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Visual and mental exploration of visuo-spatial configurations: Behavioral and neuroimaging approaches

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Abstract Do mental imagery and perception involve common processing mechanisms? Imagery researchers have devoted a great deal of effort to establishing the functional and structural similarities between images and perceptual events. Recent studies have focused on the comparison of images that are reconstructions of previous perceptual experience and images constructed from verbal descriptions. This article reports the findings of a research program based on the mental scanning paradigm; they reveal the similarities and differences between the two kinds of mental images. Neuroimaging studies have also provided evidence that the parieto-occipital cortex is involved in the processing of visual images, whether they are based on perceptual experience or constructed from linguistic inputs. However, the PET studies conducted by our research groups provide no evidence that the primary visual cortex is engaged in the generation of visual images. As there is contradictory evidence about this, further research is needed to clarify the role of the early visual areas in mental visual imagery.

Introduction

People interact perceptually with the objects in their environment, but their visual experience is not merely suspended when objects are no longer available to their perception. Internal representations may be activated in order to retrieve figural information or to access information that has not been explicitly encoded but is inferrable from processing these representations. Visual anticipation is another context in which visual aspects of an object are activated from memory. This paper concentrates on behaviorally relevant aspects of visual cognition that can be demonstrated in the absence of visual perception.

The concept of mental imagery encompasses a set of psychological processes that specialize in the creation of mental events by which absent objects are temporarily made available for a subject's conscious inspection (cf. Denis, 1991; Kosslyn, 1980, 1994). Some images consist of mere reproductions of past perceptual events, in quasi-photographic or more schematic forms. However, in recent years, imagery researchers have recognized the significance of a form of imagery that has long been neglected, in spite of it being ubiquitous in people's cognitive activity. This is the use of imagery constructed from discourse or verbal descriptions, when language is used to help a person construct the image of new objects or configurations that he/she has not yet perceptually encountered (and may well never encounter). People are able to create new visual knowledge and perform mental operations on these internal representations comparable to those executed on images resulting from actual perceptual experience.

This is the situation encountered by the person shown in the right-hand part of Fig. 1. The figure illustrates a typical communication situation. The person on the left is in the presence of a visual configuration, and her task is to convey to her listener a verbal description which should allow him to build an internal representation of the configuration. The listener may have to build this representation and store it in order to retrieve it later to perform specific operations on it (for instance, inspect it in order to answer questions such as "Is there a black object just above a white one?", incorporate further items into the configuration, or modify its internal structure). This communication situation illustrates several important cognitive issues. In particular, the very fact that a mental image can be generated from a

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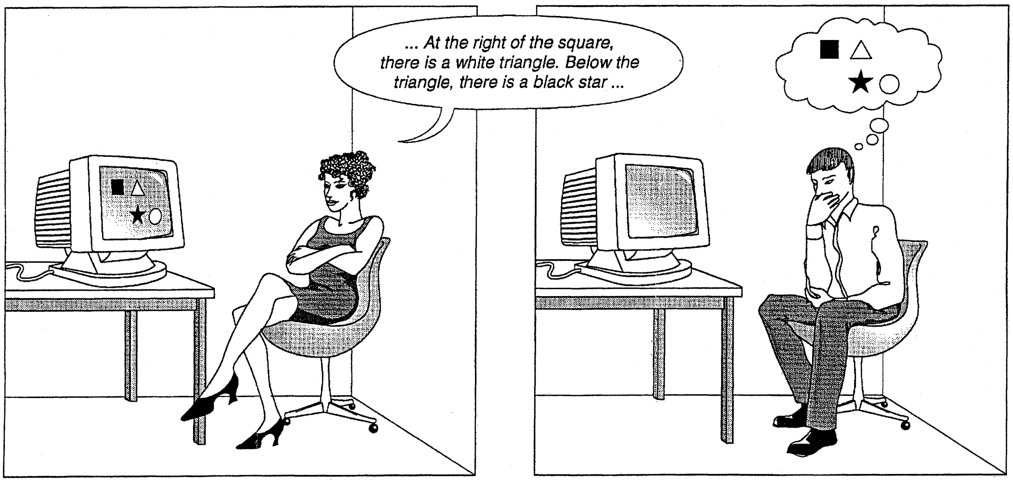


Fig. 1 A communication situation

linguistic input raises the issue of the relationships between cognitive representational systems endowed with distinct functional properties (cf. Bloom, Peterson, Nadel, & Garrett, 1996; Denis, 1996; Landau & Jackendoff, 1993).

These interfacing problems are well documented on the production side. A well-known problem is the sequencing of outputs selected by speakers during discourse. Discourse has an inherently linear structure. Any entity having two or more dimensions can only be described linearly. Although specific linguistic devices may be implemented to provide macrostructural information, speakers must convey information by adopting a sequence selected from among a wide range of options. Speakers tend to use only a subset of these possible orders, but the subset remains very large. Some orders may prove to be more friendly than others or better adjusted to the expectations of the listener, resulting in better processing conditions (cf. Daniel, Carité, & Denis, 1996; Levelt, 1989; Robin & Denis, 1991).

The listener's task is to carry out the reverse transformation, starting from a linearly organized linguistic input and building an internal representation that reflects the structure of the configuration described. There are situations where such transformation need not take place (if, for instance, the listener judges it to be advantageous to only perform rote learning of the verbal input), but we are interested in the situation where the listener makes use of visual imagery to generate an internal experience that is, to some extent, similar to the perceptual experience that the speaker has had or that he would himself have if he were exposed to the original configuration.

This situation raises the issue on which the efforts of our research groups have converged over the past few years: What is the cognitive status of visual images, and does it depend on the conditions in which they are constructed? We refer here to the contrast between two forms of visual imagery. In one, the image is constructed from a visual experience and, in the other, from verbal inputs. Both forms of imagery convey some form of figural information, and both clearly fall within the domain of visual cognition. However, do they have the same properties? Are images constructed more fuzzy without any initial visual experience, or do they lack clarity when compared to images that are essentially reconstructions of visual inputs? Could the information available in these images be insufficiently integrated? Would its internal structure be less respectful of the object's structure? The situation in Fig. 1 illustrates an ideal case, where information has been exhaustively and accurately transmitted. However, this is just a theoretical case. What is the status of images constructed from verbal inputs?

The research program described below was based on the assumption that visual images have a structure which is not random, but genuinely reflects the structure of the objects represented. This assumption is supported by a number of empirical investigations on perceptually-based visual images, which are thought to correspond to patterns of activation in a specialized medium (the so-called visual buffer). The visual buffer has structural properties which constrain the pattern of its activation. Images are thus internal representations that have structural features similar to those of the objects they represent (cf. Finke, 1989; Kosslyn, 1980, 1994).

