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ABSTRACT

Considerable discussion and debate have been devoted to the extent and nature of structural or functional correspondence between internal representations and their external visual counterparts. An analogue representation or process is one in which the relational structure of external events is preserved in the corresponding internal representations. A great deal of experimental evidence purporting to demonstrate the existence of analogue internal representations and processes has accumulated during the past decade. These experimental efforts have the use of a powerful psychophysical technique--mental chronometry--in common, thus permitting inferences about internal mental events and processes from purely observable data. However, analogue models for visual/spatial representations and transformations have recently been challenged on both empirical and theoretical grounds. The empirical challenges can be shown to be inconclusive, and further experimental work is needed to resolve inconsistencies. The theoretical challenges have taken the form of proposing nonanalogue models that may account for at least some of the findings generally regarded as supporting the need for positing analogue representations and transformations. An internal process can qualify as analogue if it can be shown that the intermediate stage in the processing has a one-to-one relation to the intermediate stage of the corresponding external process. Conceived in this fashion, the nature of analogue representations can be assessed in behavioral experiments that have the potential of elucidating the way in which mental processes simulate or model external operations and events. (HTH)

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Abstract

In this paper, the possibility of analogue internal representations of spatial objects and transformations is discussed and evaluated. A definition of an analogue process is provided, based on correspondences between intermediate stages in external spatial transformations and intermediate states of their internal or represented counterparts. Psychophysical evidence, primarily chronometric in nature, is presented in favor of this position. The experiments discussed are of two basic sorts. In one, functional similarities between the time course of external spatial transformations and internal simulations of these transformations are demonstrated. In the other, the nature of internal transformations is evaluated by probing the process at various space/time points along the transformational trajectory. Alternative accounts of these experimental findings -- based on models involving discrete symbol manipulation -- are presented, as are additional empirical findings which appear to cast doubt on the analogue account. Potential methods for discriminating between these two classes of models are proposed, and the task-dependent nature of internal spatial representations and operations is emphasized. Finally, possible parallels between the phenomena described above and more purely perceptual situations are suggested. The perceptual tasks considered include ones in which visually presented transformations of displays must be extrapolated internally and also variants of apparent motion paradigms.

ANALOGUE REPRESENTATIONS OF SPATIAL OBJECTS AND TRANSFORMATIONS

Questions concerning the nature of the internal representation or coded form of visual/spatial information have been prominent in the growing field of cognitive science. In particular, considerable discussion and debate have centered around issues of the extent and the nature of structural and/or functional correspondences between internal representations and their external visual counterparts. In this paper, evidence both for and against analogue representations of spatial objects and transformations will be presented and evaluated. Following Shepard, Cooper and their co-workers (Cooper, 1976; Cooper & Shepard, 1978; Shepard, 1981; Shepard & Cooper, 1982), a distinction between "analogue" representations and processes and "nonanalogue" representations and processes will be drawn in the following way: An analogue representation or process is one in which the relational structure of external events is preserved in the corresponding internal representations. A non-analogue representation or process is one for which this is not the case. Note that this distinction incorporates a relatively weak criterion for the demonstration of the existence of an analogue process or representation. Strict continuity of an internal process is not required, nor is a "first-order" isomorphism between the structure of an internal representation and the structure of an external object or event. Furthermore, no stand has been taken on the question of the neural mechanisms that might underlie analogue representations and processes.

It is argued below -- in the context of particular experimental findings -- that to qualify as an analogue process or representation, it must demonstrate that the internal process or representation goes through an ordered series of intermediate states that have a one-to-one relationship to the intermediate stages in the corresponding external process or object. And, this one-to-one correspondence need entail only that the internal process or representation allow the individual carrying out such a mental transformation to be particularly prepared for the presentation of the appropriate external object at the appropriate location in space, if such an external object were to be presented.

Considerable experimental evidence purporting to demonstrate the existence of analogue internal representations and processes, in the sense sketched above, has accumulated during the past decade. These experimental efforts have in common the use of a powerful psychophysical technique -- mental chronometry -- permitting inferences about internal, mental events and processes from purely observable behavioral data. The general idea underlying the use of chronometric measures is that the time required to solve a visual/spatial problem -- when considered in relation to specified, measurable properties of test stimuli -- can provide information that places significant constraints on possible internal representations and processes used to solve the problem. In much of the relevant research, the amount of time needed to determine whether two visual objects are identical in shape or different (e.g., mirror images) has been found to depend systematically on the extent of spatial difference between the orientations of the two objects. On the basis of a pattern such as this, it can be argued that the underlying internal representations and processes must be of a class that would produce the appropriate orderly relationship between solution time and extent of spatial displacement.

