Note

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Factors Affecting the Rates of Mental Rotation

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The purpose of the present study was to examine the effects of possible factors on the rates of mental rotation from various researches being available to the author. The factors to be reviewed included stimulus types and their dimensionalities, response types, stimulus complexities, methods of stimulus presentations, and practice or other memorization procedures. The results indicated that the dimensionalities of stimuli predominantly determined the rates. Stimulus attributes like complexity and familiarity, as well as stimulus presentations and amount of practice also affected the rates. The results would indicate that there were systematic effects on the rates of mental rotation by various factors and thus vitiated the analog holistic position in the analog/propositional controversy. It was also discussed that memorization should be an indispensable factor for the arguments of mental rotation experimentation.

Studies of mental rotation have been playing a central role in the fervent analog/propositional controversy over the internal representation. The controversy concerns what kind of information is unitized to internally represent an external object and how such a represented object can be internally operated. Both the analog and the propositional representations and/or processings are defined in many ways according to different researchers.

Sometimes, analog theorists, or imagists, take internal representations like perception. In this context, it is generally assumed that "the relational structure of the external events is essentially preserved in the corresponding relational structure of the internal representations" (Shepard, & Cooper, 1982, p.12-13). From this definition the analog holistic position is derived: a represented object should internally preserve its integrity and coherency just as a real still object does. If internal representations in fact assume the same characteristics as perception, this coherency principle should be applicable even to a represented object in motion.

The term "proposition" originated from philosophy, in which the term signifies a "statement whose truth or falsity can be evaluated by means of logic" (Webster's New World Dictionary, 1994). However, in the analog /propositional arguments the propositional representations usually refer to "abstract language-like entities that describe or assert facts" (Kosslyn, 1980, p.12). In propositional representations an object to be represented has no analogous element in structures to a corresponding physical object. Thus, if a represented object is to be transferred, the internal process of transference should not be constrained by any physical law as the transference of a real object should by the law of motion.

Johnson-Laird (1983) gave concise summaries of the respective positions concerning the internal representations (p.147-148).

Mental rotation studies started from a famous work by Shepard and Metzler (1971). Their newly devised stimuli were pairs of 3-D cranked blocks consisting of connected cubes projected onto two-dimensional plane (see Figure 1). They found the time to judge whether one figure of a pair was identical or mirror reflected with the other monotonously increased as the angular disparity between the respective axes of the two figures increased. Since then various types of stimuli have been employed to investigate the presence of this angular disparity effect.

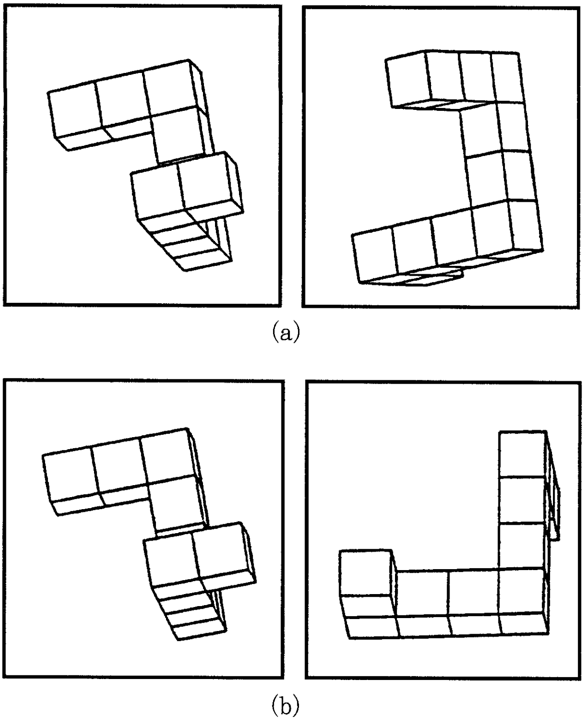

Figure 1. Shepard-type block figures: (a) a reflected pair, (b) an identical pair. From Yuille, & Steiger (1982), reproduced originallay from Shepard, & Metzler (1971).

The imagists took the presence of the angular disparity effect as evidence for the analog nature of internal representations. The result that continuously longer judgment time was consumed with the increase of angular disparities seemed to indicate that people can rotate images just like rotating physical objects. The early reports that the rates of mental rotation were not affected by stimulus complexities (Cooper, 1975;

Cooper, & Podgorny, 1976) also bolstered the analog position because such constant rates can not seemingly be congruent with the propositional assumption.