The mental scanning paradigm

Mental scanning is undoubtedly the paradigm which has contributed most to support claims about the structural properties of visual images (cf. Kosslyn, 1973; Kosslyn, Ball, & Reiser, 1978). In a typical mental scanning experiment, subjects are invited to learn a visual configuration containing several objects, each at a specific location. For instance, in the island map that popularized the paradigm (Kosslyn et al., 1978, Exp. 2), seven geographical features are located in such a way that the distances between each pair of objects are different (Fig. 2). Once the subjects have memorized the configuration and the precise locations of landmarks,

Fig. 2 The map used in Kosslyn, Ball, and Reiser's (1978) experiments

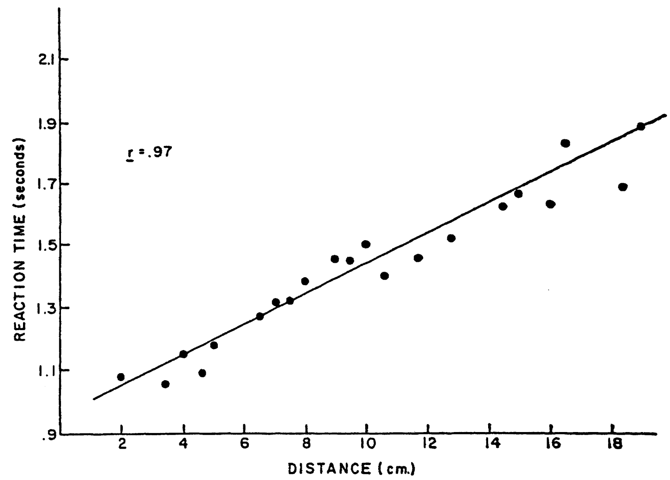


Fig. 3 Time needed to scan between all pairs of locations on the imaged map (Kosslyn, Ball, & Reiser, 1978, Exp. 2)

the experiment proper starts. In each trial, the subject focuses on a specified object (for instance, the hut). Upon hearing the name of a second object (for instance, the beach), the subject has to mentally scan the distance that separates the two objects and to indicate (by pressing a button) when scanning is completed. The subject's response interrupts a clock that gives the time taken to perform the mental scanning on each trial. The second named object may also be an object that was not present in the island map. If this occurs, the subject presses another button, indicating that the object is not part of the original configuration. The mental scanning experiments in fact focus on analysis of the first type of response.

The main finding from the experiments using this paradigm is that scanning times increase linearly with increasing distance. In addition, when times are averaged over subjects, there is usually a significant positive correlation between times and distances (Fig. 3). This finding has generally been taken to reflect the structural isomorphism of mental visual images with the objects or configurations they represent. In particular, an image exhibiting the mental scanning effect is thought to incorporate the metric information present in the original object. No claim is made that visual images have spatial properties in themselves, or that they occupy metrically defined portions of the brain. The idea is that the mechanisms that explore visual images operate on a cognitive entity which includes the spatial characteristics that were processed during perception. In other words, the chronometric pattern of the scanning process is invoked to make claims about the structure of the mental representation on which it operates. Although these interpretations elicited considerable discussion in the early eighties (e.g., Pylyshyn, 1981), the mental scanning data resisted interpretations to reduce them to the mere reflection of subjects' metacognitive knowledge about the relationships among distance, time, and speed (cf. Denis & Carfantan, 1985; Pinker, Choate, & Finke, 1984).

Thus, a visual image may genuinely reflect the spatial structure of the configuration it stands for, in particular the relative distances among specific points. These findings do not exclude the possibility that some images may lack such properties and be fuzzy or indeterminate. However, provided enough processing has taken place during learning, it seems that images can achieve structural coherence and definition, which are reflected by the mental scanning pattern. In optimal learning conditions, it is possible to show that not only do mental images have an internal structure, but that this structure is analogous to the structure of perceived objects.

At this point, a further issue has emerged. Considerable effort has been devoted to study the relationships between images and perceptual experience, but there has been less interest in images resulting from creative processes. In fact, much of the imagery used in daily cognitive activities consists of creating new images, for such things as problem solving, spatial reasoning, or reading. For instance, it is common for readers to attempt to create internal scenes providing an imaginal substrate for text comprehension (cf. Denis, 1982; Johnson-Laird, 1996). If it is recognized that language can be used to convey instructions for generating new images, possibly by the recombination of already available units, will the images constructed from verbal descriptions be of the same nature as the images of the object constructed after actually seeing it?

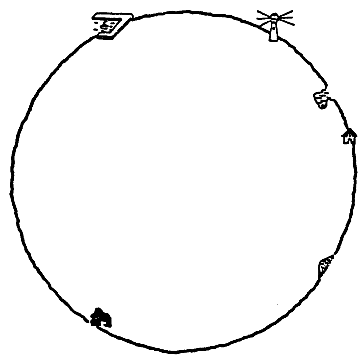
There are many situations suggesting that an image generated by processing a verbal description lacks the clarity or vividness of an image resulting from perception. Let us consider the ideal case where discourse is precise and explicit enough to allow a reader or listener to create an image whose geometry is strictly comparable to that of a perceptually-based image. This case assumes that discourse involves a high degree of coding and a number of descriptive conventions. Some highly specialized domains have such linguistic devices. For example, heraldry has a finite corpus of conventional terms that makes it possible to construct configurations that are unambiguous and practically identical for all individuals who possess the code. Other examples are spatial descriptions using precise metric and positional indications ("The vase is 30 centimeters to the left of the computer and 15 centimeters behind the telephone"), which allow several listeners to build quite similar images. Such a type of discourse is important in communication contexts that require people to have similar representations, on which depends the coordination of action of several operators. This is illustrated in ergonomic contexts such as aerial navigation or copiloting in cars, where it is common to speak of objects or directions "at 10 o'clock" to refer to the direction which points away from an observer by an angle relative to his/her frontal axis that is identical to the position of 10 relative to noon on a clock.

The research program summarized in the present article essentially consisted of creating situations in which subjects were invited to build an image of a spatial configuration without any perceptual cues, using only a verbal description. Subjects were then asked to execute cognitive operations on the newly constructed image. The chronometric patterns of these operations were compared to those observed when the subjects processed images derived from perception. This comparison made it possible to measure the similarities and differences between images derived from these two sources. The mental scanning paradigm was selected for this research program, based on the postulate that the analysis of exploration processes provides indirect, but valid, reflections of the structure of visual images. The similarity between scanning patterns is thought to justify making inferences about the internal structure of scanned images.

Scanning visual images constructed from perceptual or verbal inputs

Several constraints had to be respected in order to use comparable materials in the two learning conditions (configuration learning and description learning). First, if the structure of the object must be described completely, shapes that can be easily designated verbally are required. For instance, the outline shape of the island used by Kosslyn et al. (1978) is too complex for any reasonable attempt at precise description. We therefore replaced this shape with a simpler circular one, which is easier to refer to verbally. The landmarks were located on the periphery of the circle, and they had the same function as the landmarks on Kosslyn's island (Fig. 4a). Secondly, we needed a descriptive device which made it possible to locate each landmark at a metrically defined location that could be described very clearly, in such a way that the subject assigns to each landmark an unambiguous location in his/her image. We therefore used the conventional directions used in aerial navigation, stating, for instance, than an object is located "at 1 o'clock" (Fig. 4b). The subjects who participated in the experiments were all familiar with these conventions. Lastly, the successive steps of learning in the description condition could not be assessed by asking subjects to fill in a blank map after each trial, as this would have provided the subjects with figural information in addition to the verbal material. Thus, the description was learned in a number of trials fixed in advance. Preliminary experiments allowed us to check the minimal number of trials needed to draw the map and to indicate good memory of the configuration, its landmarks, and their positions.

(a)



(b) The island is circular in shape. Six features are situated at its periphery. At 11 o'clock, there is a harbor. At 1, there is a lighthouse. At 2, there is a creek. Equidistant from 2 and 3, there is a hut. At 4, there is a beach. At 7, there is a cave.

