LIFE-SPAN CHANGES IN VISUO-SPATIAL SHORT TERM MEMORY

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By

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To Grabinoulor...

Acknowledgements

I declare that this doctoral thesis is my own work, and I bear the whole responsibility for its content. It has been carried out at both the University of Stirling and the University of Liège between the years 1992 and 1996.

This doctoral thesis has been supervised by Professor Roger J. Watt. I wish to thank him for his advice and his receptiveness during the preparation of this work. Many thanks to Dr Robin Campbell - additional supervisor - for his comments on several developmental aspects of my research.

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The study presented in chapter six is part of a research program assessing the development of imagery abilities in normal and mentally retarded children. This research program is realised in collaboration with Dr Yannick Courbois, University Charles de Gaulle, Lille, France. Experiments 4a and 4b concern normal populations and have been totally run in our laboratory in Liège (material construction, data collecting, statistical analysis, and writing up of the report). Several studies - not reported in this thesis - have been presented in different international conferences (see Courbois & Lejeune, 1994; Courbois, Lejeune & Aslani, 1995).

Several parts of this thesis have been presented in scientific conferences, are inspired from some of my previous publications, or are in press as articles or book chapter. Chapter one has been adapted from Lejeune (1993a). The study reported in chapter four has been presented in an oral communication at the Second International Conference on Memory, Padova, Italy, 14th-19th July 1996. Part of the research reported in chapter five has been presented at the Annual Meeting of the Belgian Psychological Society, May 12, 1995, Louvain-la-Neuve, Belgium. Finally, experiment 4a will appear in Lejeune, M. and Courbois, Y. (*in press*).

ABSTRACT

Several experiments are presented to evaluate the development of visuo-spatial short term memory from childhood to old age (from five-year-olds to about 70-year-olds). Visuo-spatial short term memory was assessed through transformational imagery tasks.

The first set of experiments (chapters 3, 4 and 5) concerned the development of mental rotation abilities. A review of the literature suggested that young children (specifically so-called preoperational children) and elderly people are poor at rotating a mental image of a visual pattern. However, as some mental rotation abilities have been reported while using Shepard's paradigm, attention was focussed on the role of the first steps necessarily taken while performing a mental rotation task, specifically the maintenance of a visual pattern in STM.

The second set of experiments (chapter 6) considered another imagery subsystem, namely "mental scanning". Like mental rotation, it requires the maintenance of a visual pattern in short term memory.

Image maintenance ability has been assessed in reference to Kosslyn's (1994) model although Baddeley's (1986) working memory model - specifically, Logie's (1995) revision of the VSSP - has been sometimes considered while interpreting the data. These two different theoretical models suggest the existence of two related but different subsystems for sotring visual and spatial information.

Most of the data presented in this thesis suggest that young children and the elderly have some difficulties maintaining spatial characteristics of a visual pattern in short term memory, i.e. the orientation of the stimulus in the mental rotation tasks and the location of targets in the mental scanning tasks. These results tend to provide some developmental evidence for a dissociation between the dorsal and ventral subsystems. It seems that the two subsystems develop at different speeds. The ventral subsystem might be better developed earlier than the dorsal subsystem. Similarly, some data suggest that the same ventral system is not yet affected by ageing when the dorsal subsystem has already begun to deteriorate.

CONTENTS

General introduction [1]

Think about your very first actions in the morning when you wake up. Your eyes open... Here is vision ! Once our eyes are opened, we are able to capture a huge amount of information. We see our environment and decide what actions to take. Visual perception guides our behaviour, it is useful for prompting behaviours, for moving around and for touching things (Watt, 1991). Vision is part of all our everyday life activities. However, we might sometimes have the impression of "seeing" although our eyes are closed. In such situations, we are "seeing" mental images of our environment that we have stored in memory. We "see" with our mind's eye. Indeed, two related sets of visual representation can be activated to preserve the physical characteristics of external objects (e.g. the configuration of an environment). The first representation is elaborated when the objects are present and constitutes a physical code (i.e. the visual percept) while the second representation is actively generated in the absence of external objects - it constitutes a mental image (Shepard, 1978).

We can roughly say that visual perception corresponds to the process of interpreting and understanding sensory information (i.e. the light reflected by an object on the retina) (Ashcraft, 1994, p. 88). Levine and Shefner (1981) mentioned that "Perception refers to the way in which we interpret the information gathered (and processed) by the senses. In a word, we *sense* the presence of a stimulus, but we perceive what it is". What about mental images ? Finke (1989) has proposed a convenient definition: Mental imagery is defined as "the mental invention or recreation of an experience that in at least some respects resembles

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1 This introduction is adapted from Lejeune (1993a).

the experiences of actually perceiving an object or an event, either in conjunction with, or in the absence of, direct sensory stimulation".

Mental images arise in several everyday activities. We use mental images while solving problems, while remembering details of a painting seen in a museum, or while remembering whether a friend wears glasses.

Although it is hard to reject the phenomenological existence of imagery, its scientific study is challenging. Indeed, imagery is a *subjective* phenomenon; it is not directly observable. Moreover, mental images are elusive. Consequently, experimental methods are needed to infer the properties of imagery in an *objective* manner and to elicit the images themselves (Finke, 1989).

For these reasons, the history of mental image studies is long and controversial (Denis, 1989; Le Ny, 1994; Pinker & Kosslyn, 1983). At the end of the 19th century, psychology as the "science of mental activities" was the first discipline after philosophy to study the mind's eye. Introspection was then used to understand the human mind: Subjects were required to report what was going on in their mind. References to mental images were often reported. However at the beginning of the 20th century, psychology stated the firm wish to become a scientific discipline. Watson's (1913) radical position claiming psychology as the "behavioural science" had a dramatic impact on American studies of imagery. These "*Ghosts in the mind machine*" (Kosslyn, 1983) became very rarely studied; they were considered to have no functional role in behaviours. The situation was however somehow different in Europe where several scientists continued their researches in the field (e.g. Bartlett (1932) continued to study visual memory in United Kingdom). It was only in the fifties with neo-behaviourism that mental imagery was reconsidered in the whole scientific world as a possible mediator in human and animal behaviours; for instance, Skinner (1953, p.266) referred to *operant seeings*.

In this theoretical evolution, Paivio's (1971, 1986) *dual coding theory* was probably the first integrative theory to reconsider the mental images. Briefly stated, the dual coding theory postulates the existence of two classes of phenomena cognitively governed by two subsystems functionally and structurally distinct. One subsystem is specialised for the representation and the processing of non-verbal or imaginal information, whilst the other is specialised for verbal information. Paivio gave imagery a major status in the cognitive system. Images, for instance, were shown to be involved in language comprehension (see for a brief discussion: Lejeune, 1993e). His model continued to develop in the seventies and eighties, and still animates several debates in current research.

Cognitive psychology and mental imagery

The birth and the development of cognitivism firmly re-integrated imagery into the field of psychology. Since the 1970s, new methodologies have been developed and a huge amount of empirical data has been collected. Although different methodologies have been used, mental chronometry has been the most valuable source of information. This literature is large and it is sufficient for present purposes to highlight two central sets of studies: Mental rotation and mental scanning.

Mental rotation

Shepard and his associates (for a review, see Shepard & Cooper, 1982) pioneered the scientific study of mental rotation. They widely investigated young adults' ability to maintain and to rotate a visual image in short term memory. In the first experiment, Shepard and Metzler (1971) presented subjects with pairs of perspective line drawings of three-dimensional objects having no canonical orientation. The objects were identical or mirror images of one another, and they differed by rotations that were either in the picture plane or in depth, about the vertical axis. The angular difference between the objects systematically varied from trial to trial. The subjects judged whether the objects were identical or were different, i.e. whether one of the objects was a mirror-reversed version of the other one. Reaction times (RTs) were a *linear function* of the angular discrepancy. In other words, the time to verify that the stimuli were equivalent increased in direct proportion to the angular differences between the stimuli. This proportional increase in RTs implied that the mental rotations must have been carried out at a constant rate for all the comparisons.

Shepard and Metzler (1971) suggested that subjects mentally rotate one of the objects towards the orientation of the other before carrying out the final comparison. Mental rotation resembles the actual rotation of concrete objects or patterns. "Imagined transformations and physical transformations exhibit corresponding dynamic characteristics and are governed by the same laws of motion" (Finke, 1989, p. 93).