Whereas, propositionists gave an alternative explanation to the angular disparity effect. Pylyshyn (1981) considered that people would make use of the knowledge of physical laws (called a tacit knowledge) when they are requested to mentally rotate objects. As people know physical rotation is a continuous process, they will simulate that the wider the disparity between two given objects are, the longer they require to judge the identity of the two objects. He also asserted that internal processings should not be analog in nature unless they are implemented by intrinsic knowledge-independent properties and biological mechanisms. If an outcome of an internal processing is swayed by higher order cognitive activities like knowledge, the processing is called "cognitively penetrable" and should be diagnosed as a propositional one (e.g., Pylyshyn, 1981; Pylyshyn, 1984). Other propositionists were less radical. Some claimed that the detection of features rather than rotation should play the predominant role of figural identifications (e.g., Eley, 1982), and others insisted the descriptions of stimuli precede the induction of mental rotation (e.g., Corballis & Nagourney, 1978; Corballis, Zbrodoff, Shetzer, & Butler, 1978).

Subsequently, the effect of stimulus complexity on the rate of mental rotation has been detected (e.g., Pylyshyn, 1979; Hochberg & Gellman, 1977). Such presence of the complexity effect seemed to be incompatible with the analog account in that it violates the coherency and integrality of represented objects by the analog holistic assumption.

In this respect, the variability of the rate of mental rotation in relation to various experimental conditions, especially in relation to stimulus complexity, has been one of the focal points in the arguments over the mode of internal representations. Hence, I would like to review the data available to me and to reevaluate the relationships between the rates of mental rotation and various experimental conditions. The rate of mental rotation is to be expressed by the slopes obtained either by the authors of articles themselves or by visual estimation from figures inserted in articles. The slopes obtained by the visual estimation, which are hereafter indicated by being asterisked, should of course be rough and inaccurate. However, in this review slope values are to be classified into three categories with their differential limits by power of 10 (i.e., more than 10 ms/deg, or *Category A*; between 1 ms/deg and 10 ms/deg, or *Category B*; and less than 1ms/deg, or *Category C*), so fluctuations caused by the inaccurate visual estimation should be sufficiently small comparing with the wide categorical ranges.

The conditions to be specified in this review include the dimensionalities (i.e., 3-D figures projected onto 2-D plane and 2-D figures on 2-D plane), stimulus types (e.g., Shepard-type block figures, alphabets, random figures, symbol-like figures), presentations of stimulus pairs (i.e., simultaneous presentations, sequential presentation, and single presentations of compared figures), types of non-identical figures (i.e., mirror reflected versions of identical figures and other types of non-identical figures), response types (i.e., identity judgments and object namings), and other experimental specificities (e.g., amount of practice, stimulus complexities, axes of rotation). Unless otherwise noted, the rates of mental rotation are only to be computed to the correct judgments of identical stimulus pairs.

Review

Category A: Rates of Rotation Higher Than 10 ms/deg

In Metzler and Shepard (1974), which was the detailed version of Shepard and Metzler's (1971) initial report, they employed standard 3-D Shepard-type block figures (see Figure 1) as stimuli with the simultaneous presentations of stimulus pairs. Pairs consisted of identical figures and their mirror reflected versions. The subjects made extensive number of judgments (amount to 1600 trials). In Experiment 1 the obtained slope of latencies against the angular disparities was 20.0 ms/deg* in the condition of the picture plane as the axis of rotation, and the slope was 17.5 ms/deg in the depth plane condition. In their Experiment 2 they attached end-of-structure signs to both end blocks of each figure. The slope in the picture plane condition was 21.6 ms/deg*, and that in the depth plane was 26.6 ms/deg*.

Hochberg and Gellman (1977) invented 2-D antennal line figures as stimuli with their complexities defined by the numbers of antennas in the figures. Non-identical pairs consisted of standard figures and their mirror-reflected versions. The stimulus presentations were simultaneous. Although there existed individual differences, the slopes for complex figures varied from 12.5 to 18.7 ms/deg*. On the other hand, the slope for simple figures varied from 1.5 to 4 ms/deg*.

