In C. Cornoldi & M. A. McDaniel, Imagery and Cognition. New-York: Springer-Verlag, 1991 (pp. 247-282).

8

A Developmental Approach to Mental Imagery

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The development of capacities for mental imagery has been dealt with in both Piagetian theory and in theories of information processing (IP). The aim of the present paper is to examine the assumptions, methodology, and main findings in these two approaches, with specific focus on the development of the capacity for mental images of transformation in the child. The first part of this paper reviews the main issues in Piagetian and IP studies. Comparison shows that each field has identified a specific mode of representation. It is argued that relating these two modes of representation may be a powerful tool in conceptualizing the development of spatial operations.

8.1 Piagetian Studies

Mental imagery is one facet of the argument Piaget developed to refute the empiricism of his day. Early scientific psychologists were heavily influenced by empiricism and considered mental imagery to be an outgrowth of perception which itself was thought to mirror reality. Piaget first showed that perception involved more than passive reception, and was an active process of composition of centrations. He then undertook to demonstrate that mental images were not residues of perception but rather had their source, like perception, in action.

Piaget considered that mental images are subordinated to action because of their source, and because of their mode of structuration. In terms of source, Piagetians view mental imagery as proceeding from accommodation of action schemes (when an object cannot be assimilated - i.e., "incorporated"- in an action scheme, this scheme can be changed so that, ultimately, assimilation becomes possible). Imitation (first in the presence of a model and later in absence of the model) arises from the accommodation of action schemes elaborated during the sensory motor period. Mental images result from the internalization of imitation and appear at about 18 months along with the other features of the symbolic function. With respect to mode of structuration, Piaget considered that mental images of movement or transformations involve imaging a sequence of intervening steps. Children are only thought to be able to generate this type of representation when mental imagery is driven by operations, since only operations resulting from action coordination can incorporate the dynamics of sequencing.

Most of the Piaget and Inhelder volume on mental images in the child (1966 for the French edition; 1971 for the English edition) is devoted to substantiating these claims. As a first step, Piaget and Inhelder classify mental images into three general categories:

- static images, found in representations of states or configurations
- kinetic images, found in representation of movements of non-deformable objects
- transformational images, found in representations of deformation of objects.

Piaget and Inhelder tested a broad age range of children in situations where they were asked to represent static objects (e.g., a rod or a square), the movements of these objects (e.g., rotation or translation), or transformation (e.g., the unfolding of a cube). In these tasks the subjects are asked to externalize their representations through drawings, statements, or gestures.

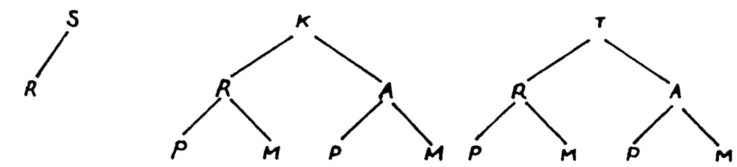

Figure 8.1. Graph summarizing the classification of mental images in Piaget and Inhelder's book (1966). S= Static, K=Kinetic, T= Transformation; R= Reproduction, A=Anticipation; P= Product, M= Modification.

The questions children are asked for transformational and kinetic images deal with the modification itself, i.e., the sequence of intervening steps, or the end state. Piaget and Inhelder make an additional distinction between reproductive mental images, where subjects are asked to represent a change they have already seen (perceptual experience), and anticipatory images where individuals are asked to represent a movement or transformation that they have never seen. The diagram in Figure 8.1 summarizes this classification.

8.1.1 Experimental Work in the Piagetian Perspective

Two experiments are described below to illustrate these distinctions and the type of methodology used to test for mental imagery capacities.

Translation of Squares. This task is classified in the reproductive kinetic images category. Square S' is placed on top of square S with both squares in the frontal plane. The subject is asked to imagine that the square on top moves slightly from the left to the right, i.e., moving from the state shown in Figure 8.2a to the state shown in Figure 8.2b.

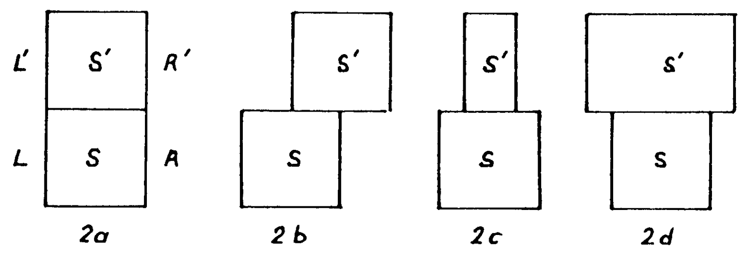

Figure 8.2. Translation of squares (from Piaget & Inhelder, 1966, p. 67).

Subjects aged 4 to 7 are then asked to draw the position of the squares after this movement (Figures 8.2c and 8.2d show typical mistakes) and then are asked to pick out the correct illustration from a series of drawings. After the drawing and choice phases they are questioned about the end state. They are then shown the correct illustration (Figure 8.2b) and are asked to copy it as a measure of static imagery.

Flipping a Tube. This example illustrates the difference between the anticipation of the end state, and anticipation of modification in a kinetic image task. A cardboard tube with one red end and one blue end is placed on a box such that one end extends. The experimenter strikes this end so that the tube flips up and over and then removes it immediately from the subject's field of vision. The subject is then asked to draw the position of the tube at the start and at the end, and indicate the position of the red and blue ends at both instances (example of anticipation of end movement). Subjects are then asked to draw the sequence of steps in the flip sequence and the trajectory taken by each of the ends, reproduce this movement holding the tube in their hands, and lastly describe the movement (anticipation of movement).

The Piaget and Inhelder (1966/1971) volume covers numerous experiments of this type dealing with the different categories of mental images. The two main findings for the entire set of studies are the following:

1. The sole developmental difference in ability for representation is between static vs kinetic and transformational images. Four to five year olds are able to correctly represent static configurations whereas movement and transformations are not mastered before ages 7-8, and thus appear at the same time as concrete operations.

   With respect to the distinction between reproduction and anticipation, Piaget and Inhelder conclude that "imaginal representation of a (known) movement or a transformation presupposes its reconstitution by a process identical to anticipation which enables the subject to represent an unknown movement or a transformation" (op. cit., 1966 p.416).
2. The anticipation of the end state of a transformation often developmentally precedes ability to correctly define the sequence of steps involved in the transformation. This is the case for example in the situation described above, where the subject is asked to anticipate the trajectory of the tube during the flip. The representation of steps in the sequence is not mastered before the age of 7-8, whereas correct identification of the end state, as demonstrated by drawings or verbatims concerning the endpoint (with correct permutation of the red and blue ends) is observed by age 5.