This principle leads to, at least, two predictions: (1) Mental rotation is *holistic*, and (2) mental rotation is *continuous.*

The *holistic* characteristics of mental rotation have been demonstrated by Cooper (1975) and Cooper and Podgorny (1976). They showed that rotation rates are not dependent on the complexity of the patterns. While using polygons varying in complexity as stimuli, RTs increased linearly with increasing departure from the initial position of the stimulus, and the rate of increase was independent of the patterns' complexity.

Moreover, Cooper (1976) demonstrated that mental rotations are *continuous*, i.e. mental rotations pass through all the intermediate points along the transformational path. Mental rotations do not occur as discrete sequences of static images but are carried out in a smooth and continuous manner. In a classical experiment, Cooper (1976) presented subjects (who already participated in experiments on mental rotation, so that their rotational speed was known) with polygons in one of six orientations that they were already familiar with (i.e. 0°, 60°, 120°). As soon as the pattern was removed, subjects were required to imagine that it was rotating clockwise at their normal rate of mental rotation. While the subjects were imagining the rotation of the polygon, a test was presented, either in one of the six familiar orientations, or in an intermediate orientation (i.e. 30°, 90°, 150°). Reaction times increased linearly with increasing departure of the test stimulus orientation from where the mentally rotated pattern should have been at that time (inferred from Cooper's knowledge of individual subject's rotational speed). These results suggested that mental rotations are continuous.

Although much chronometrical data supports the conclusions about the dynamic characteristics of mental rotation, some psychologists have not been totally convinced and several alternative explanations have been offered. Four major groups of criticisms have been formulated about imagery results.

Pylyshyn (1981) as well as Intons-Peterson (1983) has drawn attention to some biases related to the *task demands* and the *tacit knowledge* subjects may have about the processes engaged. The way stimuli are presented and/or the expectations of the experimenter might affect subjects' performances. However, as subjects are never told to imagine simulating physical motions, mental rotation studies are less susceptible to these criticisms. But, in other studies on imagery, it has been demonstrated that experimenter's expectations might influence subjects. It has been shown for instance that some of the results of imagery studies disappear when the experiment is run by naive experimenters (Intons-Peterson & White, 1981).

It seems that Shepard and Metzler's pioneering study is not the most convincing research to prove the analogical nature of mental rotation. Indeed, Just and Carpenter (1978) have shown that during such a task, *eye movements* suggest that subjects are processing the stimulus step by step considering only some stimulus segments during the task.

Hochberg and Gellman (1977) reported evidence that mental rotation is *not always continuous and holistic*. They showed that the rates of mental rotation were reduced when the landmark features of the rotated stimuli became more salient. Consequently, the rate of mental rotation might depend on the stimulus characteristics. However, in Hochberg and Gellman's (1977) study, it seems that when salient orientational features were included in the stimuli, subjects did not have to carry out mental rotations (see Shepard & Cooper, 1982, for a counter-criticism).

Finally, when congenitally blind people are required to compare normal and mirror-reversed versions of patterns (tactile modality), their RTs increased with increasing angular disparity (Kerr, 1983; Marmor & Zabeck, 1976). These results suggest that mental rotation is *not restricted to the visual modality*, but can be applied in any sensory modality.

Mental scanning

Mental scanning represents another process which has been classically studied in the field of imagery. In their pioneering study, Kosslyn, Ball and Reiser (1978) presented subjects with a map of an imaginary island which they were to memorise in the form of a mental image. Several objects (a hut, a tree, a beach...) were drawn on the island. After the memorisation of the pattern, the picture of the island was removed. Subjects had to generate a mental image of the previously memorised island and to focus their attention on a particular detail (e.g. the tree). They were then invited to mentally scan from that location to another designated one (e.g. the beach). When "arrived", they pressed a button: Scanning times were recorded. Kosslyn *et al.* (1978) showed that the scanning times were linearly dependent on the physical distance separating the two details on the map. Based on these results, they suggested that mental images preserve the visuo-spatial extension of the external referent.

Similar results were reported with other patterns and different procedures: A map representing the University Campus of San Bernardino (Evans & Pezdek, 1980); a map of Netherlands (Boer, 1991). However, although Kosslyn *et al.*'s (1978) results have been replicated, several criticisms were formulated against these experiments. This was particularly true since the generation of an image of an island from a *verbal description* of this pattern yielded similar results (see Denis & Cocude, 1989; Denis & Zimmer, 1992). It seems that there is an equivalence between images constructed from verbal descriptions and those based on memories for pictorial stimuli. But whatever the results, Denis and Cocude (1989) continued to consider that mental scanning is an entirely analogical process.

Pylyshyn (1984) has been the most sceptical about scanning studies results. He claimed that *tacit knowledge* subjects have about visual scanning rates could be responsible for the observed results. Indeed, Mitchell and Richman (1980) have replicated Kosslyn *et al.* 's (1978) results while using another experimental methodology. In this study, subjects were not required to scan across a mental image but rather to *estimate* the scanning times. The *estimated times* matched very closely the *image scanning times.*

To avoid these criticisms and especially those related to tacit knowledge, other methodologies were used. Finke and Pinker (1982) presented subjects with four dots on a screen. When the dots were removed, subjects were asked to image the precise locations of the dots. An arrow then was displayed in an unexpected orientation and location, and subjects were required to judge as quickly as possible whether the arrow was pointing to one of the previously presented dots. Although subjects were not explicitly instructed to scan across the pattern, RTs increased linearly with the distance separating the arrow and the pointed dot. This new methodology confirmed that imaginal representations preserve the visuo-spatial characteristics of the external referent.

Visual mental imagery : A representation which is functionally and structurally equivalent to visual perception.

Despite several criticisms and mainly on the basis of chronometrical studies, the image and the percept became two distinguished concepts and several models were developed to account for these different psychological phenomena. Research showed that mental imagery can be considered equivalent to the visual representations associated with the perception of visual stimuli. In other words, studies demonstrated that the generation of an image can be considered as an afferent activation of perceptual representations identical to those automatically activated during the perception of an external stimulus. This idea - going back to the philosophical essay of Hume (1739) - was developed by authors such as Hebb (1968), Shepard (1978, 1984) and Finke (1980), and an increasing number of studies continued to test the functional and structural equivalences between imagery and visual perception (Finke, 1985; Finke & Shepard, 1986; Farah, 1988).

"Imagery is... (considered to be) functionally equivalent to perception to the extent that similar mechanisms in the visual system are activated when objects or events are imagined as when the same objects or events are actually perceived" (Finke, 1989). These functional equivalences were demonstrated for instance in probe detection tasks using imagined features (see Podgorny & Shepard, 1978), or with imagery-induced color aftereffects (see Finke & Schmidt, 1977).

Similarly, "the spatial arrangement of the elements of a mental image corresponds to the way objects or their parts are arranged on actual physical surfaces or in an actual physical space. This principle requires that mental images, like a physical surface or space, be spatially continuous" (Finke, 1989). This principle was evidenced for instance in studies on imagined scanning (see Kosslyn, 1973; Pinker, 1980).

These characteristics gave rise to the notion of imagery as an *analogical representation*. In cognitive psychology, the representation of an external information is called "analogical" if it preserves the structure or other properties of this information without the intervention of a symbolic (propositional or numerical) encoding (Doron & Parot, 1991). Mental images seem to respect these criteria, and consequently can be considered as analogical representations. Indeed, "Visual images have all the attributes of actual objects in the world. That is, that they take up some form of mental space in the same way that physical objects take up physical space in the world" (Eysenck & Keane, 1990, p. 216). Kosslyn (1980, 1994) has offered a theoretical model based on these ideas (see later).

Alternative theories

However, during this period, several inconclusive debates took place. In the context of studies on problem solving (specifically, on deductive reasoning), Huttenlocher (1968) suggested that subjects solve the task on the basis of *spatial images* (a mental space). However, this position was contested by Clark (1969) who insisted on the *abstract format* of mental representations used to process syllogisms.

In addition, the propositionalist school which emerged from late behaviourist criticisms (see Anderson & Bower, 1973) had a dramatic impact on imagery studies. Pylyshyn (1973), as a representative of this school, considers images as epiphenomena to which functional properties are wrongly attributed. A more abstract representation would exist which is not equivalent to imaginal nor to verbal representations that propositionalists call *amodal representation* or *propositional representation.* Propositional representations would be the single valid form of representation underlying all types of memory. One argument of the propositionalist school is that verbal and visual information has to be connected in some way. Consequently, it would be very inefficient to store information permanently in two separate codes (as in Paivio's dual coding theory - see above).