In Experiment 1 of Yuille and Steiger's (1982) the stimulus pairs adopted were standard Shepard-type 3-D block figures, and presented pairs were either mutually identical or mirror reflected. The presentations of the stimuli were simultaneous and required rotation was vertical (around Y) axis. It must be noted that an inspection of only the bottom half of a Shepard-type figure was sufficient to judge its (non-) identity with the partner of a pair. In other words, the standard Shepard-type figures afforded redundancy information. The subjects in the experimental group were informed such redundancy information, whereas the subjects in the control group did not receive the redundancy information. The slope for the control group was 11.0 ms/deg, and for the experimental group it was 6.0 ms/deg. In Experiment 3 of the same study, the number of blocks of Shepard figures was extended from the original 10 blocks to 17. The presentations of the stimuli were simultaneous, and each non-identical stimulus pair consisted of a standard figure and the figure whose top, or a middle, or bottom part was twisted in a different direction from the original standard. The obtained slope was 33 ms/deg. By comparing the standard Shepard figures with the extended ones, they claimed that the complexity effect was present.

Experiment 1 of Steiger and Yuille's (1983), investigating the effect of memorization of stimulus figures on the rate of mental rotation, divided the subjects into "simultaneous" condition and "memory" condition. The subjects in the memory condition studied simultaneously presented standard and mirror reflected Shepard's figures in practice, and then made standard/reflected judgments of singly presented figures in test. The slope for the simultaneous presentation was 10.2 ms/deg and that for the memory condition was 2.1 ms/deg.

Parsons (1987) systematically investigated the effect of the axes of rotation on the rates of mental rotations with the use of Shepard-type identical and mirror reflected pairs. The fastest rotation was obtained by the horizontal axis (15 ms/deg). The rotation by the vertical axis proceeded with the rate of 24 ms/deg and that by the line of sight 29 ms/deg. The rates of rotation by other non-canonical axes varied from

24 to 41 ms/deg.

Experiment 1 of Just and Carpenter (1985) employed 3-D cubes projected onto 2-D plane as stimuli. Each of their surfaces was marked by an alphanumeric character. The task required of the subjects was the judgments of possible (non-) identities of simultaneously presented pairs of cubes in terms of alphanumeric marks. The subjects were free to choose any axis to rotate about. The slope for the subjects with low spatial ability was 55.5 ms/deg, whereas for subjects with high spatial ability it was only 8.3 ms/deg.

Folk and Luce (1987) intended to effectively manipulate such experimental factors as stimulus complexities and inter-stimulus similarities with the use of 2-D random polygons. The number of sides embedded in a polygon determined the complexity of the polygon. A non-identical pair consisted of a standard polygon and its mutant which was generated by the perturbation on the locations of the respective vertices of the standard. The amount of the perturbation determined the degree of similarity between a standard and a mutant. The preparatory rotation method was employed in the experiment in which each subject was requested to perform mental rotation of an initially presented standard figure for a specific angle and then he/she was to make an identity judgment with a subsequently presented compared figure. The rate of mental rotation was measured by the latency of preparatory rotation. The results indicated that the slope for complex stimulus pairs with high similarity was 38 ms/deg*, and that for simple pairs with low similarity was 20 ms/deg*.

Bethell-Fox and Shepard (1988) used a new stimulus type of random filled-in matrices in order to control the figural complexity. The familiarity with stimulus figures in terms of the amount of practice was also controlled. The preparatory rotation method was employed to measure the rates of mental rotation. In the condition of complex stimuli with little practice the slope was 49 ms/deg. In their extensive practice conditions the slopes were less than 10 ms/deg (i.e., for complex figures, 9.2 ms/deg; for simple figures, 4.8 ms/deg).

Category B: Rates of Rotation Between 1 ms/deg and 10 ms/deg

Cooper and Shepard (1973), using alphanumerics as stimuli, asked subjects whether the presented disoriented characters were normal or reflected versions. The obtained slope from the characters' upright position was 3.0 ms/deg*. When the preparatory rotation paradigm was applied as the presentation, the slope from their upright position was 2.2 ms/deg*.

Cooper (1975) attempted to clarify the effect of figural complexity on the rate of mental rotation of random polygons. One of the outstanding characteristics of this study was that the subjects were exposed to specific stimulus figures in extremely large number of times (i.e., each subject made more than 4800 judgments about eight standard polygons and their reflections). In Experiment 1 the subjects memorized eight standard polygons at the upright position and then were required to determine whether a presented compared figure was a standard or a reflected version. The obtained slope for the standard was 2.1 ms/deg. At the same time no complexity effect was found. In Experiment 2, where the preparatory rotation paradigm was adopted, the slope for the preparation was 2.7 ms/deg.

