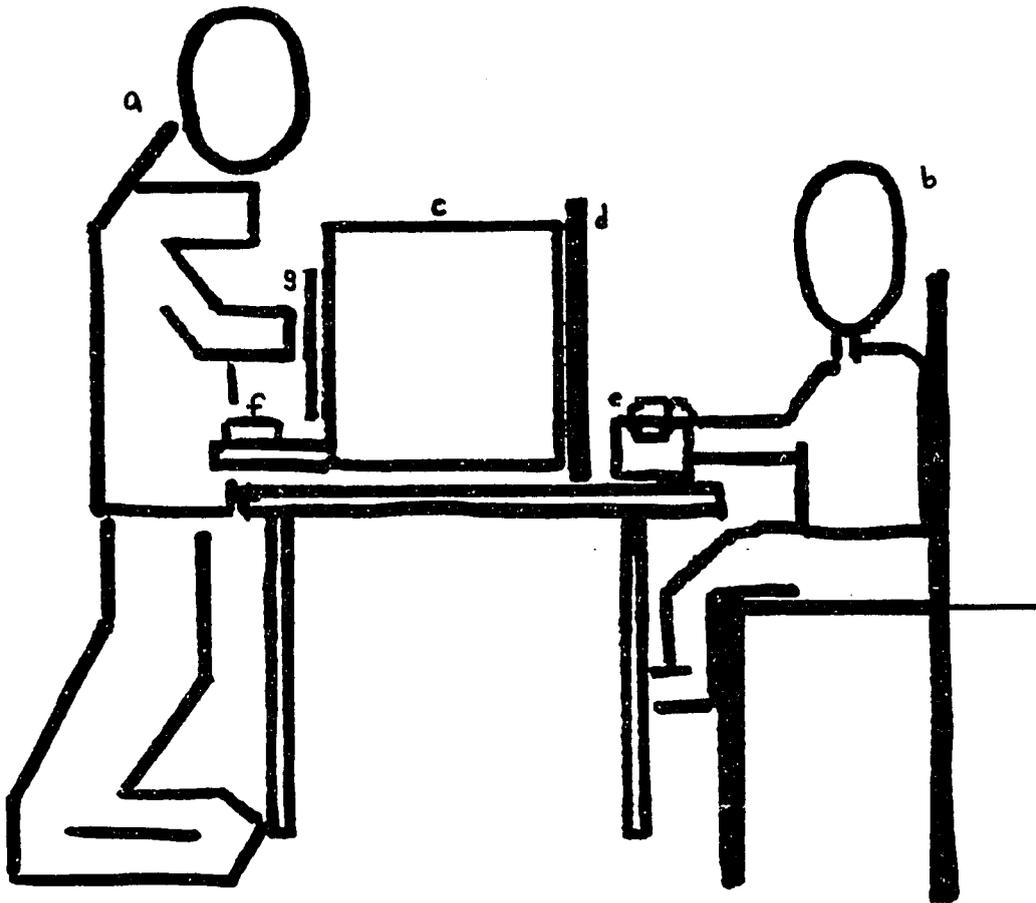


Figure 6. Mental rotation task administered by experimenter to subject.
a. experimenter. b. subject. c. mental rotation box. d. plexiglas cover.
e. subject's response box. f. experimenter's control box. g. degree wheel.