8.1.2 The Piagetian Interpretation

Result 1 is interpreted as confirmation of the subordination of mental images to operational structures since these structures appear roughly at the ages of 7-8. Piaget's explanation for this subordination is basically the following: "Any imaginal anticipation of movement or transformation presupposes that the images follow one another in order of succession ... such order derives from operational seriation" (op.cit., 1966, p.424).

"Anticipatory images frequently require a conservation frame and only an operation can form this type of frame" (op.cit., 1966, p.424).

Typical mistakes on the Translation of Squares Task can clarify this interpretation. Let L and L' respectively be the left sides of squares S and S', and R and R' be their right sides (see figure 8.2). One of the most common errors in preoperational children consists of placing R' to the right of R, and L' to the left of L to represent the end state (see fig 8.2d). The resulting dilated upper "square" thus extends to either side of the lower square. According to Piaget, this error can be accounted for by these subjects' inability to coordinate the ordering of right and left sides after the movement has occurred. Because they do not possess the structure which would enable them to carry out this operation, the youngest subjects expect that R' will extend beyond R and draw a symmetrical configuration on the left side (i.e. with L' to the left of L). The resulting dilation of the upper "square" is only rejected by subjects who have realized that movement conserves lengths, but this knowledge is also subordinated to the development of concrete operational structures.

Piaget accounts for the second finding - that the representation of end states may at times precede correct representation of the intervening states - by the fact that the outcome of a movement or translation is in fact a state, and that correct representation of the static mental image (mastered younger) is sufficient to represent the modified end state (see op.cit., p.415).

8.1.3 Discussion

Bear in mind that the methodology used by Piaget and Inhelder only tests indirectly for a direct link between concrete operations and mental representation of movement and/or transformations. In their series of experiments, the children were not tested simultaneously on tasks other than mental imagery which would have served to test their operational level, in particular as regards seriation and the conservation of length. The only empirical support for the interpretation that mental representation of movement and

transformation is dependent upon attainment of concrete operations is average age at mastery, and this is inferred from the low success rate on Kinetic and Transformation tasks before the age of 7-8. This interpretation however does not preclude the possibility that the two abilities develop simultaneously on parallel paths and are subordinated to a common source, or even (as farfetched as this may be) that the development of operations is subordinated to mental imagery.

The Piagetian interpretation of the second result is fairly unconvincing. Although the outcome of a movement or a transformation is a state, it is the final state of a process. It is difficult to understand how a child could represent this specific state without being able in one way or another to represent the transformations leading up to it. If children do have this ability, the argument for subordination of Kinetic and Transformational images to concrete operations is undermined, and implies on the contrary that the development of one form of mental imagery is not subordinated to concrete operations. Studies in information processing lend support to this line of reasoning.

8.2 Studies on Mental Imagery in the Framework of Information Processing

Whereas Piaget's studies were motivated by the empiricism-constructivism controversy, the more recent debate forming the backdrop to investigations in information processing opposes researchers on the issue of the nature of mental imagery. The anti-mental imagery argument claims that all forms of representation, including mental images, have a "propositional" (see for example Anderson and Bower, 1973; Fodor, 1975; Pylyshyn, 1973) or "symbolic" base (Pylyshyn,1981). The pro-mental imagery school has contended that mental images are "analog" representations although they do not reject the notion of a propositional mode of representation (see for example Kosslyn, 1980; Paivio, 1977; Shepard & Cooper, 1982). In propositional or symbolic theories a representation can be broken down into more elementary units -propositions- in which the association between form and meaning is arbitrary and context-free. In contrast, analog theories argue that some isomorphism is preserved between the perceptual and represented worlds. Subjects are thought to abstract wholistic representations in which certain properties such as distance and size are indissociable.

Most mental imagery studies in the framework of IP have been designed to test the explanatory power of these theories, in particular as regards isomorphism.

In contrast to Piagetian studies which focus more specifically on developmental issues, IP studies on mental representations of transformations have used trained adult subjects.

8.2.1 Hallmark Experiments and Findings

8.2.1.1 Mental Rotation

The prototypical experiment in this area was conducted by Shepard and Metzler (1971). Subjects are taught to distinguish a standard shape from its mirror image. In the next phase, subjects are shown test stimuli of the standard or symmetrical figure which have been rotated to various degrees from the orientation of the standard figure. The task consists of indicating whether the test stimulus is the same or different from the standard stimulus by a keypress. The dependent variable is response time. The findings show that response time and angular disparity between the test stimulus and the standard obey a linear function.

8.2.1.2 Visual Inspection of a Mental Image

Kosslyn, Ball and Reiser (1978) asked subjects to memorize the map of a fictitious island containing a number of specific locations (hut, tree, well, beach, etc.). The map was then removed and subjects were asked to state whether a given location appears on the map or not. Subjects were asked the same series of questions in two conditions. In condition 1, the subjects were requested to form a representation of the entire map and to reply as quickly as possible whether the locations the experimenter read out were on the map. In condition 2, the subjects were first asked to form an image of the entire island and were told where one of the locations was on the map. Subjects were instructed to enlarge their mental representation of this location such that it occupied the entire field ("zoom in on the location"), and then to "see" whether the probe locations were on the map. Kosslyn et al. only obtain the linear relationship between response times and distances between locations in the condition 2, where subjects are asked to image.

8.2.2 Interpretations

Proponents and opponents of mental imagery assign different interpretations to the spatiotemporal isomorphism between the mental image of a rotation or a translation and their physical counterparts in the real world.

8.2.2.1 Proponents of Mental Imagery

Shepard and Metzler (1971) argue that the proportionality observed between response times and angular disparity are proof of the "analog" nature of mental images, in that the linear function indicates that the representation goes through a series of intervening states, each of which is in a one-to-one correspondence with the rotation of the corresponding physical object. This "second order isomorphism" is situated on a functional level and is evidenced by the fact that "the subject is especially disposed to respond to that particular object in that particular orientation at that particular moment - if it were actually to be presented." (Shepard & Cooper, 1982,p.102).

Kosslyn accounts for the spatiotemporal isomorphism between mental inspection of an image and perceptual exploration of the same scene by reference to the structural features of mental representations (Kosslyn, 1980). The forming of a mental image taps structures that are common to both perception and representation. Information stored in long-term memory in an abstract form is retrieved during recall in a visual buffer that is shared by perception and imagery. In Kosslyn's model, this structure takes up "space" and can be divided into cells. An image is formed by the activation of these "cells" in the same way that information transformed into an abstract form in an electron beam activates the points on the surface of a cathode ray tube. Visual inspection of an image consists of directing attention to the regions of the visual buffer that have been activated. The structural isomorphism between this activity and perceptual exploration stems from the fact that the specific properties of the representation are incorporated into the structure of the visual buffer itself.