In a seminal experiment, Shepard and Metzler (1971) asked subjects to determine as rapidly as possible whether two simultaneously-displayed perspective drawings of three-dimensional objects were the same in shape or mirror images of each other. In addition to a possible difference in shape, the objects could also differ in portrayed orientation, either in the picture plane or about an arbitrary axis in depth. The results of this experiment were clear and striking. Both for the group data and at the level of individual observers the time required to determine that the two portrayed objects were the same in shape increased in a remarkably linear fashion with increases in portrayed angular difference between the orientations of the objects. Furthermore, both the slope and the intercept of the linear time functions were roughly equal for both picture-plane and depth angular differences. This central and elegant finding led the investigators to suggest that the task was performed by "mentally rotating" an internal representation of one object into congruence with the orientation of the other object and then comparing the two representations for a match or mismatch in shape. This process of mental rotation -- which Shepard and Metzler conceived of as an analogue of an external rotation -- appeared to have an average limiting rate of about 60 degrees per second for these subjects and these particular visual materials.

This orderly linear relationship between response time and extent of angular displacement has been well documented for a variety of visual stimuli and task modifications. For example, linear response-time functions have been obtained when a single rotated stimulus must be compared with a canonically oriented pattern in memory (Cooper, 1975; Cooper & Shepard, 1973). Similar functions have been found when alphanumeric characters (Cooper & Shepard, 1973) or random two-dimensional polygons (Cooper, 1975) are used as stimulus materials. This same orderly relationship has been obtained when rotations must be carried out before the presentation of a test shape, in order to prepare for its appearance in a specified orientation (Cooper, 1975; Cooper & Shepard, 1973). It is also found when rotations are combined with additional spatial transformations (Kubovy & Podgorny, 1981) and when the "same-different" discrimination is altered to include subtly different distractors, as well as mirror images, as test stimuli (Cooper & Podgorny, 1976). (Reviews of these and other studies of mental rotation can be found in (Shepard & Cooper, 1982) and (Cooper & Shepard, 1978).

The host of experiments demonstrating a linear relationship between time and portrayed difference in the orientations of visual objects has consistently been interpreted as providing evidence for analogue representation of spatial objects and spatial transformations. This is because the linearity indirectly fulfills the chief criterion for an analogue process -- viz., a correspondence between internal and external relational sttuctures and transformational distance and time suggests that the internal process used to solve rotation problems passes through a trajectory of intermediate states which have a one-to-one correspondence to the intermediate stages in the rotation of an external object. That is, the linear reaction-time function indicates that the time required to compare two visual stimuli presented at two sufficiently different orientations A and C is an additive combination of the times needed to compare those stimuli at orientations A and B and at orientations B and C. Shepard, Cooper and their collaborators have argued that such a finding constitutes indirect evidence for the claim that the internal process underlying comparison of the visual stimuli presented in orientations A and C passes through an intermediate state corresponding to orientation B (Cooper, 1975, 1976; Cooper & Podgorny, 1976; Cooper & Shepard, 1973, 1978; Shepard, 1981; Shepard & Cooper, 1982; Shepard & Metzler, 1971).

More direct experimental demonstrations of the analogue nature of mental rotation have been provided by Cooper and Shepard (1973, Experiment II) and by Cooper (1976). These experiments are powerful in that they show the required one-to-one correspondence between intermediate stages in an external rotation and intermediate states of an internal process in the specific sense of an individual engaged in the mental rotation being especially ready to respond accurately and rapidly to the appearance of an external test stimulus that is presented at just the appropriate orientation in the transformational trajectory.

In one of these studies, Cooper (1975) initially trained subjects to discriminate arbitrarily-defined "standard" from "reflected" versions of random two-dimensional polygons at one particular orientation in the picture plane. Following the discrimination training, individual polygons were presented at one of six orientations, and subjects were required to determine as rapidly as possible whether each was a standard or a reflected version. Reaction time increased linearly with angular departure of the shapes from the (canonical) orientation at which training had occurred. As in the earlier Shepard and Metzler (1971) study, the linear time function was taken as indirect evidence that subjects were mentally rotating the test polygon into the trained orientation in order to achieve the standard-reflected discrimination. Rotation rates were computed separately for individual subjects and individual stimuli.