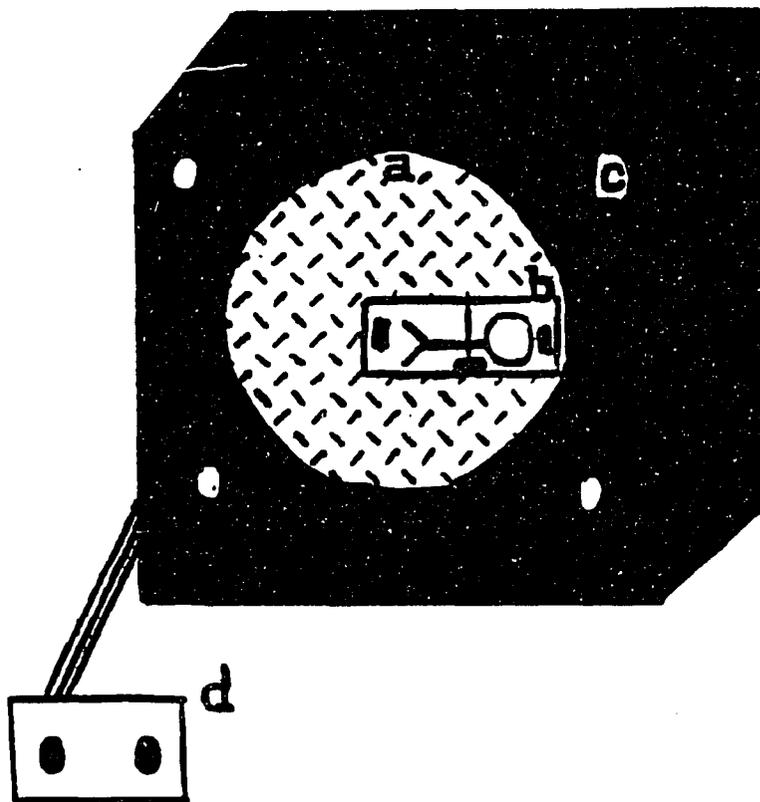


Figure 7. The mental rotation apparatus shown without the plexiglas cover. a. mental rotation wheel. b. mounted stimulus figure. c. lightbulbs illuminating mental rotation wheel when plexiglas cover is in place. d. subject's response box.

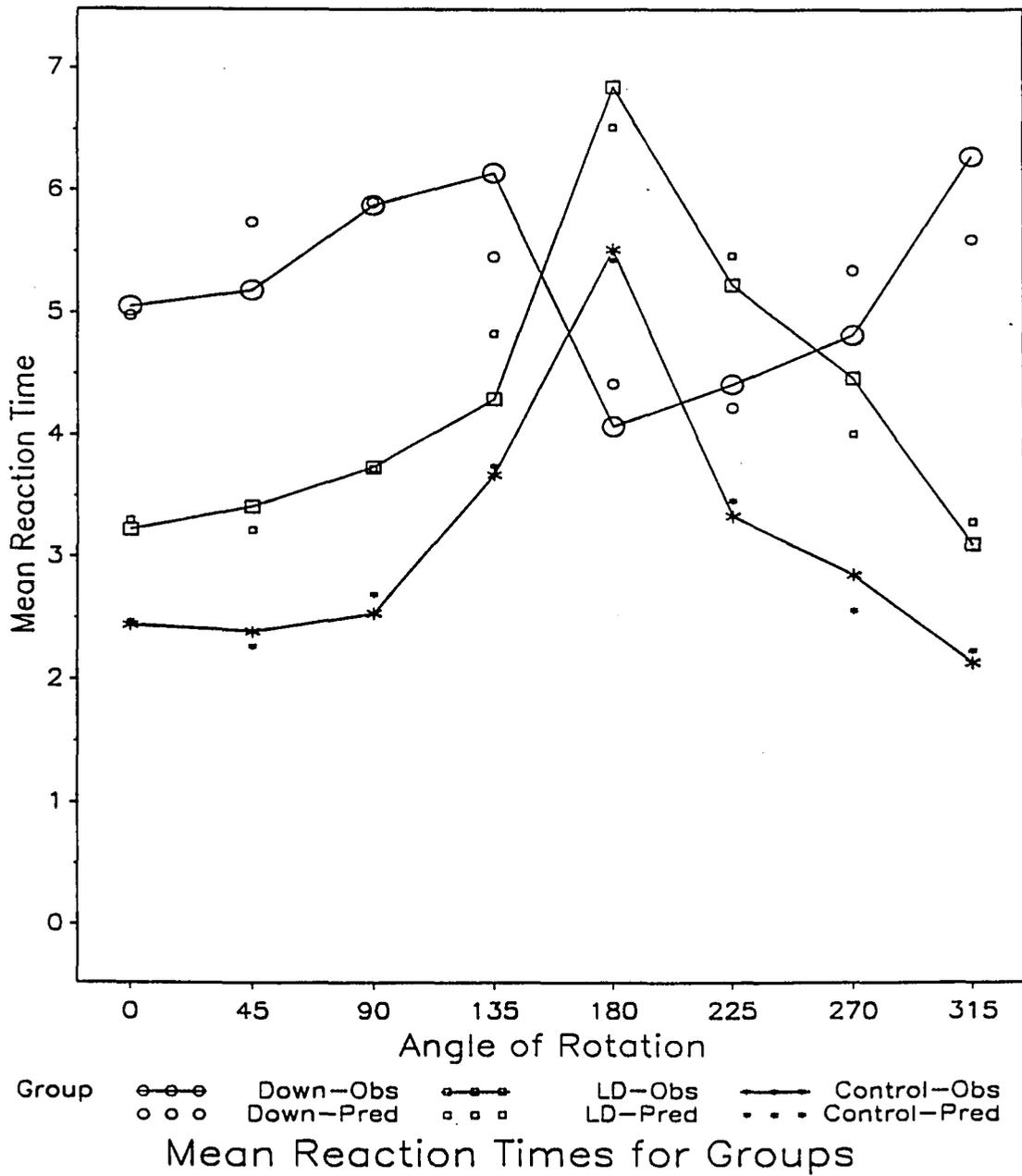


Figure 8. Observed and predicted reaction times for correct mental rotation responses.