8.2.2.2 Opponents of mental imagery

The mental imagery controversy has shifted somewhat in recent years. Debate on the existence of specific characteristics of mental imagery (see Pylyshyn, 1973) has ceased to be an issue. There is general consensus concerning the isomorphism between certain represented events and their imaginal representations, but what remains controversial is how this isomorphism is interpreted. In the physical world, there is a direct relationship between the duration of a movement, distance and speed. If this relationship holds when mental images are inspected as the Kosslyn experiments suggest, is this because of constraints inherent to the structure of the medium in which the image is generated, or is this due to tacit knowledge of the time/speed/ distance relationship on the part of the subject? Pylyshyn (1981) contends that proponents of the analog school of mental imagery rely on the first interpretation whereas he takes the latter position. According to Pylyshyn, if subjects' prior experiences affect the processing of mental images, this tacit knowledge should be cognitively penetrable. In other words, it should be possible to modify this knowledge by manipulating subjects' beliefs or tacit knowledge, whereas no effect should be observed if isomorphism is inherent to the structure of the medium. The underlying appeal to propositional models is manifest in Pylyshyn's reasoning: if the specific properties of the mental representation are based on tacit knowledge, these - like all forms of knowledge - can be represented in propositional form, thus eliminating the need to postulate a form of representation specific to mental images. We will not go into results confirming or disconfirming this claim since current evidence neither supports or infirms either theory.

8.3 Similarities and Differences Between the Piagetian and IP Approaches

Both Piagetian studies and work in the field of IP on kinetic and transformational mental images have explored the same types of representations: rotations, movements, unfolding, etc. The crucial issue for our purposes is whether the Piagetian findings on the relationship between the capacity for mental imagery and operational development are replicated when mental imagery is investigated within the framework of IP. Before examining the empirical data which shed direct light on this issue, we will examine similarities and differences in theoretical frameworks and methodology.

8.3.1 Theoretical Frameworks

The analog model of mental representation differs from both Piagetian theory and the propositional models, as far as transformational representation is concerned. Propositionalists and Piagetian theory alike make the assumption that the knowledge is structured in a unitary form and that different forms of representations are subordinated to this structure. In the Piagetian theory, perception, mental imagery, and language do not have distinct modes of structuration: the development of each of these forms of knowledge is subordinated to the development of logical structures.

Propositionalists and Piagetian theory also share the postulate that transformational representations are built up by operations or abstract rules that specify certain relationships between previously identified elementary features. For example, in the Piagetian experiment on the translation of squares, the subject presumably decomposes the square into its sides and orders sides L and L' and R and R' while coordinating their respective changes in position.

The analog hypothesis in contrast argues that there are a variety of representational modes of structuration. The analog approach also differs from the propositional approach with respect to the decomposition of mental images, in that analog hypothesis emphasizes the indissociability of certain properties. Lastly, the isomorphism between the visual experience of a transformation and mental images of transformation is as difficult to account for in Piagetian theory as in propositionalist models. In a certain way this difficulty is augmented by the nature of operational structures. Reversibility is the capacity to perform a same action in both the direct and the inverse way, with consciousness that it is the same action, allowing the subject to mentally return to the starting point. Reversibility, which is the key feature of operational structures, implies that every mental representation of a transformation is linked to other -virtual- transformations such that each simultaneously implies its counterpart. Thus knowledge acquired in structures of this type are atemporal as is the case for logical structures. How then can the subordination of mental imagery to this type of cognitive structure account for the temporal isomorphism between a perceptually observed transformation and its representation?

8.3.2 Methods

Since mental representations cannot be directly observed, their properties are inferred indirectly from the behavioral indices purported to be their outward manifestations. The two approaches use extremely different indices. In Piagetian studies, children are asked to externalize their representations verbally or through drawing. In IP studies, subjects are usually asked to press one of two keys indicating whether or not the test stimulus is identical to the standard stimulus, or to indicate that a feature named by the experimenter is or is not part of their representation.

Reliance on complex behavioral mediation in Piagetian studies has a number of drawbacks. One is that verbalization may have an effect on the properties of the representation. In addition, there is no way of telling whether the failure of young children to draw pictures of the stages in a transformation are due to defective mental images or to insufficient level of graphic ability. The IP paradigm keeps this risk to a minimum by reducing the response to a simple key press. However, this turns the experiment into a recognition rather than a production task, which has the effect of considerably diminishing the amount of information subjects provide on the properties of representations.

But above all, by asking subjects to express their representations verbally or graphically, the Piagetian approach makes the assumption that representations can be made explicit, whereas the IP approach is satisfied with an implicit representation of movement or transformation. In the latter case, the properties of the mental image are inferred from the response time curve and no explanation is demanded of the subject. In Piagetian studies questions concerning the intervening steps and their sequencing reflect the assumption that the representation of movement can be decomposed into a sequence of static steps. Similarly, objects are thought to be decomposed and recomposed by operations during the process of representing changes (for example, seriation operations are thought to affect the right and left sides of the squares in the translation task). The IP paradigm does not require a representation to possess this analytical feature: a global, non decomposable representation of the movement is sufficient here to anticipate the endstate of the transformation.

The major paradigms used to explore the properties of representations in each approach are coherent with their theoretical frameworks (note that most of the experiments in the IP framework have been conducted by proponents of the analog theory). Piagetian studies lend themselves particularly well to the identification of a decomposable, analytical and explicit form of representation whereas IP studies are more suited to identifying wholistic and implicit representations. Are the two really examining the same process ?

8.3.3 The Findings

A small number of studies have directly investigated the relationship between the development of operations and the development of the capacity for mental representation, using IP paradigms to test the latter. The findings are inconsistent.

8.3.3.1 Studies Disconfirming the Piagetian Assumptions About Relationships Between Mental Imagery and Operations

Several studies apparently demonstrate that preoperational children are able to generate mental images of movements or transformations. These results disconfirm the Piagetian assumption that these types of mental images are driven by operations, especially those allowing seriation and conservation. Marmor (1975) used the Shepard paradigm on a sample of 5 to 8 year olds. The abstract stimuli were replaced by drawings of pandas with one arm lifted. The children were asked to state whether the test panda, rotated to different orientations from the upright, was "the same" (the same front arm lifted) or "different" (the other front arm lifted) as the standard image presented vertically. Marmor successfully obtained the linear relationship between response time (RT) and the angular disparity between the standard and test figures as of age 5. The differences in age groups are related to

speed of mental rotation (faster at age 8), response time at 0° (which presumably tests for latency of other processes than rotation), and error rate (which increases with the angle of rotation and is highest at age 5). According to Marmor, these results contradict the Piagetian interpretation since the linear function present in 5 year olds indicates that the transformation is represented (in fact, a kinetic mental image in the Piaget and Inhelder classification). In other words, children can represent a transformation before having attained concrete operations.