In a subsequent experiment, Cooper (1976) tested the same subjects using the same visual stimuli, but modified procedure. Subjects were simply asked to imagine a particular shape from the previous experiment rotating from the trained orientation about a circle at a "natural" rate. On the basis of the data from the earlier experiment, it was possible to compute at what orientation in the internal transformational trajectory a given subject's (rotating) representation of a given shape would be at a particular point in time. On half of the trials, a test shape was presented at one such "expected" orientation at an unpredictable moment in time, and the subject was required to determine as rapidly as possible whether the probe was a standard or a reflected version of the shape being imagined. On the other half of the trials, a test polygon was presented in an orientation inferred not to be congruent with the orientation of the subject's (rotating) internal representation, and the same discrimination was required.

The results of this experiment were clear and elegant. Reaction times were shortest and uniformly rapid when the test shape was presented in the orientation that corresponded to the assumed spatial position of the rotating internal representation. This was true (a) regardless of the angular departure of this expected orientation from the initially-trained position, and (b) even for intermediate orientations at which test stimuli had never been previously presented in the initial experiment. Furthermore, when test shapes were presented in unexpected or incongruent orientations, reaction times increased linearly with the angular departure of the test probe from the inferred expected orientation.

These results are consistent with the notion that mental rotation is an analogue of a physical rotation in the specific sense of the internal and external processes having the required relation of readiness for responding to the appropriate external object at the appropriate stage in the transformational trajectory. Contrast this, for example, with an internal transformation such as matrix multiplication by which a computer might compute the new coordinates for a rotated system of points (c.f., Shepard & Cooper, 1982). This process would not qualify as analogue because the intermediate stages in the calculation would not have a one-to-one correspondence with intermediate orientations, in the sense that the computer would not be in a state of heightened readiness for responding to the presentation of intermediate orientations at intermediate times.

In addition to these studies of mental rotation, many other chronometric studies have frequently been interpreted as providing evidence for analogue internal representations and processes. Most extensive, perhaps, is the body of experimental work produced by Kosslyn and his co-workers. (For a comprehensive review of this research effort and a theoretical perspective, see Kosslyn 1980.) Unlike the mental rotation experiments, in Kosslyn's experiments subjects are generally instructed to generate internal representations that they would call "mental images" and to use these representations as a basis for performing a variety of visual/spatial tasks. A typical task is one used by Kosslyn (1973) and Kosslyn, Ball and Reiser (1978). In these experiments, subjects were instructed to form visual images of previously viewed objects or spatial layouts (in the case of Kosslyn, 1973, objects with a horizontal or a vertical orientation, and in the case of Kosslyn, Ball & Reiser, 1978, a map of a fictional island containing a number of identifiable landmarks). They were then asked to "mentally focus" on one end of a particular imagined object or on one landmark on the imagined map. The central experimental task required subjects to verify as rapidly as possible whether a certain property was present on the image of the object or whether a certain landmark was contained on the image of the map. The chief manipulation was the distance between the attended end of the object and the probed property or the distance between the attended and the tested locations on the map.

In both sets of studies, Kosslyn (1973; Kosslyn, Ball & Reiser, 1978) found that verification times increased linearly with the distance between the focussed end of the object or location on the map and the property or landmark that was tested. This function relating verification time to extent of spatial distance is open to an interpretation similar to that made on the basis of the data from the mental rotation experiments discussed above. That is, just as the linear relationship between reaction time and angular differences between two visual objects provides indirect evidence for a correspondence between intermediate internal processing states and intermediate external orientations, so too the linear relationship between verification and distance may suggest that an internal representation of space -- when subjected to the transformation of scanning -- has a structural correspondence to the external depiction of distance between objects or properties which is required of an analogue representation.

Chronometric data of the sort reviewed above have been interpreted by many as providing evidence for analogue representation and processing of visual/spatial information; however, this interpretation has been challenged by various investigators on both theoretical and empirical grounds. One form of the challenge has consisted of presenting experimental results that appear to infirm the notion of analogue representation and processing of visual information. Another type of challenge has centered around the development of alternative, nonanalogue accounts of the internal representations and processes that could underlie the relevant chronometric findings. These two sorts of objections are discussed below in turn.