In Cooper and Podgorny's (1976) subjects were required to discriminate memorized standard random polygons from their perturbed ones by the preparatory rotation method. The results showed that, while the time for the judgments stayed constant whether they were identical or not, the preparatory rotation time increased linearly with the increase of angular departure from the memorized positions of the standards (i.e., 1.6 ms/deg*). However, it must be noted that the subjects of this study were same in Cooper's (1975) and thus had extensive exposure to the kind of stimuli and to the experimental situation.

In Experiment 2 of Eley's (1982) subjects were required to memorize the labels of unfamiliar letter-like symbols in training blocks. Then in each trial of experimental blocks each subject was asked to determine whether a singly presented symbol was normal or reflected. The obtained slope was 4.3 ms/deg*.

As was already mentioned in *Category A*, the experimental group of Experiment 1 of Yuille and Steiger's (1982), which received the redundancy information about Shepard-type block figures, showed its slope 6.0 ms/deg. Also having been mentioned, the memory condition of Experiment 1 of Steiger and Yuille (1983), in which procedure Shepard-type figures had been memorized prior to their standard/reflected judgments, yielded its slope 2.1 ms/deg.

Robertson and Palmer (1983) invented a new stimulus type of large sized capital letters F, R, reflected F, and reflected R (called global letters) made of smaller sized letters F, R, and their reflections (called local letters). The task in Experiment 1, using the simultaneous presentation, required of the subjects to respond "yes" if the global, the local, or both global and local aspects were normal letters. The slope when letters at the local aspect were normal was 1.1 ms/deg*, at the global aspect 1.2 ms/deg*, and at both aspects 0.8 ms/deg*, respectively.

In Experiment 1, Corballis and McLaren (1984) timed the judgments about stylized alphabets *p*s and *q*s (or equivalently, *b*s and *d*s) in different angular orientations. There were four conditions: (a) each letter was to be identified as a *b* or a *d*, (b) each was to be identified as a *p* and a *q*, (c) each was to be identified as a *b* and a *p*, and (d) each was to be identified as a *d* or a *q*. The conditions (a) and (b) concerned left-right discriminations, and the conditions (c) and (d) up-down discriminations. The slope concerning the up-down discriminations was 1.7 ms/deg*, and the slope concerning the left-right discriminations 2.2 ms/deg*. In Experiment 3 the researchers presented subjects with nonverbal patterns each of which consisted of a straight line with a dot located to one side and toward one end. Hence, the nonverbal patterns were equivalent to *p*, *q*, *d*, and *b* in which the rounded parts of these alphabets were replaced with the dots. The slope for the top-bottom discriminations was 1.3 ms/deg* and that for the left-right discriminations 1.8 ms/deg*.

Shepard, S. and Metzler, D. (1988) orthogonally varied dimensionality of objects (i.e., 2-D vs. 3-D) and type of tasks (i.e., simultaneous presentation vs. single presentation) in their experiment. For the 2-D condition the discriminations of random polygons from their reflected versions were required and for the 3-D condition identity-reflection discriminations with the use of reduced Shepard-type block figures (consisting of 7 blocks instead of standard 10 blocks) were conducted. As to single presentation paradigm, the obtained slopes were 2.1 ms/deg for 2-D objects and 2.9 ms/deg for 3-D objects, respectively. Likewise, concerning the simultaneous presentation, the slopes were 6.4 ms/deg for 2-D objects and 7.7 ms/deg for 3-D objects, respectively.

In Jolicouer's (1985) subjects were asked to name as quickly as possible drawings of natural objects. In Experiment 2 the slopes dropped both with practice (i.e., 1.4 ms/deg* for 1st block and 0.4 ms/deg* for the

3rd block) and with stimulus familiarity (i.e., 0.9 ms/deg* for unfamiliar objects and 0.5 ms/deg* for familiar objects). In Experiment 4 he made use of left/right decision task to the same stimuli as in Experiment 2 and obtained the slope of 2.3 ms/deg*.

Corballis and Cullen (1986) asked subjects to decide the location of an asterisk placed to the left, right, top, or bottom of each disoriented alphabet (Experiment 1), and of each disoriented unfamiliar architectural symbol (Experiment 3). In Experiment 1, the slopes obtained for left-right decisions were around 1.8 ms/deg irrespective of structures of alphabets (i.e., they classified stimulus alphabets into vertically symmetrical letters, horizontally symmetrical letters, and asymmetrical letters), whereas the slopes for top-bottom decisions ranged 0.4 ms/deg and 0.7 ms/deg according to the structures. As for Experiment 3 the slopes varied very widely according to the structures (0.5 ms/deg to 2.1 ms/deg) in top-bottom decisions. For left-right decisions the slopes became more converged on 1 ms/deg (i.e., 0.9 ms/deg and 1.2 ms/deg).