Fig. 4a, b Materials used in Denis and Cocude's (1989) experiments. **a** Map. **b** Description

The first set of Denis and Cocude's (1989) experiments using this material confirmed the existence of the mental scanning effect when subjects had learned the map material under conditions identical to those of Kosslyn et al. (1978). They also provided new information on the variation of scanning times in a visual (perceptual) scanning task. The classic interpretation of mental scanning experiments is that the linear relationship between scanning times and distances reflects the structural similarity of the image to the perceived configuration. The tacit assumption is that the linear relationship holds true in a condition where subjects perform perceptual scanning on the configuration itself. Surprisingly, however, the literature on mental scanning did not report controls for this condition. This is why we included a perceptual scanning task to ensure that perceptual scanning does exhibit the regularities that are assumed to be transferred to imaginal conditions. The results, in fact, showed that visual scanning of an actual configuration and the mental scanning of the visual image of this configuration resulted in very similar chronometric patterns. The time to scan between locations on a visual configuration and a visuo-spatial mental representation that was learned perceptually increased with the distance between the two locations (Figs. 5a and 5b).

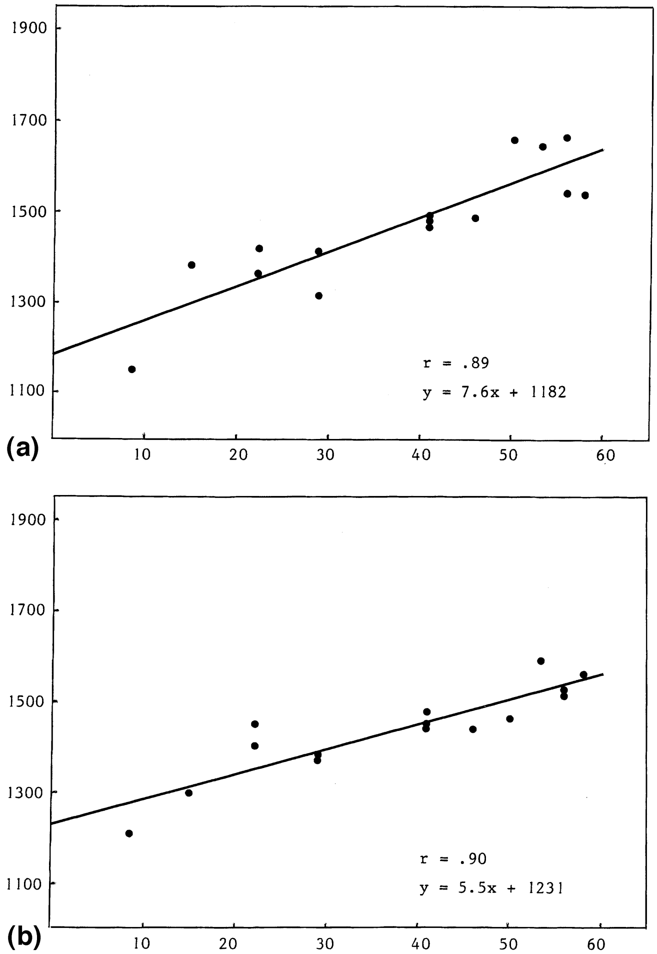


Fig. 5a, b Response time (msec) as a function of scanning distance (cm) in conditions where subjects were exposed to the map (Denis & Cocude, 1989, Exp. 1). **a** Visual scanning of the map. **b** Mental scanning following map learning

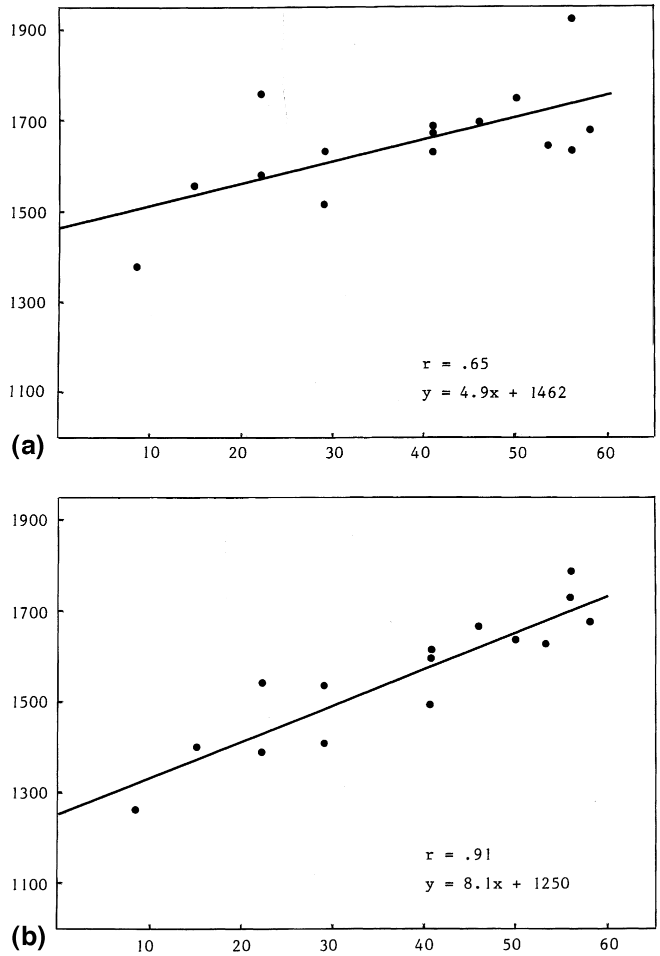


Fig. 6a, b Response time (msec) as a function of scanning distance (cm) in conditions where subjects heard the description (Denis & Cocude, 1989, Exps. 1 and 2). **a** Mental scanning following three learning trials. **b** Mental scanning following six learning trials

Similar linear time-distance relations also occurred in the mental scanning of representations formed from verbal descriptions. However, there were some differences in the scanning performance under the two imagery conditions. In the verbal learning condition, subjects were presented with the description three times. Their response times resulted in a significant, but somewhat lower, time-distance correlation coefficient than those of the subjects in the perceptual learning condition. Their absolute scanning times were also longer than in the perceptual learning condition (Fig. 6a). Although the verbal information contained in the description was memorized accurately after three trials, the structural qualities of the visuo-spatial representation were presumably imperfectly consolidated, resulting in a poorer time-distance correlation. In the verbal learning condition, another group of subjects listened to the description six times. The differences previously observed disappeared, and scanning performance was now very similar to performance following perceptual learning (Fig. 6b). Thus, for a moderate rate of learning, an image constructed from a verbal description may not attain the coherence of an image derived from perception. With additional learning of the description, the image may reach a structural coherence and resolution which makes it cognitively similar to a perceptually-based image.

These experiments provided the first demonstration that mental images generated from descriptions can have genuine metric properties, as these are reflected in the chronometric pattern of mental scanning processes, just as in scanning tasks involving images constructed from perceptual inputs. The inclusion of metric properties in images constructed from verbal descriptions is an especially interesting feature, as it shows that these images contain information in addition to the explicit information given in the descriptions. In our experiments, not only did images contain information on the nature and locations of the geographical landmarks (information that was effectively conveyed by the descriptions), but information on the relative distances among landmarks was actually available in the representations constructed by the subjects, although the descriptions said nothing about these distances. This was due to the transformation of the verbal inputs to a visuo-spatial representation, using a medium that cannot elude explicit expression of distances.

Alternative explanations of the findings must be considered. It may be, for instance, that the subjects in our experiments based their responses on a representation of the verbal description they listened to, rather than on the visual image they were supposed to mentally scan. It is possible that, after listening to the description, subjects kept a propositional representation of the text in their memory in addition to a visual image of the configuration. Their responses during the mental scanning task could have been based on the information retrieved from the propositions. If scanning between a landmark located at "1 o'clock" and another one at "2 o'clock" is based on an estimation of the distance separating the landmarks, simple computation may result in an estimate (and corresponding scanning time) that should be shorter than, say, when landmarks are located at "1 o'clock" and "4 o'clock." Some locations may indeed offer such alternate ways of computing distances. This explanation, however, is only valid for a subset of items. For instance, it can hardly be used to estimate distances separating landmarks located at "11 o'clock" and "2 o'clock." Computation based on memory for numerical values thus does not account for all the distances involved.