One set of experimental findings that has refined the account of the nature of the representations and processes involved in mental rotation and which, to some extent, has questioned the analogue interpretation favored by Shepard, Cooper, and their co-workers (Cooper, 1975, 1976; Cooper & Podgorny, 1976; Cooper & Shepard, 1973, 1978; Shepard, 1981; Shepard & Cooper, 1982; Shepard & Metzler, 1971) has come from the work of Carpenter and Just (1976, 1978). These investigators have measured not only the time required to compare the shapes of two disoriented visual objects, but also the pattern and duration of eye fixations that subjects produce while making the comparison. Their analysis of eye fixations suggests that three component operations are carried out in achieving comparisons between visual figures like those used by Shepard and Metzler (1971). The first operation is one of search, in which parts of the two figures that potentially correspond to each other are located. The second operation is one of transformation and comparison, in which corresponding segments of the figures are mentally rotated and sequentially compared. The third operation is one of confirmation, in which other parts of the figures are compared in order to determine whether they are congruent as a result of the mental rotation.

The theoretical account that these investigators offer on the basis of both their chronometric and their eye fixation data is slightly different from the analogue account offered by Shepard and Cooper (Cooper, 1975, 1976; Cooper & Podgorny, 1976; Cooper & Shepard, 1973, 1978; Shepard, 1981; Shepard & Cooper, 1982; Shepard & Metzler, 1971) in two respects. First, Carpenter and Just (1976, 1978) suggest that rotations are carried out sequentially, on individual segments of visual objects, rather than on an integrated, holistic internal representation which we might expect of an analogue process. Second, their eye fixation analysis has led them to suggest that the rotation operation operates on these portions of visual figures in discrete steps of about 50 degrees. This view, while emphasizing the possibility that rotations may be performed on discrete parts of visual representations in discrete steps, is still consistent with the criterion for an analogue process outlined in (Cooper, 1975, 1976; Cooper & Podgorny, 1976; Cooper & Shepard, 1973, 1978; Shepard, 1981; Shepard & Cooper, 1982; Shepard & Metzler, 1971). For, during a mental rotation of, e.g., 150 degrees, the internal process passes through intermediate stages corresponding to intermediate external orientations of 50 degrees and 100 degrees.

A second set of experimental findings that challenges the analogue account of mental rotation has been presented by Pylyshyn (1979). Pylyshyn has argued elsewhere (1981) that to qualify as analogue, an internal process must not be capable of being shown to be "cognitively penetrable." What this means, in essence, is that if the operation of a cognitive process can be shown to be influenced by goals, beliefs, knowledge, or other external factors, then that process is cognitively penetrable and hence cannot be regarded as a primitive, knowledge-independent process. Pylyshyn (1979, 1981) further argues that to qualify as analogue a representation or a process must exhibit a lack of penetrability. For, if an internal process can be influenced by knowledge or other symbolic factors, then that process and the representations on which it operates must themselves by symbolic in nature.

Pylyshyn (1979, 1981) has attempted to show that so-called analogue processes such as mental rotation (Cooper, 1975, 1976; Cooper & Shepard, 1973, 1982; Shepard, 1981; Shepard & Cooper, 1982; Shepard & Metzler, 1971) and mental scanning (Kosslyn, 1973, 1980; Kosslyn, Ball & Reiser, 1978) are cognitively penetrable in two ways. First, he has presented experimental evidence putatively demonstrating that factors such as stimulus structure and practice can affect the rate of these mental processes. Second, he has suggested that the response-time patterns that have commonly been taken as support for analogue processes and representations may better be accounted for by appealing to subjects' "tacit knowledge" of the demands of the experimental situation. By "tacit knowledge" Pylyshyn (1981) refers to the notion that subjects have knowledge of the nature of physical transformations and, further, interpret the experimental situation as inviting the simulation of what they know the appropriate physical transformation to be.

The experiments in which Pylyshyn (1979) has attempted to show cognitive penetrability are ones that required subjects to determine as rapidly as possible whether or not a test probe, presented simultaneously with a visual figure and in various different orientations on different trials, was a part of the figure. As in other mental rotation experiments, Pylyshyn found that reaction time for the part-verification task increased as the angular difference in the orientations of the figure and the part increased. However, the "goodness" or coherence of the test probes as parts of the figures -- which was the chief experimental manipulation -- produced variations in the slopes of these reaction-time functions, indicating that more structurally coherent parts could be mentally rotated more rapidly than less coherent parts. From these data, Pylyshyn concluded that since mental rotation rate can be influenced by aspects of stimulus structure, it is a cognitively penetrable, and hence nonanalogue, process.