In this so-called "imagery debate" (see for a review: Tye, 1991), Anderson (1978) has proposed the *thesis of indetermination.* According to this position, we are not in a position to clearly differentiate the analogical versus propositional conceptions. Both conceptions could be pertinent to account for several imaginal phenomenon; any empirical data could receive both interpretations.

Kosslyn (Kosslyn, Murphy, Bemesderfer & Feinstein, 1977) proposed a *mixed theory.* In his first version of his model, Kosslyn (Kosslyn, Pinker, Smith & Schwartz, 1979; Kosslyn, 1980) attempts a computational approach to imagery. He accurately describes several components of the imagery system and tries to determine the "deep" structure of these representations. According to his position, images are representations which preserve an *analogical* correspondence with the represented objects. He considers that imaginal processes combine properties from the visual modality (which would be roughly speaking analogical) with "profound components" of representations. Propositions could be used to describe the infrastructure and the encoding modality of images in long term memory whilst the format of images when they are consciously experienced could be analogical (Kosslyn & Pomerantz, 1977). Images would have an analogical visual format when they are generated in short term memory in a structure called the "visual buffer".

Imagery and cognitive neurosciences

Cognitive psychology could hardly answer the objections concerning the nature of mental imagery. Consequently, neurological studies were elaborated to resolve this debate. If cognitive neuroscience can provide convincing evidence that mental imagery makes use of certain regions of the brain that have specialized functions - specifically that imagery shares processing sites with visual perception -, one could narrow down the range of possible explanations (Finke, 1989). During the 1990s, a huge number of experiments in this field have concerned imagery.

Experimental and clinical neuropsychology showed that imagery is a process which requires the activation of visual processing subsystems. In her systematic review of reported cases of brain-damaged patients with imagery impairments, Farah (1984) has shown among other things that patients with left posterior hemisphere lesions are impaired in the generation of mental images. Such a report questions the widespread belief that imagery is a "right hemisphere" skill because of its popular association with "global" processing (Bruyer, 1982; Erlichman & Barret, 1983). Studies of subjects with brain focal lesions or commissurotomized patients (Farah, Gazzaniga, Holtzman & Kosslyn, 1985) as well as studies using lateralized tachistoscopy in normal adults (Farah, 1986) have produced evidence that the left hemisphere is involved in the generation of mental images. Specifically, these studies showed that imagery involved posterior areas of the brain, i.e. involved the visual cortex.

In a set of experiments, Péronnet and Farah (Péronnet & Farah, 1990; Farah, Péronnet, Gonon & Giard, 1988) demonstrated with psychophysiological techniques that the generation of mental images activates representations in the visual system. It is well known that to generate a mental image of an object (e.g. the letter H) improves the perceptual detection of a corresponding visual percept (see Podgorny & Shepard, 1978). Electro-physiological activity of the brain recorded during the processing of one of these visual detection tasks under image generation instructions showed an effect of imagery on the temporal and topographical distribution of Event Related Potentials (ERPs). These effects were also observed in the occipital regions of the brain, i.e. the visual cortex.

Similarly, Positron Emission Tomography (PET) and regional Cerebral Blood Flow (rCBF) studies have clearly confirmed that imagery activates visual cortex (Cohen, Kosslyn, Breiter, Di Girolamo, Thompson, Anderson, Bookheimer, Rosen & Belliveau, 1996; Deutsch, Bourbon, Papanicolaou & Howard, 1988; Goldenberg, Podreka, Steiner, Willmes, Suess, & Deecke, 1989; Goldenberg, Podreka, Steiner, & Willmes, 1987; Roland

& Friberg, 1985). The activation of these posterior cortical areas suggests that visual imagery is a function related to the visual system.

All these findings that demonstrate that imagery involves an activation of the visual cortex cannot easily be explained in terms of propositions or other nonvisual forms of internal representation. Indeed, the occipital cortex processes information that is predominantly visual. Similarly, tacit knowledge, experimenter's expectations, or other forms of criticisms can be ruled out. It is very unlikely that a subject would know, tacitly or otherwise, which areas of the brain are supposed to be activated during imagery tasks. Consequently, to quote Kosslyn (1994, p. 406) : "We now have strong evidence in favor of depictive representations, and a reasonably clear picture of the mechanisms that generate, interpret, and use imagery in information processing. (...) We can stop debating about the fundamentals, and can address additional questions".

Kosslyn's theory of imagery revisited: Evidence from the new Cognitive Neuroscience

Kosslyn (1994) reformulated his theory of mental imagery in the light of the new cognitive neuroscience, and as a consequence, could reply to the criticisms against the concept of imagery. His new theory not only reformulates some ideas about mental imagery but also considers the visual cognition as a whole. He integrates data from neural computations, neurophysiology (including animal models), and neuroanatomy. The "computer metaphor" used in his previous theory (see Kosslyn, 1980) - the *Dry Mind* - is replaced by a new concept: the *Wet Mind* (see Kosslyn & Koenig, 1992). His theory is extensively presented as it constitutes the most developed theory of imagery at present.

The cognitive system is conceived as a functional system composed of neurones responsible for several operations (eventually engaged in a particular task). These neurones, organised in networks, receive similar INPUT and send similar OUTPUT (Kosslyn, 1987).

For particular processing, neurones have to interact rapidly. As a consequence, complementary neurones are usually located in similar areas of the brain; it explains the localisation of the different psychological functions in the cerebral cortex.

In Kosslyn's theory, seven major subsystems are identified: the visual buffer, the attention window, the object properties encoding system, the spatial properties encoding system, the associative memory, the information lookup system, and the attention shifting mechanism.

The Visual Buffer

The visual buffer is located in the retinotopic areas of the visual cortex (Kosslyn, Alpert, Thompson, Maljkovic, Weise *et al.*, 1993). It acts as a two-dimensional space where objects are represented as patterns of neuronal activation. The visual buffer is not a physical space but rather a functional space, i.e. properties such as position or distance are determined by the relations of contiguity between the cells but do not correspond necessarily to physical properties of position or distance on the neuronal structure which is the medium of the representation. The visual buffer has a limited spatial extent, is elliptic, and has a limited resolution which decreases when the pattern is displayed at the periphery of the buffer (Finke & Kosslyn, 1980; Finke & Kurtzman, 1981).

As only a limited amount of information can be processed at a particular time, a mobile *attention window* selects visual input for the next stages of processing. The attentional window is conceived as a system which inhibits information that is not under current processing.

The selected information is then simultaneously sent to two sets of subsystems which work in parallel. These correspond to the two major visual cortical pathways (Ungerleider &Mishkin, 1982): (1) The Ventral System (*What System*) - or occipito-temporal path -

which is engaged in the processing of visual properties of objects (colour, shape, texture), and (2) the Dorsal System (*Where System*) - or occipito-parietal path - which is engaged in the processing of spatial properties of objects (localisation, orientation, size).

The Ventral System

The ventral system encodes objects properties (such as shape, color and texture) and matches them to visual representations in Long Term Memory (LTM) to allow object recognition.

A "Preprocessing subsystem" extracts the nonaccidental and signal properties of the input image. Nonaccidental properties are edges that are roughly parallel, intersecting, collinear, and so on. Signal properties include colored and textured regions that distinguish the object. In addition, a "Motion Relation encoding subsystem" encodes the object characteristics related to an actual movement of the object.

The image and extracted properties are sent to the "pattern activation subsystems". The mental representation which is most activated by these INPUTS is then "selected": The object is visually recognised.

The Dorsal System

The Dorsal System operates in parallel with the Ventral System. It encodes a representation of location, size, and orientation of each of the perceptual units within the attention window.

The information contained in the Visual Buffer is too incomplete to allow the analysis of spatial properties. Indeed, as this information is retinotopically organised, it is considerably modified by ocular saccades and head movements. A "Spatiotopic Mapping subsystem" encodes the location, the size and orientation of the object as a whole. It locates accurately the objects in space relating information about the eyes, head and body position and the visual information in the Buffer. Its OUTPUT can be considered as a set of co-ordinates which determines the spatial position of each object present in the visual field. The spatiotopic mapping subsystem sends input to the "categorical spatial relations encoding subsystem" and to the "coordinate spatial relations encoding subsystem".

The "Coordinate Spatial Relations Encoding" subsystem encodes metric information about location, size and orientation. It sends spatial co-ordinates (i.e. spatial relations) to long term memory. This subsystem is located in the posterior parietal area which not only receives visual afferences but is also implicated in the control of movement. As a consequence, the information related to the localisations could be encoded in a format directly usable for moving behaviours.