Marmor replicated this experiment two years later using a modified paradigm designed to clarify two points. In the original experiment, training in rotation prior to the test session may have prompted subjects to implement a strategy they would not have used spontaneously. Second, the subjects were not tested directly for operational level, which was simply inferred from their ages. To correct for these possible biases, the 1977 experiment included a training vs no-training condition in mental rotation. The sample was composed of three age groups: 4 year olds, 5 year olds, and adults. Operational level was assessed by a number conservation task. The main findings are the following:

- both trained and untrained subjects exhibit RTs that are proportional to angular disparity. This suggests that at age 4 (the youngest subjects in this study) children can spontaneously implement a mental rotation strategy if necessary.
- no correlation was found between conservation of number and imagery: as many conserving as nonconserving subjects exhibited TR slopes indicative of a rotation strategy.

Note that in an earlier study, Anooshian and Carlson (1973) failed to obtain a correlation between success on kinetic imagery tasks and mastery of conservation of length or substance in 7-8 year olds (although this experiment did not use the Shepard paradigm). Anooshian and Carlson conclude that operational conservation and kinetic imagery derive from cognitive processes having separate developmental pathways.

The choice of operational tasks in the experiments described above is, however, open to criticism. It is difficult to grasp why the development of kinetic imagery would be related to conservation of number or quantity. Practices of this type are most likely based on the assumption that any operational task can yield a measure of subjects' reasoning capacity in all situations. However, the range of intraindividual differences in operational level as a function of knowledge domains and experimental situations (see for example Lautrey, de Ribaupierre & Rieben, 1986b) make it increasingly difficult to defend the notion of overall structure. The essential point of Piaget's line of reasoning as concerns the relationships between kinetic imagery and operations is that subjects cannot represent movement unless they are capable of temporal seriation. The core of this argument is that the ability for mental rotation is dependent on the ability to order the steps in the transformation or movement sequence. Further, from a methodological standpoint the same stimulus should be used on the two types of tasks given what is known about the impact of situational content on operational level.

A recent study by Dean, Scherzer and Chabaud (1986) meets these requirements. The authors tested 5 and 8 year olds on a mental rotation task identical to the one used by Marmor (with the exception that the stimulus was Mickey Mouse instead of a panda), and an ordering task. The ordering task consisted of putting 7 cards representing Mickey in a series of positions from upright to upside down (a 180° rotation) in correct order. The findings reproduce the linear relationship between angular disparity and RT for the rotation task in both age groups (and hence at age 5), whereas only the 8 year olds perform successfully on the corresponding ordering task where they must seriate pictures of the intervening states. This finding both confirms and strengthens the Marmor findings since use of a comparison of rotation and ordering tasks is more directly damaging to Piagetian assumptions.

8.3.3.2 Findings Confirming the Piagetian Assumption Concerning the Development of Kinetic Mental Images

Other findings however support the Piagetian assumptions. Dean and Harvey (1979) compared findings obtained on the Shepard paradigm with those obtained on Piagetian tasks. In contrast to Marmor they did not use familiar, concrete stimuli but adapted the Piagetian (1966) square rotation task. In this task, subjects are presented with two squares, one of which remains stationary while the other, attached to its upper left corner by a pin, pivots around it. Subjects were asked to represent the intervening positions of the mobile square in its axis of rotation. Subjects (three groups of girls aged 5, 8, and 12) were simultaneously administered a version of one of the tasks used in Piagetian research on kinetic mental imagery. The subjects were shown seven animated film sequences showing the rotation of the square. Only one sequence correctly depicted the movement in the real world; the six others integrated errors related to nonconservation of either the rotational axis or the shape of the square, or both. The youngest group of subjects failed to produce the linear function between RT and angular disparity for square rotation (with the exception of 2 children) and also failed on the judgment task of the animated films. A correlation between the percentage of correct responses on the mental rotation task and performance on the judgment task was found for the other two groups. However, success on both tasks (no errors) was observed in subjects whose RT were proportional to the angle of rotation of the squares (10 subjects) and in children who did not present this linear function (8 subjects). This suggests that the material used may trigger another strategy than the analog process of mental rotation. One likely explanation for the relationship between percentage of correct responses on the mental rotation task and performance on the recognition task is that subjects used this alternative strategy on each. Nevertheless, the failure of 5 year olds on the mental rotation task shows that the Marmor results for this age group cannot be replicated with all stimuli. Five year olds succeed when the stimulus is concrete such as pandas or icecream cones, but not with geometric shapes such as squares.

In another experiment, Dean and Scherzer (1982) tested whether subjects' failure to draw end states was purely due to problems of graphic representation or whether the mental image was also defective. Subjects were administered two comparable kinetic imagery tasks, one of which was based on the Shepard paradigm (the stimulus was a square) and the other consisting of asking subjects to draw the end state of the transformation. The tasks were run in random order on 44 girls between the ages of 5 and 13 (mean age 9,2).

Subjects were classified into three groups on the basis of results on the mental rotation task. The first group (A) of 9 subjects satisfied the 3 criteria indicative of a mental rotation strategy (linearity of RT in the rotation phase, stability of RT in the comparison phase, and low error rate). Group B composed of 9 subjects had longer RT's in the rotation phase for oblique orientations (45° and 135° rotation) than for vertical and horizontal orientations (0° and 180°). Group C was composed of 26 subjects whose RT's were unrelated to angular disparity in the rotation phase.

The findings show that classification into groups A, B, or C was correlated to percentage of accurate graphic representations. The percentage of correct drawings was higher in Group A than in Group B, and higher in group B than in group C. Dean and Scherzer claim that errors in the drawings of end states are thus due to deficiencies in the mental representation and not to low drawing ability. An alternative interpretation can be put forward however. Despite the 5-13 age range, there was no significant difference between mean ages in groups A, B, and C. The factors differentiating these groups are thus differential rather than developmental. The specific difficulty encountered by some subjects for oblique orientations of the squares, which needed to be brought into congruence with the standard, upright figure, may be associated with field dependence-independence (F.D.I., see Witkin et al., 1962). F.D.I. could be a common source of difficulty on the rotation task (only 9 out of the 44 subjects succeeded) and the drawing task, and could account for the observed correlation between the two tasks.

