the typical characterization of individuals with mild mental retardation, by seldom being able to live independently.

As evidenced by the example of Williams syndrome, summary test scores often do not represent well the level of ability within individual domains. Thus it is crucial to take into account etiology when planning either basic research or intervention. At the same time, it is important to remember that there is within-syndrome variability, both in overall IQ and fit to the behavioral phenotype associated with the syndrome. Explication of both within- and between-syndrome variability depends on coordination of research efforts among researchers studying cognition, personality, brain structure and development, and genetics. Such interdisciplinary efforts should lead to a deeper understanding of basic processes and their relation to intelligence and adaptive functioning, whether the goal is to explain more fully a specific etiology or to elucidate processes relevant to mental retardation as a whole.

See also AUTISM: LANGUAGE AND THOUGHT; LANGUAGE IMPAIRMENT, DEVELOPMENTAL; LURIA

—*Carolyn B. Mervis and Byron F. Robinson*

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Mental Rotation

In Douglas Adams's (1988) novel *Dirk Gently's Holistic Detective Agency,* a sofa gets stuck on a stairway landing. Throughout the remainder of the novel, Dirk Gently ponders how to get it unstuck by imagining the sofa rotating into various positions (he eventually solves the problem using a time machine). The well-known psychologist Roger Shepard once had a somewhat similar experience, awakening one morning to "a spontaneous kinetic image of three-dimensional structures majestically turning in space" (Shepard and Cooper 1982, 7). That experience inspired Shepard and his student Jacqueline Metzler to run what has become a seminal experiment in cognitive science—one that both defines and operationalizes mental rotation.

Shepard and Metzler (1971) presented subjects with images of novel three-dimensional (3-D) objects at various orientations—on each trial a pair of images appeared side-by-side and subjects decided whether the two images depicted the same (figures 1a and 1b) or different objects (figure 1c) regardless of any difference in orientation. A given 3-D object had two "handedness" versions: its "standard" version and a mirror-reflected version (equivalent to the relationship between left- and right-handed gloves).

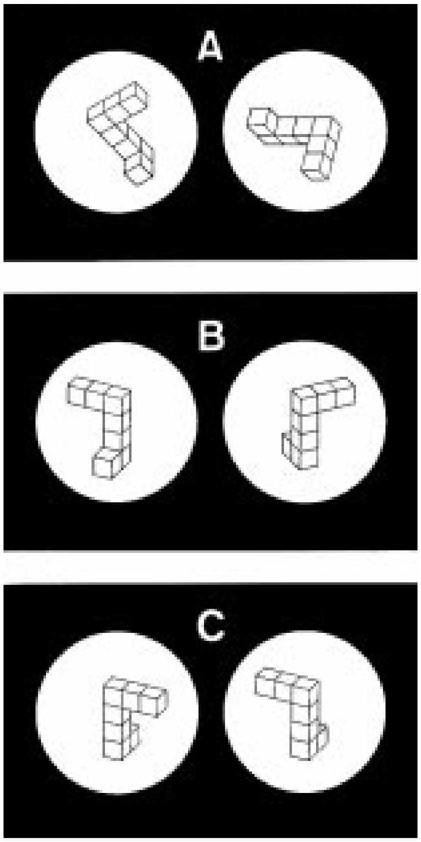

Figure 1. Illustrative pairs of perspective views, including a pair differing by an 80-degree rotation in the picture plane (a), a pair differing by an 80-degree rotation in depth (b), and a pair differing by a reflection as well as a rotation (c).

Different objects were always mirror reflections of one another, so objects could never be discriminated using distinctive local features. Shepard and Metzler measured the time it took subjects to make same/different discriminations as a function of the angular difference between them. What they found was a remarkably consistent pattern across both picture plane and depth rotations—mean response times increased linearly with increasing angular separation. This outcome provides evidence that subjects mentally rotate one or both objects until they are (mentally) aligned with one another. Shepard and Metzler suggest that the mental rotation process is an internal analogue of physical rotation, that is, a continuous shortest path 3-D rotation that would bring the objects into alignment.

A variation on Shepard and Metzler's experiment demonstrated that mental rotation is also used when subjects judge the handedness of familiar objects. Another student of Shepard's, Lynn Cooper, presented subjects with single English letters or digits (Cooper and Shepard 1973). On each trial a standard (e.g., "R") or a mirror-reflected version (e.g., "Я") of a letter or digit was shown at some misorientation in the picture plane. Because subjects had to judge whether the misoriented character was of standard or mirror handedness they could not use local distinguishing features to make the discrimination. Moreover, because handedness is only defined relative to the viewer, subjects presumably needed to align each test character with their egocentric reference frame in which left and right are defined. The results, quite similar to those obtained with 3-D objects, confirmed this assumption—mean response times for judging handedness increased monotonically as the test characters were misoriented farther and farther from their canonical upright orientations. Response times turned out to be symmetric around 180 degrees—the point at which the characters were exactly upside down. Thus subjects were apparently mentally rotating the characters in the shortest direction to the upright regardless of whether this rotation was clockwise or counterclockwise.