However, in our experiments, we systematically try to exclude any risk that the data reflect any contribution from such alternate strategies by conducting in-depth interviews of the subjects after the experiment in which they are questioned as to whether they used such a "numerical" strategy. The subjects who report having revised the hour-coded location of a landmark before mentally scanning to it are excluded and replaced to be sure that none of the response times used in the analysis reflect any strategy other than the mental scanning of images. The number of subjects excluded is generally very low, suggesting that the majority of subjects obey the instructions to construct a visual image of the configuration and base their responses on that image (not its verbal description). Further questions asked after the experiment are used to estimate how frequently subjects feel they have followed the image scanning instructions. The data from subjects who report having followed the instructions less than 75% of the time during the test phase are excluded from the analyses. Thus, even though the subjects in our experiments probably encode both verbal and imaginal information, there are good reasons to think that the data used in the analyses have been produced by subjects who processed an image representation during the scanning task. By taking similar precautions in experiments where subjects were asked to compare pairs of distances after learning verbal descriptions of spatial configurations, we collected evidence that computation was more likely to be based on images than on numerical or verbal representations. The fact that subjects scoring high on a test measuring their imagery capacities performed more accurately and faster than low scorers lent support to the notion that the substrate of their computations was a genuinely visuo-spatial representation (cf. Denis, 1996; Denis & Zimmer, 1992).

Structural properties of descriptions and images

The Denis and Cocude (1989) data support the claim that images generated from descriptions can have some of the structural properties that are characteristic of images derived from perceptual experience. However, we do not claim that both sorts of images are generally equivalent. The case illustrated in our experiment is, to some extent, an optimal one. The experimental conditions were designed to allow the phenomenon to appear, which indeed occurred. However, the equivalence of images generated from perception and from descriptions is limited to the geometrical properties of the image. Other properties such as subjective vividness, may be differently expressed in perceptually or linguistically-based images. In particular, the time course of learning and the regular sequence used for the description helped the image achieve the same structural coherence as when it was shaped by visually examining the detailed metrics of the object.

For this reason, the subsequent step in our research program was to examine the sensitivity of the mental scanning paradigm to experimental variations likely to create more difficult conditions for processing information and building a coherent, integrated image (Denis & Cocude, 1992). There is substantial literature on the effects of discourse structure on the construction of mental representations of described objects. In particular, the order in which information is entered in descriptions affects the on-line construction of internal representations and thus their availability for retrieval. Indeterminacies and referential discontinuity have also been shown to hinder the elaboration of visual mental models of spatial configurations (cf. Denis, 1996; Denis & Denhière, 1990; Ehrlich & Johnson-Laird, 1982; Mani & Johnson-Laird, 1982).

While a well-structured description was used in the previous experiments, with geographical details presented in a predictable, consistent clockwise sequence, we thought it relevant to determine whether subjects could construct effective, scannable representations from poorly structured descriptions. We constructed a version of the description that was designed to make it difficult for subjects to incorporate details into the outline structure of the map. Sentences were presented in a random sequence intended to create more demanding conditions for the formation of an image, while not impeding its elaboration, so that it should take longer to reach a stable, well-defined image than by using a well-structured description.

This new set of experiments was also intended to study image construction at different points in the learning of the description. Unlike the previous experiments in which different subjects performed the mental scanning task after three or six learning trials, the new experiments used the same subjects at each successive step in the experiment. Subjects took part in three learning trials before performing the first mental scanning task. They then resumed learning for three more trials and performed the second scanning task.

Analysis of response times revealed that the subjects who processed the clockwise description produced responses reflecting structural coherence of their images in the first scanning task, as indicated by a significant positive correlation between times and distances. After additional exposure to the same description, subjects' responses in the second scanning test resulted in a slight increase in the time-distance correlation and a decrease in absolute scanning times (Fig. 7a). The pattern of results was strikingly different for the subjects who processed the random description. The results of the first scanning test gave no suggestion that the subjects' mental images possessed any internal structure. Response times were very long, and there was no significant correlation between scanning times and distances. The situation changed markedly after three more exposures to the description. Scanning times were much shorter and there was now a significant positive correlation between times and distances (Fig. 7b).

These data confirmed that images generated from verbal descriptions can have metric properties similar to those of images derived from perceptual inputs. They also demonstrated that the structure of a description can affect the intrinsic structure of images of described objects and hence the mental operations subsequently performed on these images. The subjects still showed the standard time-distance correlation when the description was poorly structured, but the manifestation of this effect was substantially delayed. In contrast, a well-structured description, which placed minimal requirements on the subjects' processing capacities, rapidly yielded accurate, well integrated portrayals of the described objects, as well as a more pronounced correlation between time and distance. Therefore, poorly structured descriptions required additional exposure to achieve an image coherence similar to that produced by well-structured descriptions. We interpreted these results as indicating that the referential validity of images (i.e., their capacity to reflect accurately the objects they refer to) is not an all-or-nothing property, but results from stepwise elaboration.

The process of image elaboration

The gradual construction of visual images was investigated in more detail in a subsequent experiment (Denis, Gonçalves, & Memmi, 1995). A model was developed to account for the gradual process of image elaboration and the progressive increase in image accuracy. The model posits that the location of a landmark mentioned in a description is not represented as a sharp point in the mental image, but is instead associated with a region