A number of experiments have failed to replicate the Marmor

results although mental rotation was not tested on a geometric shape. Platt and Cohen (1981) attempted to replicate the Marmor experiment using pictures of concrete objects but failed to observe evidence of mental rotation in untrained 5 year olds (in contrast to 5 year olds who succeeded when provided with a training phase in mental rotation). Note however that in this experiment, untrained children simply learned to recognize a "same" or "different" bear shown vertically, and no specific instructions were given when the subjects were shown figures presented in other orientations. Failure may thus be due to flaws related to the ambiguity of similarity judgments.

Kerr, Corbitt and Jurkovic (1980) have criticized what they term the "fragility" of Marmor's findings on the basis of the small sample size and subject classification on the conservation task. The dichotomous (conserver/nonconserver) classification could in their opinion mask the fact that some "nonconservers" were midway between the preoperational and concrete stages.

To control for these variables, Kerr et al. tested a sample of 47 subjects with a mean age of 5,8. The experiment was composed of 2 conservation tasks (number and length) and a mental rotation test similar to the one used by Marmor, with training in rotation and differentiation on the basis of "same" vs "different". The conservation score was a composite calculated by taking the two tasks into account. Subjects were defined as operational if they succeeded on both, intermediate if they succeeded on one, and preoperational if they failed on both.

The findings are consistent with those reported by Marmor when the children are divided into three groups on the basis of chronological age (mean ages 4,11; 5,10; 6,8): there is a significant linear trend for RT, even in the youngest group. However, when subjects are classified according to operational level, the preoperational subjects fail to exhibit the linear trend.

Note however that on the mental rotation task, subjects classified as nonconservers who do not exhibit the RT-angular disparity linear trend had high percentages of correct responses (83% for the intermediates and 76% for the preoperationals), which suggests that another strategy than mental rotation was implemented. According to Piaget, logico-mathematical operations deal with similarities and differences between distinct or individual objects, whereas infralogical operations bear on relations between interdependent parts of the same object. The implication is that figurative aspects of knowledge play a more important role in situations tapping infralogical operations. Defining operational level by a composite score which includes an infralogical task (conservation of length) may result in contamination from imagery ability in this classification. The conjunction of these two factors could account for the fact that subjects classified as "preoperational" may have had greater tendencies to use another strategy than mental rotation.

8.4 Discussion and Perspectives

These two sets of findings may only be superficially contradictory. They are compatible with the assumption that the development of imagery is subordinated to that of operations when the representation of movement is assessed by drawings (see for ex. Dean, 1979), or when, in the Shepard paradigm, researchers have used the geometric stimuli employed by Piaget (Dean & Harvey, 1979; Dean & Scherzer, 1982). In contrast, the data fail to support the Piagetian interpretation when mental imagery is tested within the Shepard paradigm with stimuli that are meaningful and familiar to children (Marmor, 1975, 1977; Dean et al., 1986). Some studies seem to violate this rule (Kerr et al., 1980; Platt & Cohen, 1981) but an explanation nevertheless can be found.

8.4.1 Accounting for Divergences: A Hypothesis

Our argument is that test situations (paradigm and type of stimulus) may appeal to varying degrees to two distinct modes of representation

and processing of spatial information. One mode covers processes described in the field of analog representations. It would have little connection with mastery of operations and would allow subjects unable to seriate the intervening states in a transformation to anticipate successfully on the end state. This would explain why subjects classified as preoperational would be able to anticipate on end states of a transformation in certain situations. This ability cannot be reduced to processing a form of static representation as Piaget and Inhelder believed, since the conjunction of correct anticipation of the end state and presence of a linear function between processing time and magnitude of the transformation indicate that there is mental representation of the transformation.

The second mode of processing is compatible in its more general form with propositional models of representation and Piaget's operational theory. This process would consist of decomposing the symbolic structures and the steps intervening in a transformation in order to recompose them by applying abstract rules to their components (for the IP school), or by operations (in Piagetian theory). In contrast to the first mode of processing, this mode would require prior construction of these rules or operations, and could be made explicit.

8.4.2 New Perspectives for a Developmental Approach to Mental Imagery

This dual-processing hypothesis opens up new perspectives for research on imaginal representation of transformations and their relationships to the development of cognitive operations. If there is an analog mode of representation of transformations which is not subordinated to the development of operations, the immediate question is whether it exhibits a specific form of development and what characterizes this development. Further, a developmental examination of a mode of propositional processing of spatial information - where, in our opinion, Piagetian studies on mental imagery should be classified - could be revisited with constructs incorporating Piagetian theory and contemporary models of information processing. Lastly, if there are two distinct modes of representation and processing of spatial information, a series of questions arise as to their possible interactions over the course of development. These three avenues of research will be discussed briefly in the section below, along with the results of studies conducted in each.

8.4.2.1 Specific Development of an Analog Mode of Representation of Spatial Transformation

Findings in experiments on speed of mental rotation show unequivocally (Kail, 1985; Kail et al., 1980; Young et al., 1980) that speed increases with age, and that this increase cannot be attributed to modifications in the speed/accuracy tradeoff (Kail, 1985).

Other task-related parameters connected to mental rotation are however linked to development. As stated above, familiarity with the stimulus clearly affects early ability for mental rotation: differences in material may account for the disparity between Marmor's (1975,1977) and Dean's (1979) findings. Kail et al. (1980) measured speed of rotation in subjects aged 8,6 to 19 in two conditions using either alphanumeric characters or shapes taken from the Thurstone PMA spatial test. Regardless of age, subjects were slower on unfamiliar than on familiar stimuli. Familiarity with the stimulus is only one of the variables affecting performance on mental rotation tasks and is not the only one which may mediate developmental change.

Rosser et al. (1984) argue that the number of orientational cues contained in the stimulus and their location can account for the differences between the Marmor and the Dean and Harvey results. To test this hypothesis, Rosser administered a rotation task to children aged 4-5 in which the number of cues added to a roughly circular shape ranged from 1 to 4. Subjects at this age needed at least 2 orientational cues to recognize a figure successfully. Additional cues did not improve

performance. This may explain why in the Marmor study subjects succeeded when the stimulus contained several orientational cues (the panda) but failed on the Dean task since the arrow inside the square (the sole cue) was not sufficient for success in the sample of young children tested.

An additional feature of information processing mentioned in a number of studies is the persistence of a rotated figure in short term memory. In the Kail et al. experiment described above, processing time (coding and comparison) was longer for the unfamiliar stimulus. Kail et al. interpret this as showing that subjects have a model of the familiar stimulus in long term memory which is retrieved during the comparison phase, whereas the representation of unfamiliar stimuli needs to be coded and preserved in short term memory during the entire process, thus creating additional load.