Maki (1986) had subjects name outline drawings of common objects. Experiment 1 consisted of four blocks of 24 trials with each block containing all stimulus pictures once. The average slope was 1.9 ms/deg. However, when looking at slopes at respective blocks, the practice effect seemed evident (i.e., 1.5 ms/deg* for the 1st block; 0.3 ms/deg* for the second, third and fourth blocks collapsed). In Experiment 2 she asked subjects to decide whether or not two simultaneously presented symmetrical pictures would face in the same direction had one (i.e., the compared) picture been turned to its upright position. Thus the task was identity-reflection discriminations. The average slope was 1.9 ms/deg*.

Takano (1989) proposed a theory of information types based on five consecutive experiments. In Experiment 1 a target figure consisting of line segments and a box derived three distractor figures. The three distractors and their respective condition names were: the reflection of a target figure (*R*elative *O*rientation condition), the substitution of a curved line for a-line segment (*I*dentity condition), and the reflection of the line segments but the conservation of the location of the box (*C* ombination condition). At the onset of the experiment, the subjects were asked to copy the upright target on paper with pencils. For the simultaneous presentation, where the target and either the target or one of the distractors were presented side by side, the slopes were 3.6 ms/deg* for the *RO* condition, 0.3 ms/deg* for the condition *C*, and near 0 ms/deg* for the condition *I*, respectively. For the single presentation paradigm, where either the target or a distractor was singly presented, the slope was 3.2 ms/deg* for the *RO* condition, and near 0 ms/deg* for both *C* and *I*. Thus as far as the *C* and *I* conditions in both simultaneous and single presentations were concerned, the slopes belonged to the *Category C*. In Experiment 2 he employed a Chinese character as a standard figure and its partially transformed version (*C*) and its reflection version (*RO*) as non-identical compared figures. In a three-session experiment the subjects were required to make simultaneous presentations at the session 1 and single presentations at the sessions 2 and 3. The subjects were classified into two groups: an *instructed group* whose subjects were informed of the presence of a *C* change in the transformed version and a *non-instructed group* which did not receive such information. The slope at the first session of the *instructed group* was 1.8 ms/deg* and it was nearly identical to that at the first session of the *non-instructed group*. However, as to the third session, the slope for the non-instructed group was 1.2 ms/deg and for the *instructed group* the slope was almost flat.

Paquet (1991) examined whether or not mental rotation of compound stimuli is holistic. The employed stimuli were those of Robertson and Palmer's (1983). Under the divided attention task the subjects were instructed to respond "yes" if the global aspect (the global-only condition), the local aspect (the local-only condition) or both aspects (the both condition) were normal letters. The focused attention task of the global-directed session required of the subjects to decide whether the global aspect was normal letters irrespective of the local letters. Likewise, the local-directed session required of the subjects only to decide the versions of the local letters. The slopes for the both, the global-only and the local-only conditions under the divided attention task were 3.6 ms/deg, 5.0 ms/deg, and 5.5 ms/deg, respectively. Under the focused attention task the slopes for the both and the global-only conditions in the global-directed session were 2.7 ms/deg and 2.7 ms/deg, and the slopes for the both and the local-only conditions in the local-directed session were 3.0 ms/deg and 2.9 ms/deg, respectively.

Corballis and Corballis (1993) asked subjects to judge whether a small bar perpendicular to one side of a clock hand would point left or right if the hand had been pointing at the 12:00 position. The clock hand was shown in two successive orientations 30° apart, and thus induced apparent motion. The bar appeared at the first presentation of the clock hand on half of the trials and at the second presentation of the clock hand on the other half of trials. Obtained latencies against the angular departures of the bar from the upright position showed that the subjects mentally rotated the clock hand before making the decisions. At the same time, it was found that the apparent motion dragged the orientation from which the clock hand was mentally rotated. Mental rotation of the clock hand was not affected by this drag when the bar appeared at the second presentation. In the second presentation condition the slope was 2.8 ms/deg* when the direction of the apparent motion was clockwise, and 2.3 ms/deg* when the direction was counterclockwise.