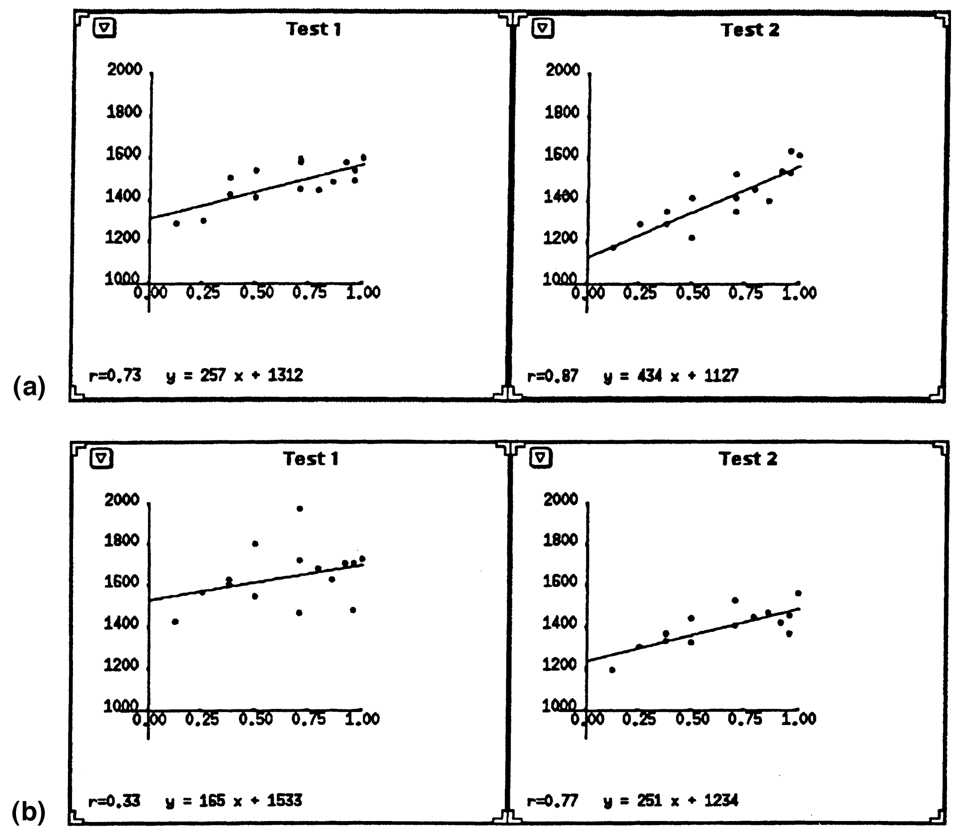


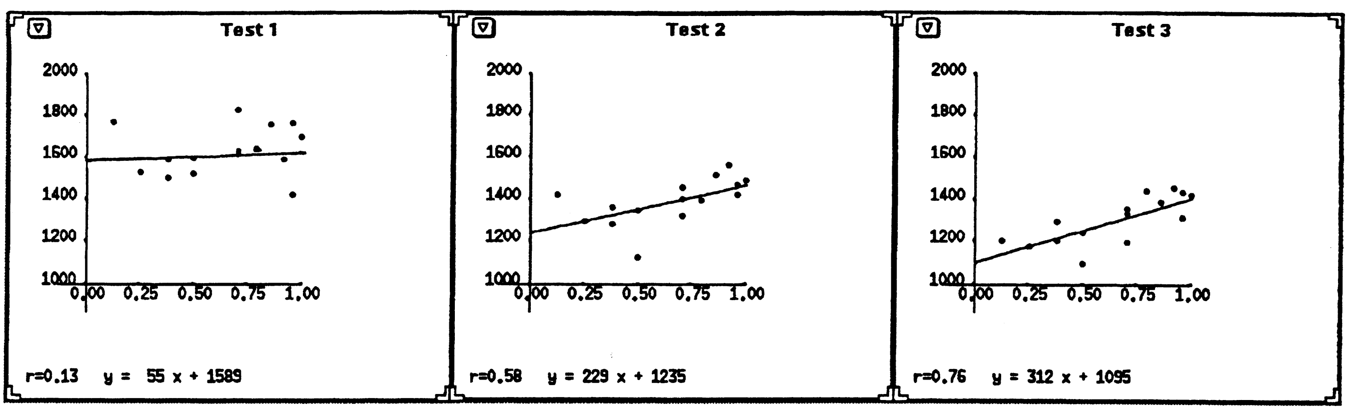
Fig. 7a, b Response time (msec) as a function of scanning distance in the first and second tests (Denis & Cocude, 1992, Exp. 1). Distances are expressed as their ratios to the diameter of the island. **a** Clockwise description. **b** Random description around this point. The region represents the possible range of the landmark's location at a given stage of the learning process. Learning the description essentially consists of progressively narrowing each "region of uncertainty" associated with a landmark to its exact location. The size of the unfocused (or "fuzzy") regions is expected to vary inversely with the degree of image elaboration. The closer the image is to its ultimate step of elaboration, the more restricted these regions are.

Additional experimental data were collected to provide a more fine-grained understanding of image elaboration. Whereas in the previous experiment the subjects heard the description six times and received two scanning tests (one after three exposures and the other after three more exposures), the new experiment used the same number of exposures, but there was a total of three mental scanning tests, one after each pair of learning trials. This procedure provided three successive "views" of the mental representation under construction. The subjects were presented with the description in random order, which should show the most dramatic effects.

The scanning times for the first test were longer than in the second test, and the times further decreased between the last two tests. In addition, correlational analyses revealed that there was no correlation between the times and distances for the first scanning test, but the coefficients reached significance for the second and the third tests (Fig. 8). These results are in agreement with those of the Denis and Cocude (1992) study. They also provide a more detailed view of the dynamics of the process. The results of the first scanning test revealed no structure at all in the image under construction. Response times were extremely long. The first two exposures were not enough to construct a coherent, accurate image, since mental exploration revealed no sign of the metric properties of the imagined map. Two more exposures changed the situation dramatically. Subjects performing mental scanning produced chronometric patterns which revealed that their images had an internal structure in which metric information was fairly correctly represented. The times were also significantly shorter, a finding compatible with the assumption that the images had an internal structure which was more readily available. The process was even more marked after two additional exposures. The numerical values at the third test (scanning times as well as correlation coefficients) all indicated further improvement in the internal structure of the image.

Our model of image accuracy was applied to the data to see whether the analysis reflected a stepwise restriction of regions of uncertainty in the mental image, and whether such restriction was more evident between the first and second tests than between the second and third. Individual scanning times for every distance separating a pair of landmarks were used to compute values reflecting the sizes of regions of uncertainty. The underlying logic was that these times could be used in conjunction with a measure of each subject's individual scanning speed to compute the distances theoretically scanned during these times. Each of these distances was thus compared with the actual distance separating the corresponding pair of landmarks, which made it possible to calculate the error in the location of the landmark. We first calculated each subject's scanning speed, using measures of the third scanning test as references. Each individual scanning time for a given subject in each test was then used to compute a corresponding estimated distance based on individual speed values. The distance was compared to the actual distance and the corresponding error was calculated. The scanning time used for a given distance was an average value for both scanning directions (e.g., "lighthouse–harbor" and "harbor–lighthouse"). The error was thus distributed evenly between the two landmarks. A total of five error values were calculated for each landmark (since there were six landmarks, any given landmark was involved in five distances). The error was expressed in terms of the ratio to the diameter of the island. Corresponding values were then entered as radii of circles reflecting the region of uncertainty associated with each landmark. The regions of uncertainty for each individual subject were expressed graphically as circles centered on the exact point of each landmark. Averaging values over subjects for each scanning test in each condition resulted in graphic representations of the

Fig. 8 Response time (msec) as a function of scanning distance in three successive tests (Denis, Gonçalves, & Memmi, 1995). Distances are expressed as their ratios to the diameter of the island



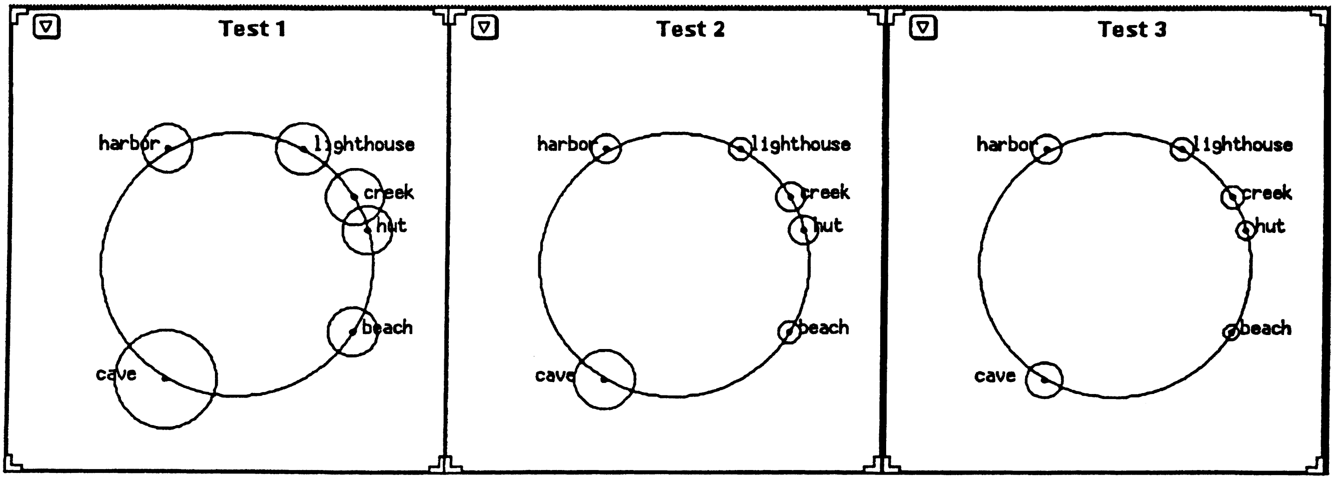


Fig. 9 Graphic representations of regions of uncertainty (Denis, Gonçalves, & Memmi, 1995)

regions of uncertainty for the three scanning tests (Fig. 9).