Comparison of adults' reaction times with children' in the condition where subjects are given an advance information about the angular disparity provides information, too, concerning the role of short term memory. When adult subjects have information on orientation of the stimulus over a sufficiently long period of time, response times are independent of angular disparity. This is because subjects perform the mental rotation before being presented with the probe stimulus, and keep the rotated position in memory to compare it with the probe. The linear relationship between response time and angular disparity observed in the no information (NI) condition is replaced by a constant function in the Advance Information (AI) condition. Childs and Polich (1979) tested three groups of subjects aged 9, 11, and 19 in NI and AI conditions on a letter rotation task. In the NI condition the average RT curves presented the same shape regardless of age, which was taken as showing that subjects employed the same mental rotation process. In contrast in the AI condition only adults exhibited a constant RT function. Eleven year olds and in particular 9 year olds presented RT curves comparable to those obtained in the NI condition. This suggests that the rotation strategy was used by all age groups in the NI condition but that in the AI condition children's performance was impaired by the restricted capacity of short term memory which prevented them from preserving and renewing visual information, and forced them to perform at least a new partial rotation when the probe stimulus was presented. Further research is necessary to dissociate these various factors to determine which plays a dominant role.

These studies provide strong arguments that the analog process of mental rotation is developmentally precocious. There is some evidence for successful rotation at age 4 (Marmor, 1977) but more research is required to identify at what point in development this becomes operational. These studies would require a modification of the Shepard paradigm for studies on infants. One possibility would be to adapt the procedure which has successfully shown that pigeons are capable of one kind of mental rotation (Neiworth & Rilling, 1987). Similarly it would be worthwhile to investigate the development of the more complex processes involved in the analog representation of transformations, as Bideaud (1988) has done. Bideaud replicated the Pinker and Finke (1980) experiment investigating the transition from a 3D representation to a 2D perspective representation on three groups of children (7, 9, and 11) and a group of adults. In the experiment, four small plastic animals are hung inside a transparent plexiglass cylinder such that they form a 3D structure. The subjects observe the cylinder from a given viewpoint such that the 2D projection on the retina is triangular in shape (three of the objects are colinear when observed from this vantage point). The subjects are then asked to make a mental image of what they have seen and the objects are removed from the cylinder. The experimenter then rotates the empty cylinder 90° and asks the subjects to imagine where the four animals would have moved to if they had been in the cylinder. They are then asked to describe the figure formed by the 4 objects from this new vantage point (a projection on the retina would form a parallelogram). Using the 2D projection formed by the objects on the retina (a triangle) the subjects must reconstitute a 3D representation whose spatial properties are preserved during the mental rotation and then translate this 3D representation once again into a 2D representation to form a mental image of the figure perspective from the new vantage point (the parallelogram). Pinker and Finke argue that their adult subjects succeeded on this task because they had two representational formats (2D and 3D) at their disposal and a system of transformation rules enabling them to go from one format to the other in both directions. The Bideaud experiment shows that this complex processing system of mental representation is operational as of the ages she investigated since no significant differences between 7, 9, and 11 year olds or between children and adults were observed for performance on this task. This approach holds promise for studies on the coordination of perspective which have grown out of work by Piaget.

In the same article J. Bideaud (1988) discusses a new paradigm for the study of mental rotation in children. The subjects are shown the imprint left by an object in modeling clay which they are asked to memorize before it is removed from view. The subjects are then shown 3 objects (made of cubes put together to form a variety of 3D structures) and are asked which of these figures made the imprint in the modeling clay. The first phase of this experiment consists of identifying the object that made the imprint, the second involves the reproduction of the imprint by correctly placing the object on a fresh piece of modeling clay, and the third judging whether the new imprint is identical to the one in memory. The imprints can be either the base or one side of the objects. In addition the objects may have been rotated 0°; 90° or 180° from the position of the imprint. Three groups of subjects aged 5,6; 6,6; and 7,6 were tested. All three groups easily succeeded on tasks 1 and 3. Task 2 however was more difficult and 7,6 year olds performed significantly better (60%) than the 5,6 and the 6,6 year olds. This may be accounted for by the fact that the comparison of static mental images is sufficient for success on phases 1 and 3 whereas phase 2 theoretically requires the subject to anticipate mentally on the rotation s/he will have to perform on the real object to obtain the correct imprint on the clay. Bideaud points out that this experiment, like the previous one, is exploratory and that a number of additional controls are called for to ensure that the task does not tap processes other than mental rotation.

8.4.2.2 Specific Development of a Propositional Representation of Spatial Information

As has been stressed, the Piagetian view of the development of the ability for mental representation is similar in many respects to the propositional models of representational architectures. In both cases, the process of information structuring is considered to be amodal, and hence identical irrespective of the nature of information. This process consists of assembling elementary symbols through context-free abstract rules, or by logical operations. The representations so produced can thus be made explicit, decomposed, etc.

A number of studies reviewed here have shown that when the methodology and situations lend themselves to revealing these properties of a representation of spatial information, the Piagetian mental imagery findings are confirmed. One interesting approach consists of reexamining these findings to articulate Piagetian concepts such as scheme and structure with those used in information processing models.

Several authors in the framework of so-called neo-Piagetian theories, have attempted to associate these concepts. In these theories, development is no longer accounted for by the construction of overall structures, as was the case for Piaget, but by a quantitative increase of information processing capacities in the child. Severely limited in the young child, these capacities increase through maturation and practice. Some authors situate the bottleneck restricting the processing capacity of young children in allocation of attentional resources (Pascual-Leone, 1970) or in the size of short-term memory storage (Case, 1985). In this conceptual framework, the growth of information processing capacities is viewed as a consequence of the development of attentional, short-term memory or more generally working memory capacities. A study by S.Morra (1988) is illustrative of this research trend.

Morra designed an experimental paradigm based on Pascual-Leone's neopiagetian Theory of Constructive Operators (TCO) (see for example Pascual-Leone and Goodman, 1979) to study the planification of a drawing. The TCO differs on various points from Piagetian theory but only those features relevant to this study will be presented here. First of all, Pascual-Leone differentiates figurative schemes from purely Piagetian operational ones. Secondly, the internal factor of development in the TCO is the M factor (mental power) a mechanism which allocates attentional resources. The capacity of the M operator, i.e. the number of schemes an individual can activate at the same time, is limited and increases with age (M = 1 at age 3 and increases roughly by one every two years up to adolescence). An individual's M factor can be assessed by certain tests developed by Pascual-Leone but also by standard measures such as number repetition.