Why are these findings so important? Much of the theorizing about COGNITIVE ARCHITECTURE during the 1960s assumed a symbolic substrate (e.g., PRODUCTION SYSTEMS) in which all mental representations were thought to have a common amodal format. Shepard's results demonstrated that at least some cognitive processes were modal, and, in particular, tied to visual perception. The hypothesis that mental rotation is a continuous process akin to a real-world rotation also has implications for the nature of IMAGERY, namely, that humans have the capacity to make judgments using inherently spatial representations and that such representations are sophisticated enough to support PROBLEM SOLVING, spatial reasoning, and SHAPE PERCEPTION. Not surprisingly, this claim evoked a great deal of skepticism.

In response, Shepard and Cooper went on to meticulously demonstrate that mental rotation indeed involved a continuous mental transformation. Three critical results provide converging evidence for this conclusion. First, Cooper and Shepard (1973) ran a variant of their familiar characters experiment in which they preceded each letter or digit with a cue to the test character's orientation, identity, or both. They found that neither orientation nor identity alone was sufficient to diminish the effect of stimulus orientation on response times. In contrast, providing both, along with sufficient time for the subject to prepare, removed almost all effects of orientation. Thus it appears that mental rotation operates on a representation that depicts a particular shape at a particular position in space—properties associated with an image.

Second, Cooper and Shepard (1973; see also Cooper 1976) ran an experiment in which they controlled an individual subject's putative rate of rotation across a series of trials. Given this information, for a misoriented test letter or digit, they could predict the instantaneous orientation of the rotating mental image of that character. On each trial, a test character was presented, followed at some point by a probe character. The task was to begin rotating the test character, but then to judge the handedness of the probe. Under these conditions, response times were essentially unrelated to the absolute orientation of the probe, but increased monotonically with increasing angular distance from the presumed orientation of the rotating mental image of the test character. For example, when the predicted orientation of the test character image and the visible probe corresponded, response times were independent of the actual orientation of the probe. Thus the changing image actually passes through all of the intermediate orientations—a property expected for a truly analog transformation mechanism.

Third, Cooper and Shepard ran an experiment in which subjects were given extensive practice judging the handedness of characters mentally rotated in only one direction, for example, 0 degrees to 180 degrees counterclockwise. When these subjects were tested with characters misoriented slightly past 180 degrees, say 190 degrees, the distribution of response times had two peaks—one corresponding to mentally rotating the short way around (clockwise) and one corresponding to mentally rotating the long way around (counterclockwise and consistent with the practice subjects had received). Thus it was the actual angular distance traversed by a rotation that determined the time consumed—again consistent with an analog mechanism.

In summary, there is compelling evidence for the use of a continuous mental rotation process that brings images of two objects into correspondence or the image of a single object into alignment with an internal representation. The existence of such a mechanism suggests that models of cognitive architecture should include modality-specific mechanisms that can support mental imagery. Mental rotation may also play a role in HIGH-LEVEL VISION, for example, in shape perception (Rock and Di Vita 1987), FACE RECOGNITION (Hill, Schyns, and Akamatsu 1997; Troje and Bülthoff 1996), and OBJECT RECOGNITION (Jolicoeur 1985; Tarr 1995; Tarr and Pinker 1989).

See also MENTAL MODELS; MENTAL REPRESENTATION; MODULARITY OF MIND

—Michael Tarr

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Metacognition

Broadly defined, *metacognition* is any knowledge or cognitive process that refers to, monitors, or controls any aspect of cognition. Although its historical roots are deep (e.g., James 1890), the study of metacognition first achieved widespread prominence in the 1970s through the work of Flavell (1979) and others on developmental changes in children's cognition about MEMORY ("metamemory"), understanding ("metacomprehension"), and communication ("metacommunication"). Metacognition is now seen as a central contributor to many aspects of cognition, including memory, ATTENTION, communication, PROBLEM SOLVING, and INTELLIGENCE, with important applications to areas like EDUCATION, aging, neuropsychology, and eyewitness testimony (Flavell, Miller, and Miller 1993; Metcalfe and Shimamura 1994). In this sense at least, metacognition is a domain-general facet of cognition.

Although theorists differ in how to characterize some aspects of metacognition (see Schneider and Pressley 1989), most make a rough distinction between metacognitive knowledge and metacognitive regulation. *Metacognitive knowledge* refers to information that individuals possess about their own cognition or cognition in general. Flavell (1979) further divides metacognitive knowledge into knowledge about persons (e.g., knowing that one has a very good memory), tasks (e.g., knowing that categorizable items are typically easier to recall than noncategorizable items), strategies (e.g., knowledge of mnemonic strategies such as rehearsal or organization), and their interactions (e.g., knowing that organization