Cohen and Kubovy (1993) systematically investigated the effects of experimental paradigms, stimulus types, stimulus complexities and other factors on the rates of rotation in their Experiment 1. As to the experimental paradigms, the slopes were greatest for the simultaneous presentation (i.e., 2.9 ms/deg), intermediate for the sequential presentation (i.e., 1.7 ms/deg), and smallest for the preparatory rotation paradigm (i.e., 0.2 ms/deg). There was no difference of slopes between random matrices and random polygons (1.4 ms/deg vs. 1.8 ms/deg). Here, it is necessary to note that the authors used only two polygons and two matrices as standards. Complexity had no effect on slope either (1.6 ms/deg for simple figures vs. 1.6 ms/deg for complex figures). In Experiment 2 still using only two standard polygons, subjects were given pressure to hasten identity-reflection discriminations while maintaining error rates low (RT pressure). The slope was 0.7 ms/deg for simultaneous presentation and -0.08 ms/deg for sequential presentation. In Experiment 4 they generated total of 1440 simple and complex polygons as standards. Under RT pressure the slope was 3.9 ms/deg while when there was no pressure the slope was 7.6 ms/deg. Still no complexity effect was found.

Several derivative conditions of *Category A* studies had the rates of rotation below 10 ms/deg: discriminations of Shepard-type block figures with redundant information (Yuille, & Steiger, 1982), and with memorization procedure (Steiger, & Yuille, 1983); identity judgments of cubes in terms of surface information by subjects with high spatial ability (Just, & Carpenter, 1985); identifications of random matrices after extensive practice (Bethell-Fox, & Shepard, 1988); and discriminations of simple antennal line figures from their mirror reflections (Hochberg, & Gellman, 1977).

Category C: Rates of Rotation Less Than 1.0 ms/deg

Corballis, Zbrodoff, Shetzer and Butler (1978) had subjects make timed decisions about alphanumerics. In Experiment 1 the subjects were asked to name singly presented normal and backward characters in two blocks which contained 72 characters each. The angular disparity effect was only significant for backward characters in the block 1 (slope=0.3 ms/deg*). The effect was not significant for normal characters in the block 1 nor for either versions in the block 2 (i.e., the slopes were assumed to be nil). In Experiment 3 there were two different tasks: identification task and orientation task. The identification task requested each subject to press one button whenever a given goal character (both normal and backward) appeared and to press the other button in all other cases. In the orientation task each subject was assigned a given orientation in advance and told to press one button whenever a character appeared in that orientation regardless of the character. As to the identification task the slopes were 0.5 ms/deg* for backward versions and 0.3 ms/deg* for normal versions. For the orientation task, although ANOVA showed a significant angular effect, the results gave bimodal distribution of latencies against angular disparities irrespective of versions (peaked at 60° and 300°). Thus respective inspections of the latencies to both versions yielded near flat slopes.

In Corballis and Nagourney's (1978) subjects were instructed to decide whether a presented alphanumeric was a letter or a digit. The latencies against the angular disparities from the characters' upright position showed that in the range of 0° and 300° they were virtually flat except at 240° where there was a sudden jump. In this respect no angular disparity effect was observed in the letter-digit decision task.

Experiment 1 of Eley's (1982) required of subjects to name unfamiliar letter-like symbols whose labels had been learned in training (see *Category B* for his Experiment 2). Two variables were taken into account beside angular disparity: symbol familiarity and identification set size. Naming was faster for symbols in a small set size but the familiarity did not have an effect. Although angular disparity effect was detected by ANOVA, the inspection of the latencies indicated almost flat slopes.

As was already mentioned in *Category B*, Jolicoeur (1985) made use of drawings of natural objects as stimuli. In Experiment 1 subjects were instructed to name water color drawings of natural objects. The stimuli were divided into six blocks of 36 trials. The slope for the first block was 0.6 ms/deg* while that for the sixth block approximated to nil. Therefore evidently there was the practice effect. Such decrement of latencies below 1.0 ms/deg was also observed in the practice condition (0.4 ms/deg*) and familiarity condition (0.5 ms/deg*) in Experiment 2.

McMullen and Jolicoeur (1992) employed line drawings of objects as stimuli. Three different tasks were assigned to each subject in Experiment 1. In top-bottom discrimination task the subjects were instructed to enunciate "top" or "bottom" to indicate the location of a mark which appeared in the proximity of top or bottom of each disoriented object. In old naming task the subjects were asked to name objects which they had already seen in the top-bottom discriminations. In new naming task the objects to be presented had not been used in the top-bottom discriminations. As for the top-bottom discriminations the slope of latencies against the angular disparities from the objects' upright position was 0.6 ms／deg*, and for the naming (including both old and new objects) the slope was 0.6 ms／deg*. And thus there was no difference in the effect of orientation across tasks. However, the effect of stimulus orientation was smaller for the old naming task than for the new naming task (0.3 ms／deg* for the former slope, and 0.6 ms／deg* for the latter).