The Morra, Moizo and Scopesi (1988) working hypothesis in their study of drawing planification is that figurative schemes, as defined in the TCO, are the basic units of analogical thinking, and the number of figurative schemes a child is able to handle in the planning of a drawing is restricted by his/her M factor. This hypothesis was tested by comparing the number of elements that chidren plan to put in their drawings with the number that were actually drawn. The experiment, conducted on three age groups (1st, 3d and 5th graders) was composed of a free and a constrained drawing condition. In the free drawing condition the experimenter asks the child to state what he intends to put in his drawing and to indicate on a sheet of paper where he intends to put each feature mentioned. The experimenter records this information and the child goes back to his seat and executes the drawing. In the constrained condition the experimenter imposes the number of elements the child must include in the drawing (ranging from 3 to 7 for all the subjects). The subjects are also administered tasks measuring their M capacity. Morra, Moiso and Scopesi predicted that in the free drawing condition, the drawings would include a number of elements whose distribution would be random but would never exceed k (k being the maximum number of schemes that the M factor can activate). By constrast, in the constrained condition the expectation was that the number of planned elements which are actually produced in the drawing would approximate but never exceed k. The findings confirm predictions; nevertheless a crucial and sensitive point in this type of study lies obviously in the definition and scoring of what constitutes an "element" of a drawing.

Although Morra (1988) states having conducted a "quantitative analysis of analog thinking", it bears greater resemblance to studies of the development of the capacity for propositional processing of representations. If figurative schemes proceed from an analog mode of representation, the mechanisms through which the M factor keeps these discrete representational units in memory are not specific to mental imagery (the M factor is thought to be amodal). The fact that the subject is asked to verbally enumerate the elements s/he plans to put in the drawing is further evidence of this: there is no reason why the information in working memory could not being coded verbally and that the pictorial content would only be generated when the specific element is executed graphically.

Rather than referring to Pascual-Leone's amodal M factor to account for restrictions in processing capacities, a slightly different interpretation can be drawn from Baddeley's (1986) bimodal working memory model. In Baddeley's model, a limited-capacity central executive co-ordinates two slave subsystems, namely the Visuo-Spatial Sketchpad and the Acoustic-Articulatory Loop. Since these two slave subsystems are relatively independent, the elements processed in the drawing planification could be stored in a verbal format in the Articulatory Loop or in a visual format in the Visuo-Spatial Sketchpad (as images or as figurative schemes). In both cases, however, the number of discrete information units retained by the child depends on the limitations imposed by the central executive which manages the same (sequential) type of processing.

Nevertheless, the distinction between Visuo-Spatial Sketchpad and Articulatory Loop does not parallel the distinction between propositional and analog processing. The analog mode, in as much as it is assumed to process an entire set of embedded properties in a holistic fashion, is likely to be parallel, and as a result should not be prone to such limitations. Empirical studies of the relationships between stimulus complexity and mental rotation rate provide some support for this view. In certain cases, the time required to process a visual pattern is unrelated to the number of distinctive features contained in that pattern (Cooper, 1975; Folk & Luce, 1978). This does not imply that there are no limitations at all on this processing mode, but rather that its limitations are not identical to the ones constraining a sequential process.

8.4.2.3 Relationships Between the Propositional and the Analog Modes of Representation in Development

Postulating that two distinct modes of representation of spatial information coexist leads directly to the issue of their interrelations. Do preferences for a given mode of representation evolve over the course of development? What defines the relationships between age and modes of representation and/or determines the interactions between the two modes?

Dominance of one mode of representation

If individuals can opt for either mode of representation, is one dominant and does preference remain stable over the course of development? A recurrent argument is that there is less recourse to mental imagery, when defined as an analog form of representation, as cognitive development proceeds. Kosslyn (1976) whose theory combines the two modes of representation, has obtained empirical support for a decrease in spontaneous generation of mental images over the course of development.

In this experiment Kosslyn studied the role of imagery in a task requiring search in long-term memory. Kosslyn predicted that children would access long-term memory through imagery whereas older children or adults would have recourse to propositional processing of the semantic features. Three groups of 14 subjects were tested (1st and 4th graders and undergraduates). The subjects were asked to state whether or not an animal had a given property. Properties were contrasted such that the name of the animal was strongly associated with a small property or conversely the name was weakly associated with a large property (e.g. teeth and tail for an alligator). Erroneous (not present in the animal) properties were also included (stripes and a stinger in the mouse). In the first block of trials (22 animal-property pairs) no type of strategy was suggested. The instructions for the second block of trials explicitly requested subjects to form a mental image of the whole animal.

The major finding of this experiment is that over the course of development propositional access to information in long-term memory becomes progressively more efficient and subjects tend to have greater spontaneous recourse to it. Performance in young children is roughly comparable in the imagery and no imagery conditions whereas older children and virtually all adults have significantly different RT's as a function of condition: when no imagery instructions are provided, response times are much faster. Nevertheless, this experiment cannot be seen as providing conclusive evidence as to whether young children spontaneously rely on imagery when not instructed to do so. The developmental trend reported by Kosslyn may be due to differential improvement in propositional access to memory through practice and schooling.

Note that in this study the subjects were asked to form static images. One may wonder if the same trend would be observed in the case of images of transformation. It would be interesting to test whether children tend to use analog representations of information to a greater extent than adults on these tasks too.

Interactions between the two modes of representation

The fact that analog representation of movement or transformations makes it possible under certain conditions to anticipate on the end state before the corresponding operations have developed, suggests that this mode of representation may play a role of guidance in the construction of these operations. The knowledge of an end state may guide the structuring process of the intervening states. This applies to the origin of spatial operations, but can be extended to cover logical operations. In Piagetian theory there is no reason to postulate that mental imagery plays a role of guidance in the elaboration of operations such as ordering or classification since the level of structuration of the mental representation is assumed to be dependent upon the level of operations. Under the interpretation developed here, this form of guidance is a possibility. Data on the emergence of the notion of inclusion (see Bideaud & Lautrey, 1983) and seriation (see Lautrey et al., 1986a) could support this interpretation. Anyway, this is another direction for research, proceeding from the hypothesis of two distinct modes of representation for spatial information.

Much remains to be explored as concerns the development of the capacity for mental imagery in a field where there are many more unanswered questions than firm responses. This in itself should motivate researchers to delve deeper into this area.

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References

Anderson, J.R. & Bower, G.H. (1973).
Human Associative Memory. Washington: Winston.

Anooshian, L. & Carlson, J.S. (1973).
A study of mental imagery and conservation within the Piagetian framework. *Human Development, 16*, 382-394.