Inspection of the data first revealed that the sizes of regions of uncertainty (i.e., the reciprocal of accuracy) varied widely among landmarks. Overall, the landmarks in the part of the map which was the richest in landmarks tended to be located most accurately (i.e., by smallest regions of uncertainty). This result is consistent with the assumption that landmark location is favored when a landmark has close neighbors. Isolated landmarks were less accurately located at the outset. The other feature of interest is that the size of regions of uncertainty decreased after each new exposure of the subjects to the description. This decrease occurred for all regions, although it was more marked for some of them, and the hierarchy among the six landmarks remained the same throughout the experiment. As expected, there was a greater decrease between the first and second tests than between the second and third. The fact that there was a slight additional restriction of regions of uncertainty between the second and third tests confirms that there can still be a further improvement in image coherence and resolution even when the verbal description is perfectly memorized.

The robustness of the mental scanning effect and the role of individual imagery capacities

The mental scanning experiments described above focused mainly on the spatial (metric) properties of the objects represented. We did not investigate the effects of semantic content of the geographical landmarks on the map. For instance, "harbor," "lighthouse," and so on, were used as instantiations of points for which only topological and metric properties were considered. However, in memory of real-world spatial configurations, the structure of mental representations depends to some extent on knowledge, experience, and the value attached by the subjects to the landmarks. For example, subjects required to estimate distances in natural environments tend to underestimate distances which separate them from a landmark which is well-known or with which they have had repeated interactions, whereas they tend to overestimate the distances to less frequently visited landmarks. This bias is probably at work in the experiments showing that distances are underestimated in the center of cities and overestimated in peripheral zones (cf. Byrne, 1979; Moar & Bower, 1983).

The sensitivity of the mental scanning paradigm to descriptions in which some of the landmarks underwent special cognitive processing likely to give them particular cognitive salience was examined (Denis & Cocude, 1997). We wanted to determine whether a specific manipulation of the description could be responsible for systematic biases in the representation constructed from it, as in real-world configurations. Our expectation was that such biases would be revealed through scanning times differing from those recorded previously.

The first experiment devoted to this issue ensured that three of the six landmarks on the periphery of the island would be processed in a particular way. The description of each landmark not only gave information on its location, but also provided a short narration containing many concrete details, in order to increase the salience of this landmark. The other three landmarks were described in a rather neutral fashion. Subjects learned the descriptions and were required to perform the mental scanning task. The relevant aspect of the data here was the scanning times towards an important landmark and a secondary one. The results showed that there was no difference between these times, and time-distance correlation coefficients were virtually identical, whatever the type of scanning. This suggested that the time-distance correlation in the mental scanning paradigm is relatively robust, since the additional semantic content did not affect it.

The importance of the landmarks was then manipulated by including additional descriptions referring to imaginary actions of the subjects themselves in the landmarks. The subjects had to imagine their own activity in three landmarks, while the other three landmarks were described in neutral terms and did not imply any associated activity. This manipulation also produced no differential effect on scanning times or on correlations. Lastly, the descriptions of three of the six landmarks were enriched by a detailed picture designed to give these landmarks greater cognitive salience. The results still revealed no significant effect of differential treatment of the two sets of landmarks. Thus, on the whole, experimental attempts to modify the salience of landmarks in materials newly learned by subjects from a verbal description did not result in representational biases similar to those which were demonstrated in cognitive maps of natural spatial environments.

Lastly, we tested the sensitivity of mental scanning to subjects' individual characteristics. The studies on mental scanning performed to date were done without much concern about individual differences and the possible influence of the imagery capacities of subjects on scanning performance (see, however, Dror, Kosslyn, & Waag, 1993; Kosslyn, Brunn, Cave, & Wallach, 1984). The present research was done to identify the effects of individuals' imagery capacities on the mental scanning of images constructed from a verbal description. The subjects of the experiments reported above were asked to complete the Minnesota Paper Form Board (MPFB: Likert & Quasha, 1941), a visuo-spatial test widely used in imagery research. They were split into two groups, those who scored above and those who scored below the median of scores. Thus, we compared a group of subjects who were apt at generating and manipulating visual images and a group of subjects less prone to imaging.

Two contrasting patterns of results emerged. The subjects with high visuo-spatial capacities produced the pattern typical of mental scanning (relatively short scanning times and a significant time-distance correlation coefficient; Fig. 10a). Conversely, the subjects with poorer visuo-spatial capacities produced responses whose chronometric characteristics indicated that their images had no stable, consistent structural properties. Their scanning times were quite long, and there was no consistent relationship between scanning times and distances (Fig. 10b). This pattern suggests that these subjects had difficulty controlling the generation and exploration of their images. Their images probably contained a large amount of noise, which may have resulted from the difficulty experienced by these subjects in maintaining their mental representations at a sufficiently high level of activation.

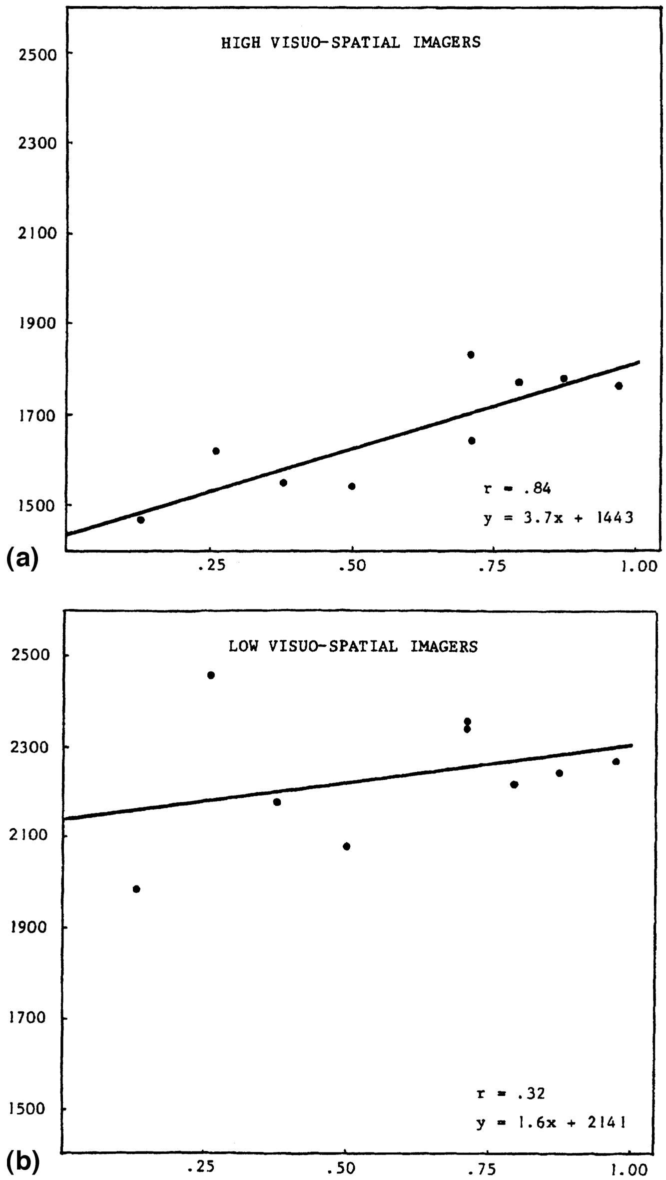


Fig. 10a, b Response time (msec) as a function of scanning distance (Denis & Cocude, 1997, Exp. 1). Distances are expressed as their ratios to the diameter of the island. **a** High visuo-spatial imagers. **b** Low visuo-spatial imagers