Some conditions of *Category B* studies yielded the slopes less than 1.0 ms／deg. Such were, for example, top-bottom decisions of alphabets (Corballis, & Cullen, 1986); naming of common objects after extensive practice (Maki, 1986); discrimination of a curved line from a straight line (condition *I*) and judgment of the location of a box whether at the end of a line segment or at the intersection of two lines (condition *C*) (Takano, 1989); and discriminations of overlearned standard random polygons under the pressure to hasten response (Cohen, & Kubovy, 1993).

Evaluations

Dimensionalities and Types of Stimuli

One of the predominant factors to influence the rates of mental rotation was the dimensionalities of stimulus figures. In *Category A*, six out of nine experiments were those with 3-D stimulus figures projected onto the 2-D plane. In *Category B,* where 26 experiments were listed, there were only three experiments with the use of 3-D dimensional figures. And there was no case of 3-D stimuli in *Category C.*

Dimensionalities and types of stimulus figures were closely related. The 3-D studies were almost limited to those used by the Shepard-type block figures with the only exception of Just and Carpenter's (1985) cube manipulations. For 2-D studies stimuli could roughly be divided into two groups: nonsense stimuli and meaningful (or well-known) stimuli. Random polygons, random matrices and antennal figures were in the former group, while the latter group typically included alphanumerics and drawings of common and well-known objects. Although studies with the use of nonsense stimuli and those with meaningful stimuli were intermixed in *Category B*, studies in *Category C* employed predominantly meaningful stimuli. There were a few 2-D experiments in *Category A* but these experiments all used nonsense stimuli. Thus it seems evident that mental rotation would be facilitated when stimuli are meaningful and slowed when they were nonsense.

Practice

Practice had a clear decremental effect on the rates of mental rotation. Comparing Cohen and Kubovy's (1993) Experiment 4 with their Experiment 1, it seems evident that memorization of specific stimuli contributed to the faster rotation. However, it would be noteworthy that the practice effect was still observed in object naming tasks (e.g., Jolicoeur, 1985; Maki, 1986) even though the association between the internal representations of common objects and their names should have been sufficiently established. For these tasks the memorization of stimuli should not be considerable for the cause of the faster rotation. Rather, the formation of stronger connections between internal representations and corresponding motor responses would better explain the reduction of the slopes. Thus, that the identifications of alphanumerics and namings of common objects were in the fastest category of rotation (e.g., Corballis, Zbrodoff, Shetzer, & Butler, 1978; Eley, 1982; Maki, 1986) would comprehensively be explained by the overlearning and complete memorization of these items on the one hand and by the already existed strong connection between the memorized items and motor responses to them (i.e., implicit or explicit utterance of names and labels) on the other.

Complexity

Despite the initial reports of the absence of the complexity effect by Cooper (1975) and others, subsequent studies gave strong evidence for the presence of the effect (e.g., Yuille, & Steiger, 1982; Folk, & Luce, 1987; Bethell-Fox, & Shepard, 1988; Pellegrino, Doane, Fischer, & Alderton, 1991). However, more recent study by Cohen and Kubovy (1993) could not find the effect. On this point one note will be worth: beside the argument that complexity effect directly reflects the nature of internal processing, which is the basic tenet of the propositionists, a certain alternative explanation seems possible for the occurrence of the complexity effect. In this respect, it would be necessary to scrutinize the experimental conditions when the effect appeared and when not.

Most prominent characteristic of the experiments reporting the absence of the effect (including Cohen, & Kubovy's) was that specific standard stimuli were exposed to subjects with extensive repetition. On the other hand, most experiments showing the presence of the effect used many standard figures, by which relatively good control of stimulus specific factors was obtained. Thus, at least as far as 2-D figures and symbols are concerned, repeated presentations of unstable and fragmented representations about a complex figure will work to combine themselves into a unitized representation. If such unitization occurs, the speed and efficiency of the processing will increase, and there will be no more complexity effect beyond when the speed comes to be asymptotic. This inference based on the degree of memorization is in accord with the results concerning the practice effect and the complexity effect and also relevant to the effect of stimulus presentations.