Whether or not one accepts Pylyshyn's criterion of nonpenetrability as a condition for an analogue process, his conclusions should nonetheless be viewed with caution (cf., Shepard & Cooper, 1982, Chapter 8). The method of stimulus presentation and the judgment required of the subject were sufficiently different from those used in other studies of mental rotation (Cooper, 1975, 1976; Cooper & Podgorny, 1976; Cooper & Shepard, 1973, 1978; Shepard, 1981; Shepard & Cooper, 1982; Shepard & Metzler, 1971) to question the comparability of the experimental findings. Furthermore, the processing time measured by Pylyshyn included components other than rotation -- such as encoding and comparison of the figures and the parts -- which themselves could have produced the reaction-time differences associated with part "goodness." Nonetheless, while Pylyshyn's experiment is not conclusive, exploration of the influence of stimulus and judgmental factors on the rate of operations like rotation and scanning seems a fruitful avenue to pursue. The results of such experiments may yet prove, and, in the case of one study discussed below (Cooper & Podgorny, 1976) already have proved to be theoretically incisive.

Pylyshyn's (1981) second attempt to invoke cognitive penetrability has involved arguing that subjects use tacit knowledge of the nature of physical transformations in making the timed judgments required in mental rotation and mental scanning experiments. Hence, the linear reaction-time data do not necessarily reflect the operation of an internal analogue process; rather, these data may reflect nothing more than subjects' beliefs about the time course of physical operations coupled with a desire to conform to the implicit demands of the experimental situation. This is a difficult argument to evaluate since introspective evidence might not reveal the use of such "tacit" knowledge, in the absence of a conscious strategy on the part of the subject. Kosslyn (1981) has, however, provided a twofold rejoinet to Pylyshyn's argument based on the use of tacit knowledge. Kosslyn's criticisms of this position can be summarized as follows: First, results consistent with an analogue account can be obtained in the absence of explicit instructions to generate visual images or to engage in processes analogous to physical transformations. Second, subjects will sometimes exhibit performance that indicates that their internal representations of spatial objects and transformations have properties similar to those found in perceptual experiments and which, further, are counterintuitive. These results are most likely not attributable to tacit beliefs about physical objects and events.

A second line of objection to the usefulness of postulating internal analogue representations and processes has proceeded in a somewhat different direction than that of the empirical work discussed above. In essence, it has involved the attempt by various investigators -- most notably, Anderson (1978, 1982) -- to produce discrete, nonanalogue systems that mimic the behavior of analogue systems, and thus to account for certain of the critical chronometric findings. Anderson (1978) argues further that nonanalogue accounts are to be preferred on grounds of parsimony. That is, only one symbolic representational system need be postulated to explain the coding and processing of both linguistic and spatial information. (For a somewhat modified view, see Anderson, 1982.)

This a difficult argument to evaluate, for as Anderson (1978) shows formally, it is possible with the proper set of representational and processing assumptions to design a nonanalogue system that will indeed produce performance frequently attribured to an analogue system. However, in response to this position, two interrelated points should be noted. The first -- attributable to Kosslyn and Pomerantz (1977) -- is that certain discrete, propositional theories may be too powerful, in that any empirical result may be explained after the fact. Such theories, though, may have insufficient constraints to predict a particular experimental outcome in advance. In contrast, versions of an analogue account can make rigorous experimental predictions that place serious constraints on the nature of the representations and processes underlying certain empirical phenomena.

Consider, for example, the study by Cooper (1976) discussed above, in which points in a hypothesized underlying transformational trajectory were probed with test forms at appropriate temporal intervals. An analogue account of the representations and processes tapped in this experiment makes a clear prediction concerning the relative speed of "probe-expected" and "probe-unexpected" trials. The prediction, which was confirmed in the experiment, is that reaction times should be rapid and virtually constant for all orientations on "probe-expected" trials, but should increase with increasing angular difference between the probed and the expected orientations on "probe-unexpected" trials. While some form of a discrete, propositional model may be able to accommodate such results, there seems little or not priori reason for such a system to behave in the manner described above. Still another experimental finding that, minimally, constrains the class of nonanalogue models that can account for so-called analogue phenomena has been reported by Cooper and Podgorny (1976). Using a restricted set of visual stimuli, these investigators were able to show that the complexity of the stimuli had no influence on the rate of menral rotarion. While this finding may prove to be highly task, stimulus, and practice specific, it nonetheless is consistent with an analogue interpretation of the undetlying representations and processes and is handled with difficulty only be certain versions of nonanalogue accounts (cf., Anderson, 1978).