Baddeley, A. (1986).
Working Memory. New York: University Press.

Bideaud, J. (1988).
Rotation of mental image with respect to children and adults. In Cornoldi C. (Ed.). *Imagery and Cognition Proceedings of the Second Workshop on Imagery and Cognition*, University of Padova, Italy.

Bideaud, J. & Lautrey, J. (1983).
De la résolution empirique à la résolution logique du problème d'inclusion: evolution des réponses en fonction de l'âge et des situations expérimentales. *Cahiers de Psychologie Cognitive, 3*, 295-326.

Case, R. (1985).
Intellectual development: Birth to Adulthood. Toronto: Academic Press.

Childs, M.K. & Polich, J.M. (1979).
Developmental differences in mental rotation. *Journal of Experimental Child Psychology, 27*, 339-351.

Cooper, L.A. (1975).
Mental rotation of random two-dimensional shapes. *Cognitive Psychology, 7*, 20-43.

Cooper, L.A. & Podgorny, P (1976).
Mental transformation and visual comparison processes. *Journal of Experimental Psychology: Human Perception and Performance, 2*, 503-514.

Dean, A.L. (1979).
Patterns of change in relations between children's anticipatory imagery and operatory thought. *Developmental Psychology, 15*, 153-163.

Dean, A.L. & Harvey, W.O. (1979).
An information-processing analysis of a Piagetian imagery task. *Developmental Psychology, 15*, 474-476.

Dean, A.L. & Scherzer, E. (1982).
A comparison of reaction time and drawing measures of mental rotation. *Journal of Experimental Child Psychology, 34*, 20-37.

Dean, A.L., Scherzer, E. & Chabaud, S. (1986).
Sequential ordering in children's representations of rotation movements. *Journal of Experimental Child Psychology, 42*, 99-114.

Fodor, J.A. (1975).
The Language of Thought. New-York: Thomas Y. Crowell.

Folk, M.D. & Luce, R.D. (1987).
Effects of stimulus complexity on mental rotation rate of polygons. *Journal of Experimental Psychology: Human Perception and Performance, 13*, 395-404.

Kail, R. (1985).
Development of mental rotation: a speed-accuracy study. *Journal of Experimental Child Psychology, 40*, 181-192.

Kail, R., Pellegrino, J. & Carter, P. (1980).
Developmental changes in mental rotation. *Journal of Experimental Child Psychology, 29*, 102-116.

Kerr, N.H., Corbitt, R. & Jurkovic, G.J. (1980).
Mental rotation: is it stage related? *Journal of Mental Imagery, 4*, 49-56.

Kosslyn, S.M.
(1980). *Image and Mind.* Cambridge, MA: Harvard University Press.

Kosslyn, S.M. , Ball, T.M. & Reiser, B.J. (1978).
Visual images preserve metric spatial information: evidence from studies of image scanning. *Journal of Experimental Psychology: Human Perception and Performance, 4*, 47-60.

Lautrey, J. (1987).
Structures et Fonctionnements dans le Développement Cognitif, Thèse de doctorat ès Lettres et Sciences Humaines, Université de Paris V.

Lautrey, J., Bideaud, J., & Pierre-Puységur, M.A. (1986a).
Aspects génétiques et différentiels du fonctionnement cognitif lors des tâches de sériation. *L'Année Psychologique, 86*, 489-526.

Lautrey, J., de Ribaupierre, A., Rieben, L. (1986b).
Les différences dans la forme du développement cognitif évalué avec des épreuves piagétiennes: une application de l'analyse des correspondances. *Cahiers de Psychologie Cognitive, 6*, 575-613.

Marmor, G.S. (1975).
Development of kinetic images: when does the child first represent movement in mental images? *Cognitive psychology, 7*, 548-559.

Marmor, G.S. (1977).
Mental rotation and number conservation: are they related? *Developmental Psychology, 13*, 320-325.

Morra, S. (1988).
A quantitative approach to the complexity of analog thinking.In Cornoldi C. (ed.). *Imagery and Cognition Proceedings of the Second Workshop on Imagery and Cognition*, University of Padova, Italy.

Morra, S., Moizo, C. & Scopesi, A. (1988).
Working memory (or the M Operator) and the planning of children's drawings. *Journal of Experimental Child Psychology, 46*, 41-73.

Neiworth, J.J. & Rilling, M.E. (1987).
A method for studying imagery in animals. *Journal of Experimental Psychology: Animal Behavior Processes, 13*, 203-214.

Paivio, A. (1977).
Images, propositions and Knowledge. In J.M. Nicholas (Ed), *Images, Perception and Knowledge*. Dordrecht: Reidel.

Pascual Leone, J.(1970).
A mathematical model for the transition rule in Piaget's developmental stages. *Acta Psychologica, 32*, 301-345.

Pascual-Leone, J. & Goodman, D. (1979).
Intelligence and experience: A neo-Piagetian approach. *Instructional Science, 8*, 301-367.

Piaget, J. & Inhelder, B. (1966).
L'image mentale chez l'enfant. Paris: Presses Universitaires de France.

Pinker, S. & Finke, R.A. (1980).
Emergent two-dimensional patterns in images rotated in depth. *Journal of Experimental Psychology: Human Perception and Performance, 6*, 244-264.

Platt, J.E. & Cohen, S. (1981).
Mental rotation task performance as a function of age and training. *Journal of Psychology, 108*, 173 178.

Pylyshyn, Z.W. (1973).
What the mind's eye tells the mind brain: a critique of mental imagery. *Psychological Bulletin, 80*, 1-24.

Pylyshyn, Z.W. (1981).
The imagery debate: analogue media versus tacit knowledge. *Psychological Review, 88*, 16-45.

Rosser, R.A. , Ensing, S.S., Glider, P.J. & Lane, S. (1984).
An information-processing analysis of children's accuracy in predicting the appearance of rotated stimuli. *Child Development, 55*, 2204-2211.

Shepard, R.N. & Cooper, L.A. (1982).
Mental images and their transformations. Cambridge, MA: MIT Press.

Shepard, R.N. & Metzler, J.(1971).
Mental rotation of three-dimensional objects. *Science, 171*, 701-703.

Vuik, R. (1981).
Piaget's genetic epistemology 1965-1980 (Vol.1). London: Academic Press.

Witkin, H.A., Dyk, R.B., Faterson, H.F., Goodenough, D.R. & Karp, S.A. (1962).
Psychological Differentiation. New York: Wiley.

Young, J.F., Palef, S.R. & Logan, G.D. (1980).
The role of mental rotation in letter processing by children and adults. *Canadian Journal of Psychology*, *34*, 265-269.

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