Stimulus Presentations

As Cohen and Kubovy (1993) explicitly noted, the slopes obtained in the simultaneous presentation paradigm were greater than those obtained in the single presentation paradigm. In most naming tasks the slopes were in the category of fastest rotation. This order of the rates of rotation is consistent with the just stated memorization account. However, these results should not be a surprise when we design experiments with the use of stimuli having varying degrees of familiarity. The simultaneous presentation is generally required for unfamiliar stimuli because this paradigm enables subjects to make concurrent checking on both a standard and a compared figure. The quality of both (or at least standard) figures in representation need not be high. Whereas, for the single presentation paradigm to be feasible, standard figures must have been firmly established in representation prior to the comparison time. For their firm establishment, the procedures like extensive memorization and practice on a small number of figures are usually necessary. As to the naming task of alphanumerics and common objects, subjects have abundant experience to encounter such symbols and objects in their daily lives, and thus their representations have been sufficiently established together with the strong association between represented objects and their attached labels.

To sum up, the more is an object in representation firmly established via memorization, however complex it is, the more will it be unitized as a holistic entity. Consequently, the decline of the slope will come about. For example, when rotation of many standard polygons is requested, or inversely, each polygon is rather poorly memorized, the rotation generally takes more than 20 ms/deg (see Folk, & Luce, 1987). But the rate will drastically decline to less than 1.0 ms/deg, or to the level of the identifications of alphanumerics and common objects, when only two highly memorized random polygons are used as standard stimuli (see Cohen, & Kubovy, 1993). The implication seems clear: the rate of rotation is determined by the degree of memorization, or the degree of cohesiveness, of a represented object.

Other Factors

Researchers have asserted that other factors like redundancy information (Yuille, & Steiger, 1982), spatial abilities (Just, & Carpenter, 1985), attention (Podgorny, & Shepard, 1983; Paquet, 1991), and RT pressure or the pressure to urge quick responses (Cohen, & Kubovy, 1993) should be involved in determining the rates of mental rotation.

Subjects' ability to make use of redundancy information would be favorable to the propositional position in that possessing the knowledge about a part figure facilitates the rate of mental rotation which should be indivisible and cohesive by the analog holistic assumption. Yet, there is an alternative explanation. That is to say, it may not be the knowledge by itself but a highly resolved image of a part figure that facilitates mental rotation. This explanation necessitates to loosen the imagists' coherency principle by allowing the quasi-separate accessibility to a part of an image of a whole object.

The effects of attention and RT pressure on the rates of mental rotation could be construed as direct evidence for the presence of the cognitive penetrability and thus are also siding with the propositional explanation. However, this interpretation has not without room for contradictions. Firstly, the claim of the cognitive penetrability in itself is a dubious criterion (see Johnson-Laird, 1983, p.152). Secondly, the modified coherency principle stated above will be able to incorporate the results indicating the attentional control on the rates of rotation and still can maintain the imagists' principle concerning the analogous structure between an external object and its internal representation. Thirdly, besides the cognitive penetrability, the implication for the RT pressure condition seems tenuous. Namely, the pressure was only defined by the experimental procedure and no other possibility of the involvement of a cognitive factor as truncation of confirmation processings or utilization of redundancy information was considered.

As to the abilities of spatial cognition, it is also difficult to evaluate the presence of individual differences as favorable either to the analog or to the propositional position.

Concluding Remarks

It is evident that the rates of mental rotation are affected by dimensionalities and types of stimulus figures, degree of memorization, complexities of figures, methods of stimulus presentations and others. Therefore, in overall, due to the significant susceptibility of internal processing to such external experimental/stimulus variables, the analog holistic position based on the coherency principle is most difficult to be upheld. However, as far as the data obtained in this study are concerned, it is indeterminate whether the modified analog explanation or the propositional explanation should be more plausible.

However, these experimental / stimulus variables do not seem to influence the internal representations and processings separately but do them interactively. Or in some cases, an apparent effect of some variable might better be conceived as a manifestation of the effect of other more fundamental variable. What has become sufficiently clear is the flexibility of the cognitive system to accommodate vastly different types of stimuli in completely different experimental settings and procedures. Nonetheless, the system can perform very efficiently to reach correct identifications and judgments. Especially important role seems to be played by memorization. Although the effect of stimulus memorization has often been a focus of mental rotation experiments, scarcely has the metamorphic aspect of memorization in cognitive activities been argued. In this respect, without sufficiently controlling the memorization factor, any claims about mental representations and processings will become futile in future researches.

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