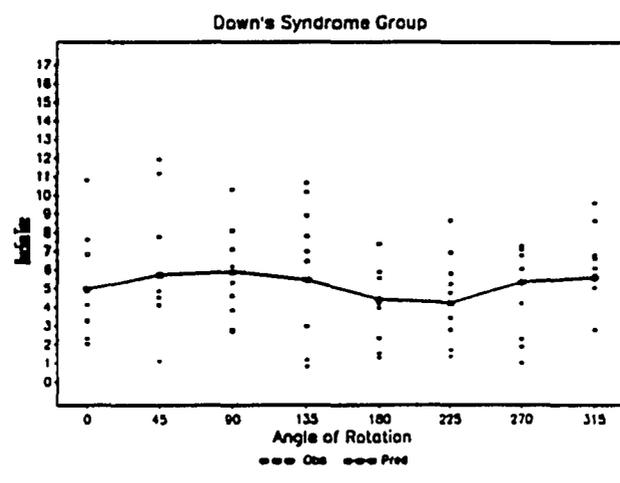
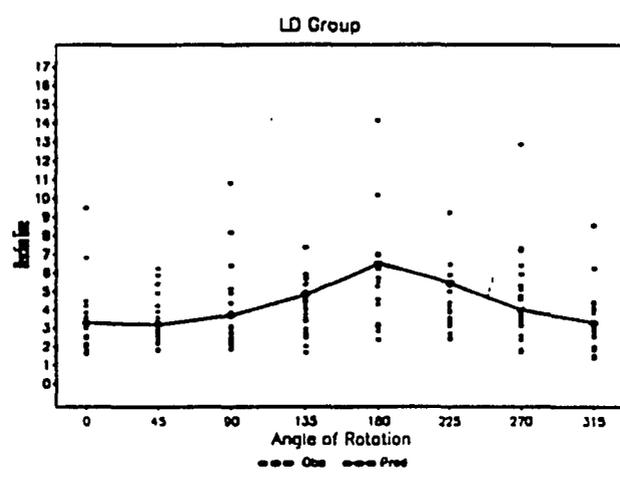
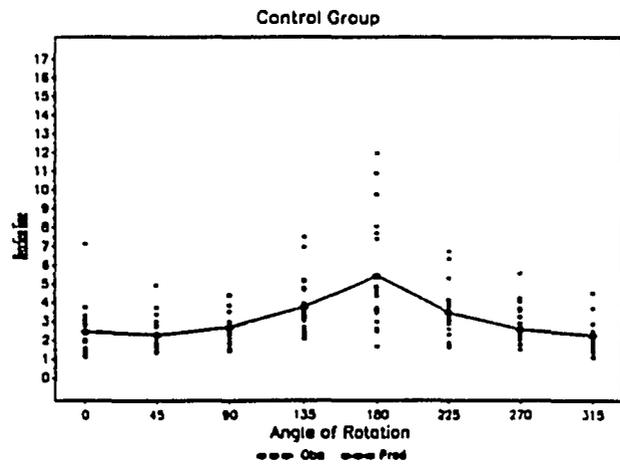


Figure 9. Reaction time dispersion for each of the groups for correct mental rotation responses only.