The "Categorical Spatial Relations Encoding" subsystem works in parallel with the former subsystem. It encodes spatial relations in the format of categorical representations (e.g. "connected to", "on", "under", "on the right of"...). The categorical representations preserve the invariant parameters, i.e. those which do not affect the purely metrical properties of the objects.

Associative Memory, Information lookup and attention shifting

The information from the Ventral and Dorsal Systems then converge in the associative memory (LTM). The information is synthesised and associated to other information kept in this amodal memory such as the name, the category, the function, etc.

The information lookup subsystems and the attention shifting subsystem are used when the object is not immediately recognised. They allow the search of other information both in the associative memory and in the visual buffer (through a shifting of the attention window).

Mental imagery in Kosslyn's (1994) theory

We have known since the late 1980s that visual imagery shares with visual perception the same structures. It has been demonstrated that visual imagery activates the same cortical areas of the brain (*cf. infra*). As a consequence, subsystems involved in visual information processing should help to explain imagery processes. However, in the case of imagery, the INPUT is no longer sensorial but originates in associative memory. The system is acting backwards, i.e. the reversed scenario of visual perception : associative memory > dorsal and ventral subsystems > visual buffer.

Moreover, Kosslyn (1994) adds to his model a subsystem called "Configuration shifting" to refer to the *image transformations* (mental rotation, mental scanning...). This subsystem transforms the patterns in the visual buffer.

Baddeley's (1986) working memory model

Another theoretical model which could be considered with interest is Baddeley's (1986) working memory model. However, it is concerned with not only visual information but also auditory information. Although less explicit on imagery subsystems, the working memory model shares some common characteristics with Kosslyn's (1994) model. It will be considered only in this context.

According to Baddeley (1986, 1992), working memory is a system with a limited capacity for temporary storage and manipulation during information processing. It includes a central executive for complex decision and control processes and a number of subsidiary slave systems thought to be involved in specific processing. Two such subsystems were envisaged in the original formulation, namely the articulatory loop and the visuo-spatial scratch pad. The former subsystem is thought to act as a subvocal rehearsal buffer and has received the largest share of fruitful research effort. The visuo-spatial scratch pad (VSSP) has received rather less attention, and its characteristics are somewhat less clear as a result.

The VSSP is responsible for storage of visuo-spatial information in short term memory. The most interesting aspect of this model for our concern is that Logie and Marchetti (1991) have suggested that this system is decomposed into two subsystems: A spatial and a visual one. These concepts parallel the dorsal and ventral subsystems in Kosslyn's (1994) model. Indeed, visual distractor tasks can interfere with visual, but not spatial, working memory (Baddeley, Grant, Wight & Thomson, 1975; Baddeley & Lieberman, 1980). Conversely, spatial processing interferes specifically with spatial working memory (Baddeley & Lieberman, 1980; Logie & Marchetti, 1991).

According to Baddeley (1986), VSSP would be involved in the active manipulation of mental images. He wrote (1986, p. 143) that "there is good evidence for the occurrence of a temporary visuo-spatial store... that is capable for retaining and manipulating images". However, a recent neuropsychological case study of a patient with a left parieto-occipital lesion (Morton & Morris, 1995) has demonstrated selective impairment in mental transformation in the absence of an impairment in visuospatial working memory. This case questions the strict association of VSSP and image transformation.

Conclusion

In the present thesis, two imagery subsystems are considered : Mental rotation and mental scanning. Neither Kosslyn (1994) nor Baddeley (1992) considered imagery from a developmental perspective although it might help to clarify some issues in this field. The approach of the present thesis is clearly a developmental one. Abilities in mental rotation and mental scanning will be approached in a life-span perspective.

Mental rotation as well as mental scanning can be decomposed into several subsystems. This thesis sets out to examine the development of these components in order to understand the maturation and deterioration of mental rotation and mental scanning. In Kosslyn's (1994) theory, many subsystems are engaged in imagery processes. For the sake of clarity, only some components will be considered in the present research. These components have been selected because they seem to be particularly important when we have to carry out mental rotation or mental scanning. Basically, two general components will be considered in this thesis : (1) processes engaged in the encoding of a visual pattern (dorsal/spatial and ventral/visual subsystems), and (2) processes engaged in the transformation of a mental image.

In Chapter 2, the developmental literature on mental rotation abilities is reviewed. As only very few papers have considered the development of mental scanning, these studies will be presented in the introduction of Chapter 6. The literature on mental rotation is organised into several sections corresponding to the different subsystems supposed to be engaged in mental rotation.

Chapter 3 presents a study which provides information on children's, young adults' and the elderly's ability to carry out a mental rotation of an object in space. To my knowledge, this study is the first experiment to assess mental rotation ability with identical tasks across ages.

Visuo-spatial short term memory with large capacity seems to be particularly necessary to carry out transformations of mental images. In Chapter 4, the central issue in this thesis is introduced: Is the development of mental rotation abilities dependent on visuo-spatial short term memory ? A correlational analysis between mental rotation abilities and short term memory span for visual patterns is presented.

However, according to Kosslyn (1994) and Baddeley (1992), mental imagery functions are strongly related to processes engaged in visual *and* spatial short term memory. They suggest that the stimuli are encoded in two parallel subsystems : A visual/ventral and spatial/dorsal subsystems. These components encode specific characteristics of the visual pattern. The visual component encodes the "visual" characteristics, i.e. color, texture, shape, etc. The spatial component encodes the "spatial" characteristics, i.e. orientation, location, etc. Both subsystems are engaged in the encoding of a visual pattern. In Chapter 5, visuo-spatial short term memory is no longer considered as a single structure but is decomposed into these two sub-components. The role of the localisation processes is particularly assessed in three consecutive experiments.

Chapter 6 generalises the conclusions of previous chapters to another mental imagery subsystem: Mental scanning. Visuo-spatial short term memory capacity is assessed and its impact on mental scanning abilities is analysed.

Development of mental rotation : Studies of children and elderly people

As described in the general introduction, imagery studies have developed dramatically since the 1970s, and still more clearly in the 1990s. Imagery as a whole has received much attention not only from classical cognitive psychologists but also from cognitive neuroscientists. It has allowed an integrative approach of imagery.

Another valuable source of knowledge about imagery could be provided by developmental psychology. Developmental psychology might help to clarify some controversies in this field of research. As mentioned by Mandler (1983) and Paivio (1986), a developmental approach could allow, for instance, some clarification of a potential distinction between an analogical versus propositional format of imagery. But more interestingly, a developmental approach - especially if considered in a life-span perspective - could bring us some information about how the different subsystems postulated in Kosslyn's (1994) theory evolve with age. Are all subsystems equally developed in childhood ? Are they affected equally by ageing ? Can we identify developmental trends among the different subsystems ?

As mentioned in the previous chapter, several theoretical models of imagery were formulated in the 1980's, and all of them state the *composite* character of the imagery system (e.g. Kosslyn, 1980; Kosslyn, 1994). A common aspect of these models is that they propose the *generation* and the *transformation* of mental images. The generation of images refers to processes which allow subjects to create an image in mind; they "see" what an apple looks like, they remember the face of their closest friend. These images are generated from information kept in an associative memory (see Kosslyn, 1994). In contrast, the transformation refers to a set of subprocesses which modify the content of images or animate them through particular movements. Image transformations are defined by their dynamic characteristics. Subjects can scan across mental images, they can increase or reduce its size, they can mentally rotate an image. This distinction between image generation and image transformation is useful in a developmental approach.

This review considers the development of one imagery subsystem: "Mental rotation". Roger N. Shepard and Lynn A. Cooper referred to this term in the 1970s while carrying out a number of classical experiments (see chapter 1). The process is classically used for instance when we have to identify what the letter *p* looks like when 180° rotated.

Cooper and Shepard (1973b) referred to a specific algorithm to describe mental rotation processes. When particular characters or figures have to be compared or identified, their structure *and* orientation are first globally encoded in short term memory. Second, a transformational process is activated to rotate a mental image of the stimulus to its canonical or learned orientation. When mental rotation has been carried out, the mental image of the object is compared with the referent. When the image is in congruence with its referent, we respond.

In terms of Kosslyn's (1994) theory, the first step probably corresponds to the activation of the ventral and dorsal subsystems which send their OUTPUT to the associative memory (which allows object recognition). The second step corresponds to the activation of the so-called "Configuration shifting" subsystem which transforms the patterns in the visual buffer. The third phase allows a comparison between the information in the visual buffer and the representation of the corresponding information in the associative memory.