Neuroimaging investigations

The experiments reported in this paper have contributed to document the functional and structural similarities between images and the perceptual events from which they were formed. The images derived from perception and those constructed from verbal descriptions were also found to be very similar. In addition to the behavioral evidence that visual imagery and perception share functional properties, there is a strong suggestion that the two systems involve common brain structures. Several neuropsychological studies support this assumption (e.g., Basso, Bisiach, & Luzzatti, 1980; Farah, 1984; Farah, Levine, & Calvanio, 1988). The involvement of cortical structures common to visual imagery and perception is also indicated by studies on evoked potentials (Farah, 1995; Farah, Weisberg, Monheit, & Péronnet, 1989) and regional cerebral blood flow (Goldenberg et al., 1989; Kosslyn et al., 1993).

However, some findings have raised doubts that visual imagery and visual perception use the very same neural substrate. The most significant are those showing that brain-damaged patients with severely impaired object recognition may have fully preserved visual imagery (cf. Behrmann, Winocur, & Moscovitch, 1992). On the other hand, tests on patients with visual imagery disorders have shown that these subjects may have no perceptual disorder (cf. Guaraglia, Padovani, Pantano, & Pizzamiglio, 1993). The double dissociation between imagery and perception in brain-damaged patients may simply reflect the fact that visual imagery depends on brain structures that perception does not require. However, it is also possible that selective damage to early visual areas impairs visual perception while leaving visual imagery intact, if the areas subserving visual imagery are considered to be a subset of those active in visual perception (cf. Roland & Gulyás, 1994).

Little information is available on the brain structures that are involved in visual imagery based on verbal inputs. It is reasonable to assume that the same neural substrate is activated whatever the origin of an image (derived from visual perception or constructed from a description of a never-seen object). A neuroimaging study on visual imagery of described objects using single photon emission computerized tomography (SPECT) was conducted by our research groups, with an additional investigation of the influence of individual differences in imagery capacities (Charlot, Tzourio, Zilbovicius, Mazoyer, & Denis, 1992). Two visuo-spatial tests, the MPFB and the Mental Rotations Test (Vandenberg & Kuse, 1978), were used to select two groups of subjects, one with high and the other with low visuo-spatial capacities (corresponding to the upper and lower thirds of scores). The subjects first learned the map of the island used in our previous experiments from a purely verbal description. They then took part in two cognitive tasks (in addition to a rest condition). One task consisted of mentally conjugating abstract, irregular verbs. The other task was reconstructing the visual image of the island and performing mental exploration of the distances separating the landmarks. Upon hearing the name of one landmark, they were asked to mentally fly from this landmark to each of the five others and return, while maintaining as vivid a visual image as possible. Because of the technical constraints of this type of experiment, chronometric measurements of individual scanning performances were not done.

High visuo-spatial imagers showed a selective increase in blood flow in the left sensorimotor cortex over the resting state while performing the verbal task, whereas there was a significant increase in blood flow in the left temporo-occipital cortex when the subjects imagined and mentally scanned the visual configuration (without activation of the primary visual cortex). This result is compatible with the idea that visual representations constructed from visual experience and those constructed from descriptions involve the same cortical areas. In contrast, the low visuo-spatial imagers showed much less clearly differentiated increases in their cerebral blood flow.

The issue of the involvement of the primary visual cortex in visual imagery remains open. Kosslyn et al. (1993) reported experiments using positron emission tomography (PET) in a variant of Podgorny and Shepard's (1978) paradigm. Subjects were presented with a grid of 5×5 cells. One of the cells contained an X-mark. In the imagery condition, subjects had to visualize an uppercase letter and decide whether this letter would have covered the X-mark if it were present in the grid. In the perceptual condition, the uppercase letter was superimposed on the grid and the same kind of decision was required. The primary visual cortex was activated in both conditions, suggesting that imagery and perception call upon common cerebral mechanisms. Activation was also greater in imagery than in perception, indicating that the generation of a visual image is a more demanding cognitive task than perception. Other PET studies have also reported increases in blood flow in the primary visual cortex when subjects created mental images of places and persons familiar to them and inspected these images in detail (Damasio et al., 1993). Similar conclusions were drawn from studies using functional magnetic resonance imagery (cf. Le Bihan et al., 1993), but other research programs using the same technique found that the visual association cortex, and not the primary visual cortex, was engaged during the generation of mental images (cf. D'Esposito et al., 1997).

The data indicating that early visual areas are activated in visual imagery support the hypothesis that the visual areas subserving visual imagery are identical to those subserving visual perception (cf. Kosslyn et al., 1993; Kosslyn, Thompson, & Alpert, 1997; Kosslyn, Thompson, Kim, & Alpert, 1995). However, these areas are not activated during visual imagery in all subjects (cf. Le Bihan et al., 1993; Ogawa et al., 1993), and it is possible that they are activated only by tasks that require high-resolution images (cf. Sakai & Miyashita, 1994). There is also evidence that early visual areas are not involved in visual imagery, but that neuronal populations in temporo-occipital and parieto-occipital areas represent objects and scenes during imagery (cf. Roland & Gulyás, 1995).

Given the controversial nature of this issue, we designed an experiment to compare PET activations in perceptual and imagery conditions (Mellet, Tzourio, Denis, & Mazoyer, 1995). In the learning phase, subjects were invited to inspect and memorize the map of an island similar to those used in previous experiments, with landmarks around the periphery of the map. The subjects were then examined in a perceptual or an imagery condition. In the perceptual condition, the subjects were shown the map and required to scan from landmark to landmark, alternatively in clockwise and counterclockwise order. In the imagery condition, the subjects were placed in total darkness and were instructed to recreate a vivid image of the map and then to perform a mental exploration of the landmarks by following the same procedure. Brain activity was recorded during the two explorations and compared to a rest condition.

The results clearly indicated that both tasks involved a common network of cerebral structures, including a bilateral superior external occipital region and a left internal parietal region (precuneus) (Figs. 11a and 11b). While there are grounds for claiming that the occipital region is responsible for the generation and maintenance of the visual image, the parietal region is likely to be involved in the exploration component of the process. Other PET studies have also indicated that memory-related imagery is associated with precuneus activation (cf. Fletcher et al., 1995). The most critical finding was that bilateral activation of the primary visual areas occurred in the perceptual condition, but these areas were not activated during the mental exploration in the imagery condition.

The involvement of regions belonging to the "dorsal route" in the mental exploration of a previously learned visual configuration is in line with current assumptions about the role of the parieto-occipital cortex in the spatial processing of mental images (cf. Farah, Hammond, Levine, & Calvanio, 1998; Levine, Warach, & Farah, 1985). These findings may indicate that mental imagery involves the same dichotomy as the one in the visual system between the dorsal pathway – which is responsible for processing spatial attributes of visual stimuli – and the ventral pathway, which processes figural attributes (e.g., Haxby et al. 1991). We attempted to investigate the capacity of the cognitive system to generate images based on verbal descriptions, conducting an experiment designed to establish whether a highly specialized network for visuo-spatial processing can be activated by purely verbal inputs (Mellet et al., 1996).