In summary, then, analogue models for visual/spatial representations and transformations have recently been challenged on both empirical and theoretical grounds. The empirical challenges can be shown to be inconclusive and further experimental work is needed to resolve the inconsistencies. The theoretical challenges have taken the form of proposing nonanalogue models that may account for at least some of the findings generally regarded as supporting the need for positing analogue representations and transformations. While there appears at present to be no satisfactory way to test alternative models, consideration of an entire body of converging experimental findings may help to constrain the class of models capable of providing an adequate account of visual representation and processing.

The theoretical account provided thus far of analogue representations and transformations underscores the similarity between perceptual and imaginal operations and codes, e.g., between carrying out a mental rotation and perceiving an external physical rotation. (See Shepard & Podgorny, 1978, for a more complete description of relevant experimental evidence.) After Shepard and Cooper (1982) and Neisser (1976), the internal representation undergoing an analogue mental transformation might be viewed as an anticipation for perceiving the appropriate external object in the appropriate external spatial location, were it actually to appear. Given this theoretical framework, the question naturally arises as to whether correspondences can be found between the time course and nature of mental transformations and those of more strictly perceptual processes.

One experimental paradigm that has recently been introduced by Cooper and Vallone (1979) explored the question of the continuity between perceiving transformations on depictions of objects in space and internally extrapolating such transformations. Their procedure involves displaying a line drawing of an object undergoing a specified transformation (e.g., a rigid rotation about an axis in the picture plane or in depth) at some specified rate. At some unpredictable moment during the transformation, the object disappears from view, and at some later and again unpredictable time the same object reappears at a new position in the transformational trajectory. The observer's task is to determine whether or not the object has reappeared at the appropriate spatial location, were it to have continued transforming during the blank period, at the rate and in the fashion originally viewed. Experiments using this procedure have been initiated only recently and results are as yet quite preliminary (Cooper & Vallone, 1979). Nonetheless, the paradigm appears to have promise for investigating questions concerning the limiting conditions for performing mental simulations of perceived spatial transformations in terms of the type and rate of the transformation, the correspondence between the rate of transformation and rate of spatial transformations generally encountered in the environment, the distance along the transformational trajectory along which the mental extrapolation occurs, and the nature of the object being transformed.

Another experimental situation, which has been used by Shepard and his co-workers (Farrell & Shepard, 1981; Shepard & Cooper, 1982; Shepard & Judd, 1976) to examine the relationship between mental transformations and certain perceptual phenomena, presents observers with visual displays shown in rapid alternation. In an initial experiment Shepard and Judd (1976) found that when perspective views of the same three-dimensional object were shown alternately in two different orientations, observers reported an illusion of rigid rotation of a single object under certain conditions. As in the case of the earlier mental rotation experiments, using the same visual displays, the minimum exposure time required to produce coherent apparent rotational motion of a single three-dimensional object increased linearly with the angular difference between the portrayed orientations of the two separate views. Again, in accordance with findings from mental rotation experiments, the slope of the minimum cycle durations, as a function of angular difference, was equivalent for rotations in the picture plane and in depth. (Similar results have been obtained using random polygons as stimuli when those polygons are asymmetric, Farrell & Shepard, 1981).

One notable difference between this apparent rotational motion and the mental rotation task is found in the time necessary to produce a perceptual illusion of rigid rotation and the time required to undertake a purely imaginal rotation of an internal representation of a visual object. In the case of the former, perceptually-driven type of transformation, critical times are on the order of only hundreds of milliseconds whereas in the case of the latter, effortful type of transformation -- in which an internal representation of the spatial structure of an object continually preserved during the transformational process -- times are on the order of several seconds. Nonetheless, the striking similarities in the pattern of results obtained in the two situations have led Shepard (Farell & Shepard, 1981; Shepard & Cooper, 1982; Shepard & Judd, 1976) to argue that both the perceptual and the imaginal transformations reflect the operation of underlying analogue processes and representations.