Previous reviews (see Dean, 1990; Lautrey & Chartier, 1991) have considered the development of mental imagery *as a whole*. They argued that young children are very poor at transforming mental images. However, such an approach is misleading. These authors seem to consider imagery as an undifferentiated system. They reviewed the literature as if there would be just one general system which deals with imagery. Such a conception supposes that the different imaginal abilities (mental rotation, mental scanning, etc.) develop at the same speed since they belong to the same general system. Or in other words, to acquire knowledge on the development of one subsystem gives us information on the other subsystems (in Dean, 1990, and Lautrey & Chartier, 1991, they used mainly mental rotation studies to infer a general theory on the development of imagery). Such an approach is incorrect. Indeed, computational, neuropsychological, differential as well as developmental studies have clearly demonstrated the specificity of each imagery subsystem (e.g. Kosslyn, Flynn, Amsterdam & Wang, 1990; Farah, 1984; Kosslyn, Brunn, Cave & Wallach, 1984; Kosslyn, Margolis, Barrett, Goldknopf & Daly, 1990).

This chapter reviews *only* the development of mental rotation. Studies are organised around Shepard's basic algorithm. Both children's and the elderly's capacities are considered and their difficulties are categorised in terms of the different steps they necessarily take during a mental rotation task.

Stimulus encoding

When an adult is confronted with a visual stimulus, he spontaneously extracts global characteristics of the structure and the orientation of the perceived objects. During this first processing, which covers in fact several parallel processes, the object is recognised. Stimulus recognition is fundamentally based on a dissociation between two main processing sets: the perception and the elaboration of the percept, and the comparison of this percept with representations kept in memory.

Stimulus recognition is not extensively considered here, however we must be conscious that this step necessarily precedes the activation of the mental rotation processes *per se* (see for a discussion on the recognition of misoriented shapes: Corballis, 1988; or for a broader discussion of the models of visual cognition: Pinker, 1984; Humphreys & Bruce, 1991; Kosslyn, 1994). Pinker (1984) grouped the different theories of object recognition into three categories: (1) Viewpoint-independent models, (2) Multiple-views models, and (3) Single-view-plus-transformation models. In the *Viewpoint-independent models*, a single representation is attributed to the object independently of its size, orientation or position. Marr's (1982) theory falls into this category. His approach is to use simple, low-level properties of an object's shape, such as axes of elongation, to define a reference frame intrinsic to the object. The shape of the object can then be represented in terms of relation of the object's parts to its intrinsic reference frame. This description yields to an "object-centered" representation. Because intrinsic reference frames change orientation with the object, object-centered representations are orientation-invariant. In the *Multiple-views models*, an object is represented in a set of representations, each associated with a familiar orientation. The object is recognised when it matches one of them. Finally, in the *Single-view-plus-transformation models*, the objects are represented in a single viewer-centred orientation and the recognition is reached through transformation processes which convert a representation of the perceived object into a canonical orientation kept in memory, or which match memory representations with the perceived form. The *mental rotation* process has been proposed to be a candidate for this transformation process.

However, many studies in cognitive psychology and neuropsychology suggest that mental rotation is not *always* used when we have to recognise "misoriented objects". Corballis (1988) has suggested that mental rotation would be only used when the identification or recognition tasks are unusual or difficult. It would particularly be the case in a handedness recognition task where discriminations between normal and mirror-reversed versions of the stimuli have to be realised. On the contrary, faster mechanisms would be used when the stimuli are simple or highly familiar. For instance, Corballis, Zbrodoff, Schetzer and Butler (1978) have shown that RTs to name rotated alphabetical characters do not depend on the stimulus orientation, and Eley (1982) has reported a similar flat RT trend in a task requiring the identification of misoriented letter-like symbols.

However, the familiarity of the stimuli does not always seem to prevent the use of transformation processes. Jolicoeur (1985, 1988, 1990) and McMullen and Jolicoeur (1992) have shown that the time to name misoriented line drawings of familiar objects and animals increases systematically as a function of stimulus orientation. The recognition of a disoriented natural object requires the alignment of visual inputs with the stored representations through a normalisation process (Ullman, 1989). Naming time functions seem to reflect a transformation process related to mental rotation. This suggests spatial processing similar to those carried out in mental rotation tasks.

In these chronometrical studies, the *slope* of the RT function has been used as a criterion to state whether a mental rotation process has been used to recognise the misoriented object. Indeed, Metzler and Shepard (1974; quoted from Shepard & Cooper, 1982) wrote that "The subject... can perform mental rotation at no faster than some limiting rate". Cohen and Kubovy (1993) summarised the data mentioning that a rate of 1 ms/rotational degree is the limiting value in interpreting the RT slopes as evidence for a mental rotation process. This limiting value is based on reported data in several published papers (e.g. Corballis, Zbrodoff, Shetzer & Butler, 1978, p.100 : 0.97 ms/degree; Takano, 1989, p.35 : 1000°/s.; Tarr & Pinker, 1989, p.256 : 0.78 ms/degree). As in many object identification studies recognition time has been shown to be below this value (e.g. Jolicoeur & Landau, 1984; Takano, 1989), another process might be used while naming misoriented objects. In fact, Jolicoeur (1990) has suggested a dual-system model of object identification in which a slow normalisation process - i.e. mental rotation - is needed to maintain the spatial relations among stimulus features so that these descriptions might be mapped onto memory representations (Koriat & Norman, 1989; McMullen & Jolicoeur, 1992). However, *with* *practice*, subjects are able to name the objects more quickly, and the steepness is reduced to less than the value mentioned above. It seems that subjects shift from an analogue-transformation process to a feature-based system when knowledge is acquired about the objects to be identified (Murray, Jolicoeur, McMullen & Ingleton, 1993). It is only under particular conditions - namely, when orientation-invariant information is difficult to isolate - that subjects continue to rely upon an alignment system to recognise misoriented objects (Tarr & Pinker, 1989). Apparently, object recognition can be reached through two different but related transformation processes during repetitive presentations of natural objects. Mirror-reversed versus normal discriminations and object naming activate related spatial processes which tend to become independent with practice. According to Murray, Jolicoeur, McMullen and Ingleton (1993), the diminution of the orientation effect with practice could be explained by learned representations which keep orientation-invariant parts or attributes, independently of their spatial relations. In terms of Biederman's (1987) theory, one source of orientation-invariant parts may be geometric primitives called geons, derived from viewpoint-invariant nonaccidental properties of the stimulus.

Neuropsychological data also support object recognition models increasing the standing of hypothesised relations between viewers and objects. However, some single case studies suggest a dissociation between mental rotation and rotated object recognition: L.B., a commissurotomized subject, who was very poor at mentally rotating letters presented to the left hemisphere, was well able to identify the same letters in varying orientations (Corballis & Sergent, 1989). Similarly, Farah and Hammond (1988) have reported clear evidence for a dissociation between mental rotation and object recognition abilities. Their patient R.T., who had a large right frontotemporoparietal lesion, was presented with different mental rotation and object recognition tasks. While he preserved the aptitude to recognise rotated objects, he performed badly in the different mental rotation tasks.

In this section, I consider whether these components affect children's and elderly people's performances in mental rotation tasks. First, are they able to recognise misoriented stimuli ? Second, are they able to encode and to maintain visual information in short term memory ?

Studies of children

Object recognition

So far as children's ability to recognise rotated stimuli is concerned, many empirical studies (e.g. Bower, 1967; Gibson, Owsley & Jonhson, 1978) have demonstrated object constancy across changes in orientation in infants.

Spelke and associates (Kellman & Spelke, 1983; Spelke, 1985) have run a number of experiments to test young infant's object knowledge and identification of object features to which they respond. Using an habituation paradigm, they demonstrated that separated fragments of an object are interpreted as parts of a single object if they undergo a common motion.

Kellman and associates (Kellman, 1984; Kellman & Short, 1987) confirmed that infants abstract information about geometric form from kinetic information. In their studies, three-dimensional objects were presented under several orientations. When four-months-old infants observed a continuously moving stimulus, they recognised it across changes in orientation. However, two different views of a single form seen in a static view (without being presented with the rotational motion between the two end-states of the form) were not considered as identical.

Testing older children (five and eight-year-olds), Lejeune (1992b, 1996) clearly showed that they have no difficulty in naming misoriented familiar objects, an ability which was shown to be independent of mental rotation ability. Subjects who achieved good performance in object recognition tasks often performed very poorly in mental rotation tasks.