The PET technique was used to monitor variations in regional cerebral blood flow while subjects constructed mental images of objects that they had never seen before from oral instructions. These objects were three-dimensional cube assemblies that subjects were trained to mentally construct and visualize by listening to specific sets of verbal instructions. This task involved a strong spatial component, since the objects to be imagined ex-

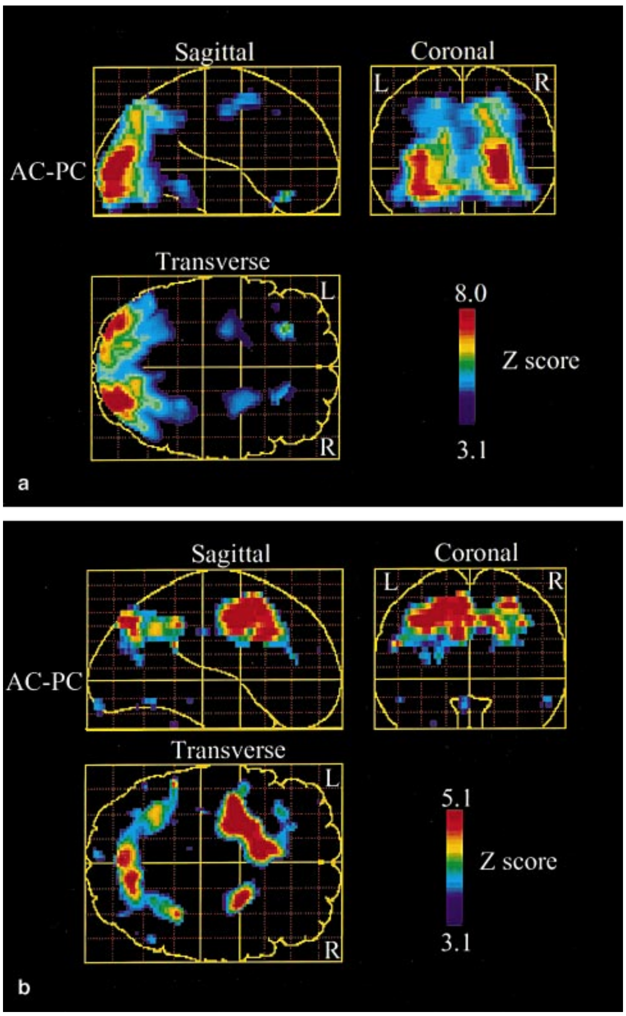


Fig. 11a, b Statistical parametric maps corresponding to two comparisons (Mellet, Tzourio, Denis, & Mazoyer, 1995). **a** Visual exploration minus rest. **b** Mental exploration minus rest

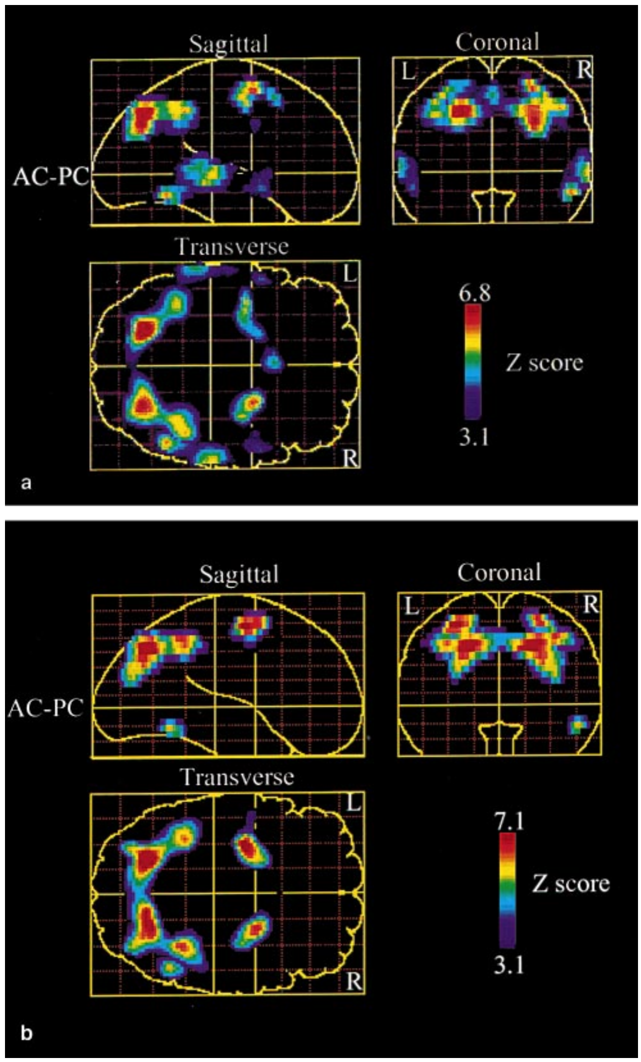


Fig. 12a, b Statistical parametric maps corresponding to two comparisons (Mellet et al., 1996). **a** Mental imagery minus rest. **b** Mental imagery minus word listening tended along all three dimensions. This mental imagery task was contrasted with two control conditions, one involving passive listening to phonetically matched non-spatial word lists, and the other involving silent rest. All three tasks were performed in total darkness. The results showed that the mental imagery task activated a bilateral occipito-parieto-frontal network, including the superior occipital cortex, the inferior parietal cortex, and the premotor cortex. The right inferior temporal cortex was also activated in this task, but there was no activation of the primary visual areas (Figs. 12a and 12b). There was bilateral activation of the superior and middle temporal cortex during both mental imagery and passive listening when they were compared to the rest condition.

These data confirm that at least some mental imagery tasks may not involve any detectable participation of early visual areas. They also provide evidence that the dorsal route, which is known to process visuo-spatial information, can be recruited in the absence of any visual input by auditory linguistic inputs only. This is an important finding, since it indicates that the involvement of the dorsal route for spatial processing is not linked to the modality under which information is presented to the subject. This network involving visual unimodal and multimodal association regions can thus operate on non-visual inputs and be activated whatever the nature of input. It is thus engaged in both the mental scanning of visual images and the creative construction of purely mental objects.

A brief conclusion

It is probably too early to draw a "conclusion" in a field where so much work remains to be done. A few major points, however, should be mentioned. Imagery research has for some time been devoted to assessing the functional similarities between mental images and perceptual events. A new domain of investigation has been recently opened by researchers looking for the similarities and differences between two sorts of mental images, those which are reconstructions of previous perceptual experience and those which are constructed anew from verbal descriptions. We used the mental scanning paradigm, which has been shown to be a sensitive tool for assessing the analogies between the structures of visual images and visual percepts, to compare the processes involved in the exploration of visual images derived from direct perception and verbal description. This approach provided a more fine-grained assessment of the process of image construction, as well as the robustness of the mental scanning effect.

Neuroimaging techniques have recently been used to identify the regions of the brain that are engaged when people generate and explore mental images, whether the images are reconstructed from perception or constructed from verbal inputs. The assumptions about the role of the parieto-occipital cortex in the processing of visuo-spatial images are clearly supported by PET investigations. Our studies, however, provide no indication that the primary visual cortex is involved in the generation of visual images, but the fact that there is contradictory evidence about this issue suggests that it should be one of the priorities of future neuroimaging investigations of mental imagery.

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