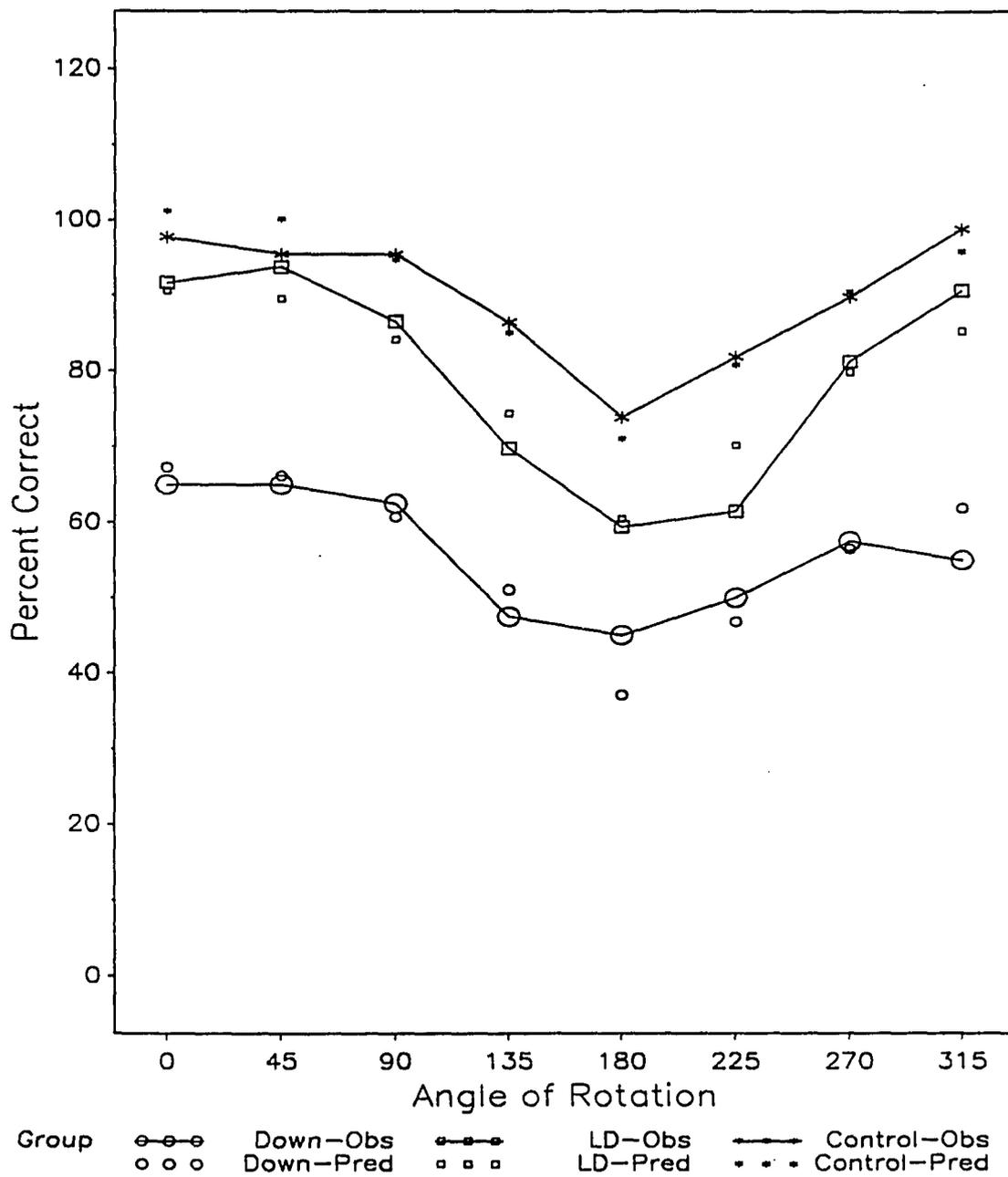


Figure 10. Observed and predicted accuracy rates.

Table 1

Mean Correct Reaction Time

| DEGREE OF ANGULAR DISPARITY | DOWN SYNDROME | LEARNING DISABLED | CONTROL |
|--------------------------------------|-------------------|----------------------|-------------------|
| 0 | 5.21/5.29 2.78 | 3.40/3.53 1.71 | 2.48/2.46 1.25 |
| 45 | 6.00/5.94 3.37 | 3.40/3.25 1.21 | 2.39/2.30 .89 |
| 90 | 5.57/6.00 2.41 | 3.86/3.83 2.10 | 2.54/2.72 .89 |
| 135 | 6.24/3.70 3.72 | 4.58/5.24 3.13 | 3.75/5.48 1.51 |
| 180 | 4.03/4.38 2.19 | 7.90/7.51 7.65 | 5.26/5.25 3.11 |
| 225 | 4.53/4.26 2.43 | 5.29/5.57 4.00 | 3.48/3.58 1.37 |
| 270 | 4.80/5.46 2.30 | 4.55/3.97 2.38 | 2.93/2.67 .97 |
| 315 | 6.33/5.58 1.99 | 3.21/3.28 1.62 | 2.13/2.29 .81 |