In summary, this paper has presented a brief and incomplete overview of experimental evidence that argues for the necessity of positing an analogue system for the representation and processing of visual/spatial information in certain situations. The evidence has come from psychophysical experiments in which the time course of performing mental transformations on representations of visual objects has been shown to correspond to the time course of performing analogous physical transformations on external objects. The level of description at which internal processes have been characterized as analogue is sufficiently abstract to avoid any speculation concerning underlying neural mechanisms. Rather, an internal process can qualify as analogue if it can be shown that the intermediate states in the processing have a one-to-one relation to the intermediate stage of the corresponding external process. And, this one-to-one relationship is of a behavioral disposition or of a readiness to perceive and respond to a particular external object in a particular external spatial position, if such an object were actually to be presented. Conceived in this fashion, the nature of analogue representations and transformations can be assessed in behavioral experiments that have the potential of elucidating the way in which mental processes simulate or model external operations and events.

References

Anderson, J. R. Arguments concerning representations for mental imagery. Psychological Review, 1978, 85, 249-277.

Anderson, J. R. Representational types: A tri-code proposal. Technical Report No. ONR-82-1, 1982.

Carpenter, P. A., & Just, M. A. Eye fixations during mental rotation. In J. W. Senders, D. F. Fisher, & R. A. Monty (Eds.), Eye movements and the higher psychological functio..s. Hillsdale, N.J.: Erlbaum, 1978.

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

Cooper, L. A. Demonstration of a mental analog of an external rotation. Perception & Psychophysics, 1976, 19, 296-304.

Cooper, L. A., & Podgorny, P. Mental transformations and visual comparison processes:

Cooper, L. A., & Shepard R. N. Chronometric studies of the rotation of mental images. In W G. Chase (Ed.), Visual iformation processing. New York: Academic Press, 1973.

Cooper, L. A., & Sheperd, R. N. Transformations on representations of objects in space. In E. C. Carrerette & M. P. Friedman (Eds.), Handbook of perception, Vol. VIII, Perceptual coding. New York: Academic Press, 1978.

Cooper, L. A., & Vallone, R. Mental extrapolation of a perceived transformation. Unpublished data, 1979.

Effects of complexity and similarity. Journal of Experimental Psychology: Human Perception and Performance, 1976, 2, 503-514.

Farrell, J. E., & Shepard, R. N. Shape, orientation, and apparent rotational motion. Journal of Experimental Psychology: Human Perception and Performance, 1981, 7, 477-486.

Just, M. A., & Carpenter, P. A. Eye fixations and cognitive processes. Cognitive Psychology, 1976, 8, 441-480.

Kosslyn, S. M. Scanning visual images: Some structural implications. Perception and Psychophysics, 1973, 14, 90-94.

Kosslyn, S. M. Image and mind. Cambridge, Mass.: Harvard University Press, 1980.

Kosslyn, S. M. The medium and the message in mental imagery: A theory. Psychological Review, 1981, 88, 46-66.

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

Kosslyn, S. M., & Pomerantz, J. R. Imagery, propositions, and the form of internal representations. Cognitive Psychology, 1977, 9, 52-76.

Kubovy, M., & Podgorny, P. Does pattern matching require the normalization of size and orientation? Perception and Psychophysics, 1981, 30, 24-28.

Neisser, U. Cognition and reality. San Francisco: W. H. Freeman, 1976.

Pylyshyn, Z. W. The rate of "mental rotation" of images: A test of a holistic analogue hypothesis. Memory & Cognition, 1979, 7, 19-28.

Pylyshyn, Z. W. The imagery debate: Analogue media versus tacit knowledge. Psychological Review, 1981, 87, 16-45.

Shepard, R. N. Psycholphysical complementarity. In M. Kubovy & J. R. Pomerantz (Eds.), Perceptual organization. Hillsdale, NJ: Erlbaum 1981.

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

Shepard, R. N., Judd, S. A. Perceptual illusion of rotation of three-dimensional objects. Science, 1976, 191, 952-954.

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

Shepard, R. N., & Podgorny, P. Cognitive processes that resemble perceptual processes. In W. K. Estes (Ed.), Handbook of learning and cognitive processes (Vol. V). Hillsdale, NJ: Erlbaum, 1978.