This suggests that the ability to recognise misoriented objects emerges well before the ability to mentally rotate an image. However, Lejeune's (1992b, 1996) studies could be criticised. It might be that the two sets of tasks were not matched for difficulty. In particular, the object recognition tasks could have been much easier. However, as Farah and Hammond (1988, p. 42) mentioned: "Could it be the case that mental rotation is simply harder than orientation-invariant object recognition, and that this alone accounts for the observed dissociation between the two types of task ? Mental rotation may well be harder than orientation-invariant object recognition, but if this is true then our case has already been made: Logically, it cannot be true both that mental rotation is harder than orientation-invariant object recognition and that mental rotation is required for (i.e., a component of) orientation-invariant object recognition".

Maintenance of visual information in short term memory

Does this mean that a reason for children's failure in mental rotation tasks should be sought in the development of visuo-spatial memory ?

Childs and Polich (1979) and Waber, Carslon and Mann (1982) considered this problem in examining differences in performance between children and adolescents. Subjects were asked to decide whether rotated stimuli were normal or mirror-reversed. Without advance information about the structure and the orientation of the test character, RTs increased with the departure of the stimulus from its upright orientation as in classical experiments (see Cooper & Shepard, 1973a). The chronometrical index suggested that subjects mentally rotated stimuli into congruence. In another condition, subjects were provided with structural *and* orientational information about the object that was to be presented. Provided with such information, they were expected to generate a mental image of the pattern in a particular orientation before the presentation of the target and, as a consequence, were expected to respond uniformly and rapidly to all orientational conditions. Indeed, in such situations, when young adults are presented with information on the forthcoming target, their answers are the same for all orientational conditions, i.e. RTs are no longer dependent on stimulus orientation but rather a flat function is observed. It is classically interpreted that this flat function suggests that young adults, when provided with information, do not carry out mental rotation. This RT pattern was expected in children and adolescents. However, although younger subjects (9-year-olds) claimed to generate an imaginal representation of the stimulus, RT curves strongly suggested that they did not. RTs still depended on the stimulus orientation just as in a condition without advance information. The authors concluded that children can use mental rotation strategies to solve the problem, but are impaired in preparing and maintaining visuo-spatial information for 1000 msec in short term memory.

Could we reasonably suppose that young children are not able to maintain visual information for 1000 msec in working memory ? Kosslyn, Margolis, Barrett, Goldknopf and Daly (1990) demonstrated that the maintenance of visual images is far superior to 1000 msec in 5-year-olds; it is indeed equal to at least 3 seconds. Moreover, Wilson, Scott and Power (1987) showed that the memory span for visual patterns does not decrease between 2 and 10 seconds in five-year-olds. Such empirical evidence calls the previous interpretation into question.

In Childs and Polich (1979) and Waber, Carlson and Mann (1982), visual short term memory was conceived as a single structure. However, since the development of Baddeley's working memory model, and still more specifically, Logie's (1995) revision of the visuo-spatial sketchpad (VSSP) - the slave system in charge of the maintenance of visuo-spatial information -, we know that visual short term memory is a dual structure where visual and spatial information are encoded separately.

Similarly, recent computational models of high-level vision subsystems (Kosslyn, 1994; Kosslyn & Koenig, 1992) could help us to reinterpret these data. As mentioned in the general introduction, two sets of subsystems (corresponding to the two major visual cortical paths in brain) have been identified in these models: The first path, classically referred to as the ventral system - or occipito-temporal path - analyses the structure of the stimulus, whilst the second path, referred to as the dorsal system - or occipito-parietal path - considers the spatial dimensions of the stimulus. It would be worth identifying developmental trends of these two subsystems in the context of mental rotation tasks. It could be that the information young children forget during the 1000 msec retention interval is more related to spatial characteristics, i.e. the stimulus orientation, rather than structural characteristics of the stimulus.

Complexity of the stimuli

The idea of a poor encoding of the stimuli in mental rotation task was suggested both in Kail, Pellegrino and Carter's (1980) and in Carter, Pazak and Kail's (1983) studies. They demonstrated not only that the speed of mental rotation increases with development but that *unfamiliar* characters (abstract shapes from Thurstone's P.M.A. task *versus* alphanumeric characters, i.e. familiar characters) require more time to be rotated, encoded and compared. However, it is unclear whether the reported results were due to the complexity of the stimuli or due to the experimental procedure. Although in both tasks two stimuli were presented simultaneously (one upright stimulus and one rotated stimulus), it could be that subjects did not use the upright version of the alphanumeric character to carry out the comparison but rather used the mental representation of the letter they had in LTM. As a consequence, when submitted to this version of the task, subjects were, in a way, confronted with a mental rotation task where a *single* shape was presented. We know that such task lead to higher rotational speed (see Shepard & Cooper, 1982). The authors might have then wrongly attributed the effect on RTs to stimulus complexity. It would rather be due to the experimental procedure.

Rosser, Ensing, Glider and Lane (1984) and Rosser, Ensing and Mazzeo (1985) also considered the issue. They tested the role of stimulus features in the prediction of the appearance of rotated objects. They showed that to add at least one orientational marker to poor stimuli such as squares or other simple geometric figures increases success rates in young children (4- and 5-year-olds).

However, these results lead to a dilemma. Adding orientational features improves children performances but also increases both the difficulty of encoding the stimulus and the memory load. The more features there are, the more difficult it is to keep them in short term memory. A way to solve this issue is to suggest that only orientational features are encoded and later rotated. Such a hypothesis is consistent with some data collected in adults (e.g. Carpenter & Just, 1978) suggesting that they rotate part of the figure. Similarly, Bialystok (1989) has shown that children (9- and 11-years-old) encode only *critical features* (those related to the orientation of the stimulus) and not the whole figure. Such results could be partially related to Lejeune's (1994) findings which suggest that before the emergence of mental rotation abilities in children, the strategies used are based on a perceptual analysis of the location of some stimulus details.

Studies of elderly people

Object recognition

In a review of the literature, Bruyer (1994) has suggested that ageing has little effect on visual recognition. When deficits are reported, they rather concern low level vision. For instance, Fozard (1990) reported that ageing affects sensitivity to luminosity and spatial resolution (e.g. visual acuity, contrast sensitivity or depth perception). Specifically, Hoyer (1990) has suggested that ageing might affect localisation processes (see Kosslyn's (1994) model) but not object identification.

Visuo-spatial short term memory

No study has considered the effect of ageing on visuo-spatial memory in connection with the development of mental rotation abilities. However, it seems that visuo-spatial memory span decreases with age. In a recent study, Feyereisen and Van der Linden (1992) showed that ageing does affect spatial memory span (measured with the *block-tapping test*). Similarly, Dror and Kosslyn (1994) showed that image maintenance is affected by age.

Transformational phase: The mental rotation itself

Studies of children

Piagetian perspective

Before the mid seventies, most of the studies on the development of mental imagery in children had been carried out by Piaget and Inhelder (1966). Two major questions were at the origin of their work: (1) Is mental imagery a by-product of perception or is it a reproductive mechanism like imitative behaviours, (2) Is the development of imagery independent of other intellectual abilities or is it related to the development of "operations" ?

To assess their ideas, Piaget and Inhelder (1966) tested broad samples of children in several experimental conditions. It appeared in most of their studies that so-called "preoperational children" (i.e. children younger than about 7 years of age) were particularly poor in image transformational tasks. Consequently, Piaget postulated that only reproductive images are present in young children: Children are able to generate static images of an object or a scene but cannot transform them. It is only after the age of seven or eight that anticipatory images appear: Children become able to implement transformations of images[1].

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1 Interestingly enough, dreaming studies in subjects younger than seven-years-old suggest that children's dreams are simple and static (e.g. Foulkes, 1982).

These imaginal transformations are only possible when children can distinguish the invariant parameters of the object, and have explicitly understood the transformation itself. According to this hypothesis, the development of mental imagery would parallel the development of "concrete operations". The static character of images before age seven would depend on the preoperational tendency of the child to centre himself (herself) on the objects and to ignore them when they are moved from an initial position to a final one. The child does not understand that the parts of the moving object change their position in a co-ordinated way. As a consequence, preoperational children would distort one or more of its properties. Moreover, he thinks that any imaginal anticipation of movement presupposes that the images follow one another in order of succession, which derives from operational seriation; the child would need to understand the logical sequence of movement to imagine correctly the transformation imposed on the object. Clearly, the Piagetian conception was developed in a context which tended to attribute a *symbol* status to mental imagery (see Meyerson, 1923). The image is no longer an extension of perception, it seems to be a product of the interiorization of intellectual acts: It is an interiorized imitation. Such ideas were at that time suggested in psychophysiological work (e.g. Rey, 1947, 1948; Jacobson, 1931). However, the relationship observed between motor activities and imagery would be now interpreted as an effect of *motor imagery*, used for instance in mental rehearsal techniques in sport training (see Murphy & Jowdy, 1992), rather than *visual imagery*.