Note. Actual reaction times/Predicted reaction times
Standard deviation

Predicted reaction times for stimuli disoriented < 180
degrees were generated from the following regression
equations: DS $y = 4.9766 + .02361x - .00014x^2$

$$LD \quad y = 3.30107 + .00847x + .00015x^2$$

$$C \quad y = 2.47067 - .01156x + .00016x^2$$

Regression equations for stimuli disoriented > 180
degrees were DS $y = 4.9766 + .02361x - .00014x^2$

$$LD \quad y = 3.30107 + .00847x + .00015x^2$$

$$C \quad y = 2.47067 - .01156x + .00016x^2$$

Table 2

Between Group Analyses of Correct Reaction Times for
"Upright" and "Rotated" Angles

| | CONTROL AND LD |
|-----------|----------------------|
| UPRIGHT 1 | 9.56*** |
| UPRIGHT 2 | 3.31* |
| ----- | |
| ROTATE 1 | 5.76** |
| ROTATE 2 | 10.61*** |

Note. UPRIGHT ANGLE 1 = 0, 45, AND 315 DEGREES
UPRIGHT ANGLE 2 = 0, 45, 90, 270, AND 315 DEGREES

ROTATED ANGLE 1 = 90, 135, 180, 225, AND 270 DEGREES
ROTATED ANGLE 2 = 135, 180, AND 225 DEGREES

* p < .1, ** p < .05, *** p < .01

Table 3

Between Groups Analyses of Correct Responses for "Upright"
and "Rotated" Angles

| | ALL GROUPS | CONTROL AND LD | LD AND DS | CONTROL AND DS |
|-----------|---------------|----------------------|-----------------|----------------------|
| UPRIGHT 1 | 20.20*** | 1.65 | 19.28*** | 56.29*** |
| UPRIGHT 2 | 17.37*** | 2.23 | 17.13*** | 46.32*** |
| ----- | | | | |
| ROTATE 1 | 7.18*** | 3.56* | 4.77** | 18.65*** |
| ROTATE 2 | 4.85** | 3.66* | 2.09 | 10.73*** |

Note. UPRIGHT ANGLE 1 = 0, 45, AND 315 DEGREES
 UPRIGHT ANGLE 2 = 0, 45, 90, 270, AND 315 DEGREES

 ROTATED ANGLE 1 = 90, 135, 180, 225, AND 270 DEGREES
 ROTATED ANGLE 2 = 135, 180, AND 225 DEGREES

* p < .1, ** p < .05, *** p < .01

Table 4

Mean % Correct Responses

| DEGREE OF ANGULAR DISPARITY | DOWN SYNDROME | LEARNING DISABLED | CONTROL |
|--------------------------------------|------------------|----------------------|-----------------|
| 0 | .65/.67 .24 | .92/.91 .20 | .97/1.01 .07 |
| 45 | .65/.66 .29 | .94/.90 .13 | .96/1.00 .15 |
| 90 | .62/.61 .27 | .87/.84 .20 | .96/.95 .15 |
| 135 | .47/.51 .22 | .70/.74 .35 | .86/.85 .26 |
| 180 | .45/.37 .33 | .59/.60 .37 | .74/.71 37 |
| 225 | .50/.47 .26 | .62/.70 .35 | .82/.81 .28 |
| 270 | .57/.56 .21 | .81/.80 .28 | .90/.90 .21 |
| 315 | .55/.61 .28 | .91/.85 .25 | .99/.96 .05 |

Note. Actual accuracy/Predicted accuracy
Standard deviation

Predicted accuracy was generated from the following regression equations when the degree of disorientation was < 180:

$$\begin{aligned} \text{DS} \quad y &= .67285 + .00022x - .00001x^2 \\ \text{LD} \quad y &= .90643 + .00022x - .00001x^2 \\ \text{C} \quad y &= 1.01262 + .00022x - .00001x^2 \end{aligned}$$

When the degree of disorientation was > 180 degrees, the following regression equations were used:

$$\begin{aligned} \text{DS} \quad y &= .63032 + .00022x - .00001x^2 \\ \text{LD} \quad y &= .86390 + .00022x - .00001x^2 \\ \text{C} \quad y &= .97008 + .00022x - .00001x^2 \end{aligned}$$

TABLE 5

DICHOTIC LISTENING: % REA AND LEA

| | CONTROL | LEARNING DISABLED | DOWN SYNDROME |
|-----|---------|----------------------|------------------|
| REA | 52.5455 | 49.5417 | 32.0000 |
| LEA | 30.7272 | 30.6667 | 26.8000 |

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