The information-processing approach

Cognitive psychology has considered the development of mental imagery, mainly through mental rotation processes. Shepard and Metzler's (1971) paradigm has been applied in developmental studies. Most of the time, mental chronometry has been used to assess Piagetian ideas. Specifically, several studies tried to determine whether mental imagery is static or kinetic in young children. However, at present, no empirical evidence has been brought to explain the *origin* of mental imagery; only Kosslyn (1981) and Shepard (1984, 1988) have suggested some hypotheses about the genesis of this cognitive function.

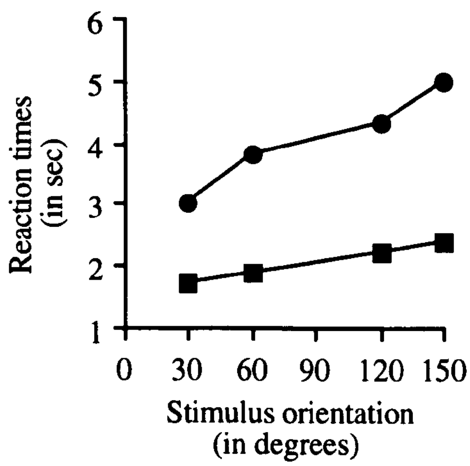
It is common to distinguish between the origin of imaginal representations and transformational imagery processes. Structures and processes might be innate, but the content of mental images would be - of course - acquired through visual experiences (see Dean, 1990).

Shepard (1984, 1988; see also Lejeune, 1992a) has offered the most developed theory of the origin of mental imagery. Humans move and live in a three-dimensional world in part populated with mobile objects. The constraints on mobility imposed by this three-dimensional space would be physical invariants which have prevailed throughout biological evolution; Evidence for mental rotation abilities has been reported in baboons (see for instance: Vauclair, Fagot & Hopkins, 1993) and in very young human subjects (see Darcheville, Bideaud & Devos, 1992). Among these constraints, the kinetic component (governing the displacement or the spatial transformation between objects, and between objects and us) would be essential. Stable spatial transformational rules based on the six degrees of freedom of the environment would have interiorized: Three translational components (up-down, left-right, backward-forward) and three rotational components (angular shifts of attitude, pitch, yaw - in aeronautical parlance).

It is in this particular space that mental rotation would take place. Mental rotation would respect intrinsic characteristics of this space and consequently would respect the "least action principle": The constructed and mentally used path would tend to be the simplest and shortest one in a set of possibilities. Lejeune (1993b) showed that the representation of rotational movement in three-year-olds respects this principle.

Empirical work: Evidences from mental chronometry

Marmor (1975) used Shepard's paradigm to study the development of mental rotation capacities in young children. She presented five and eight-year-olds with pairs of panda shapes differing in orientation by a rotation in the picture plane. Children were instructed to imagine visually the rotation of one of the pandas to superimpose it on the other one, and to determine after the rotation whether the two pandas were the same or different. The pandas could have the same or different legs raised. One of the stimuli was rotated by 30°, 60°, 120° or 150°. RTs served as an evidence for the use of mental rotation. Results indicated that young children could use kinetic imagery: RTs showed a significant linear relationship with stimulus orientation as in young adults (see figure 1). It should be emphasized that, in this experiment, children were *instructed* to imagine the rotation of the patterns. Consequently, this study does not inform us whether such results would be observed without these explicit instructions.



Errors (in %)
5-year-olds : 5,4 - 5,4 - 13,3 - 20,4
8-year-olds : 2,5 - 2,5 - 06,7 - 12,1

Figure 1 : Reaction times and errors (in %) for stimuli 30°, 60°, 120° and 150° rotated in five-year-olds (circles) and in eight-year-olds (squares). Adapted from Marmor (1975).

Although several studies have replicated Marmor's results (Courbois, 1994; Dean, Scherzer & Chabaud, 1986; Hatakeyama, 1989; Kosslyn, Margolis, Barret, Goldknopf & Daly, 1990; Kerr, Corbitt & Jurkovic, 1980; Lejeune & Decker, 1994; Marmor, 1977), others have failed (Dean, Duhe & Green, 1983; Dean & Harvey, 1979). One possible explanation for such failure might be the nature of the stimuli used in these experiments. The later two studies used abstract shapes as stimuli which might be more difficult to encode.

In addition to reporting a linear trend of RTs as a function of stimulus orientation, Marmor (1975) also suggested that mental rotation speed evolves with age. The increasing of rotational speed with age has also been reported by Carter, Pazak and Kail (1983), Kail (1985) and Kail, Pellegrino and Carter (1980). Several explanations have been offered for this. Kail, Pellegrino and Carter (1980) first suggested that a *global* transformational processes could explain the lower rotational speed in young children. In older subjects, just one part of the stimulus would be rotated which would result in higher rotational speed. However, this hypothesis has been later rejected in favour of a general reduction of processing time in children (Kail, 1991, 1993; Kail & Park, 1990). Whatever the task, RTs at a particular age could be expressed by $RT_c = m_c \, RT_a$ (with RT_c for the Response time in children at a particular task, m_c as a variable which is function of age - m_c is constant at a particular age and decreases as an exponential function of age to reach the value of 1 at adulthood -, and RT_a as the value of RT in young adults in a corresponding task). The change in rotational speed is not specific to mental rotation but is also observed in other tasks.

Shepard and Metzler (1971) demonstrated that mental rotation obeys the same rules when stimuli are rotated in depth. However, all the developmental studies mentioned so far used two-dimensional stimuli rotated in the frontal plane. Two studies tested mental rotation in a three-dimensional space in young children: Foulkes and Hollified (1989) and Lejeune and Decker (1994).

In the first experiment, although the performance of five to six-year-olds was as good as that of young adults, the classical linear RTs trend was not reproduced in five-year-olds either for two- or three-dimensional rotations. On the contrary, in the second experiment, RTs with a linear trend were observed in six, seven and ten-year-olds for two-dimensional rotations, but was only observed in the younger children for depth rotations. Moreover, error rates increased in younger children in the three-dimensional condition. Lejeune and Decker (1994) suggested that an imaginal processes was used for frontal rotations in all subjects but, in the older subjects, logical reasoning might be used for three-dimensional rotations. Such interpretation is in congruence with the hypothesis which states that the development of imagery goes from an analogical mode to a more propositional (abstract ?) mode (see for instance: Dean, Duhe & Green, 1983; Lautrey & Chartier, 1991). Divergences between Foulkes and Hollifield's and Lejeune and Decker's studies are difficult to interpret. However, it should be noticed that stimuli and stimulus orientations were different in these two studies. In Foulkes and Hollified's study, stimuli were rotated by only 0°, 30°, 60° and 150° rotated.

In summary: Compromises between the Piagetian and the information-processing approaches ?

New methodologies (especially mental chronometry) have allowed psychologists to examine the development of mental rotation abilities. Does it mean that the Piagetian position has to be definitely abandoned ?

In fact, several studies have systematically tested the relationship between mental rotation abilities and the operational level of development (see Dean, Scherzer & Chabaud, 1986; Foulkes, Sullivan, Hollifield & Bradley, 1989; Hatekeyama, 1989; Kerr, Corbitt & Jurkovic, 1980; Marmor, 1977). Generally, no correlation appeared between mental rotation abilities and the operational level of development.

However, a Piagetian approach is not totally irrelevant in imagery studies. Methodologies used by the information-processing school are just different (Dean, 1990; Mandler, 1983; Lautrey & Chartier, 1991). In Piaget and Inhelder's (1966) studies, drawings, statements or gestures were used to externalise the mental representations; such methods might not be good methods to study the development of children's representations (Kosslyn, Heldmeyer & Locklear, 1977; Kosslyn, 1980; Marmor, 1977). All Piagetian tasks require the child to have an explicit knowledge of the processes used to solve the task. On the contrary, in information-processing studies, an implicit knowledge is sufficient to solve the task. As a consequence, the two approaches might deal with different aspects of the development of imagery.

In fact, Dean, Duhe and Green (1983) and Lautrey and Chartier (1991) have suggested that spatial cognition would evolve from an analogical to a propositional format. The analogical representation would allow children to mentally represent transformations without an explicit representation of the transformation. These analogical representations would allow the prediction of successful anticipation of end-states in a transformational task (see for instance some results reported in Piaget & Inhleder, 1966, Dean *et al.*, 1986; Marmor, 1975). On the contrary, the propositional representations would be based on abstract and logical rules. They would result in an explicit knowledge of the transformation. During the preoperational period (in Piaget's parlance), children's kinetic images would be global units. They would become progressively differentiated and abstracted in sequences with meaningful relations during the next developmental stage. Very young children, who succeed in end-state comparison tasks such as those used classically by Shepard (see Shepard & Cooper, 1982) may be able to imagine rotations by using a qualitatively different mental imagery than do older children.

Although interesting, the hypothesis offered by Lautrey and Chartier (1991) is too general. Consequently, other empirical studies will be necessary to test their hypothesis. What can be remembered from their approach is the distinction between implicit and explicit knowledge of the transformation. It seems that this distinction could account for the differences between Piagetian and information-processing studies.

Studies of elderly people

If many empirical works have tested the development of mental rotation abilities in children, very few studies have considered the ability of the elderly. All the published work has used an information-processing approach, and has applied Shepard's paradigm.

At present, there is no elaborated theory on the effect of ageing on imagery abilities. However, we know that imagery has a complex underlying structure (see Kosslyn's (1994) model presented in the general introduction). The imagery subsystems result from the workings of specific regions of the brain. Hence, changes in the brain with ageing could selectively affect different aspects of individual cognitive functions (Bruyer, 1994; Dror & Kosslyn, 1994).

Empirical works: Evidence from mental chronometry

Johnson and Rybash (1989) reviewed several studies on mental rotation abilities in elderly (Berg, Hertzog & Hunt, 1982; Cerella, Poon & Fozard, 1981; Gaylord & Marsh, 1975; Hertzog, Vernon & Rypma, *in press*; Jacewicz & Hartley, 1979; Puglisi & Morrell, 1986; Sharps & Gollin, 1987).

Some of these studies reported slower rotation rates in elderly (e.g. Cerella, Poon & Fozard, 1981; Dror & Kosslyn, 1994; Gaylord & Marsh, 1975), others did not report differences between elderly people and young adults (e.g. Jacewicz & Hartley, 1979). However, it has to be mentioned that in the later study, for instance, subjects as young as 56-years-old composed the group of elderly people. Age of the subjects might explain the differences in performance. Moreover, stimuli and procedures varied in the different experiments (letters, human figures, etc). These differences could also explain the different results reported so far (see Sharps, 1990).

Considering the different published works as well as the performance of elderly people in other imagery tasks (mental scanning, image maintenance, etc), Dror and Kosslyn (1994) proposed an explanation for the difficulties elderly people encounter in mental rotation tasks. They suggest that a deficit in *spatial location* could explain their poor performance; however, it is not clear how this explanation works (this issue will be reconsidered later).

Many studies have also considered the modification of response times with ageing (see Welford, 1988). All of them demonstrated that ageing increases response times. Reviewing the literature, Feyereisen (1994) suggested that this general slowing down might be due to both sensori-motor deficits and modifications of central operations, i.e. attentional mechanisms, signal identification, selection and control of action.

Conclusion

The present chapter addressed the question of the evolution of mental rotation capacities from childhood to old age. The literature has been reviewed through Cooper and Shepard's (1973b) algorithm: (a) The encoding phase and the maintenance of visual information in short term memory, (b) The mental transformation of the stimulus (mental rotation itself).

At first glance, we may be surprised to notice the similarity between the abilities of children and the elderly. Both groups encounter similar difficulties while carrying out a mental rotation task. However, it is difficult to draw accurate conclusions since age categories, stimuli, and experimental conditions are often different in the reported experiments.

If we accept Shepard's (1988) theory of the origin of imagery subsystems which postulates an innate origin for all transformational imagery subsystems, we should admit that the difficulties encountered both by children and the elderly should be sought in *other* related cognitive subsystems. Indeed, the innate origin of transformational subsystems seems to be plausible since mental rotation abilities have been reported in animals such as pigeons (Hollard & Delius, 1982) or baboons (Vauclair, Fagot & Hopkins, 1993) which suggest that it has prevailed through biological evolution.

As a consequence, a poor functioning of the transformational process *itself* (the so-called "Configuration shifting subsystem" in Kosslyn's (1994) theory) could not explain the difficulties encountered by young children and elderly people. Indeed, several studies showed some mental rotation abilities in children (e.g. Marmor, 1975) and in the elderly (e.g. Dror & Kosslyn , 1994) - at least, when Shepard's paradigm was used - although their performance is usually poorer than those of young adults. In many studies, RTs have been shown to increase linearly as a function of stimulus orientation just as in studies assessing mental rotation abilities in young adults.

Just one noticeable difference was always reported: Processing speed in mental rotation tasks has been shown to be lower in children (see Kail, 1986, 1988) and in the elderly (see Feyereisen, 1994). But in both groups of subjects, it seems that a *central mechanism* could be responsible for the speed of information-processing. A plausible candidate could be the quantity of processing resources (or effort, attention, etc) subjects have at their disposal to execute a cognitive processes. Brandimonte, Hitch and Bishop (1992) raised similar conclusions while studying other imagery abilities (e.g. image combinations) in children.

Where else could the difficulties come from ? As is shown by this review, children as well as the elderly seem to be poor in encoding and maintaining the stimulus which has to be rotated.

During the recognition of the stimulus, young children (3- and 4-year-olds) have some difficulties in discriminating rotation differences between stimuli (see Rosser *et al.*, 1985). Moreover, older children (around 9 years of age) seem to be even poorer in keeping visuo-spatial information in short term memory (Bialystok, 1989; Carter *et al.*, 1983; Childs & Polich, 1979; Waber *et al.*, 1982).

It might not be surprising then that several papers have insisted on the role of stimulus characteristics: Better performance in children has always been observed while using familiar objects as stimuli (e.g. Bialystok, 1989; Dean *et al.*, 1986; Marmor, 1975, 1977). On the contrary, an increase in error rates has often been reported when more abstract stimuli were used (e.g. Dean & Harvey, 1979; Piaget & Inhelder, 1966). Similarly, Kail and Park (1990) have suggested that what seems to be acquired during development is the use of mental rotation in *various* situations. They (Kail & Park, 1990) have reported that, with massive practice, young subjects (11 and 20 years of age) answer more quickly. However, the practised skill did not generalise to other stimuli: Subjects trained with rotating letters did not improve their performances when they were tested with other stimuli. In fact, what has been interiorized with practice is not mental rotation *per se*, but a catalogue of stimuli in different orientations.

In elderly people, several studies have reported that they do not seem to be poor at recognising objects (see, Bruyer, 1994). However, it seems that some basic processes in vision might be affected by ageing (specifically, the localisation processes - see, Hoyer, 1990). Moreover, their ability to maintain visuo-spatial information in short term memory seems to be poor (Dror &Kosslyn, 1994).

Does this mean that children and elderly have difficulties in encoding the stimulus and keeping short term memory traces ? This could explain the difficulties they meet during the transformational phase.

The study of mental imagery development, and consequently of mental rotation, is still in its infancy stage. We need both new methods and procedures to analyse empirical data. We need parametric studies to systematically compare the different results reported so far. Different stimuli do not yield similar performance, and angular orientations have not always been identical in published work (notably, the absence of the stimulus presentation at 180 degrees in some studies). We could also regret that only two studies in children (and no study in the elderly) have considered depth rotations although such rotations may be more common than picture-plane rotations. The age categories are sometimes too broad and are often different across studies. All these parameters should be considered in future research.

Rather than simply multiplying studies, we should systematically focus on each step of the process, taking into account theories of memory, space and perception. We know that mental rotation is not just a "small box" in the cognitive system. Mental rotation is a complicated processes which requires the activation of several parallel subsystems. The development of these subsystems has to be understood if we want to gain insight to the genesis of mental rotation. Some systems could be innate and some could be acquired through development, some could be stable across ages while others could deteriorate with ageing.

Mental Rotation from childhood to old age: Some preliminary empirical data

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As reported in chapter two, both children and elderly people have difficulty in carrying out mental rotation. However, no study, at present, has assessed mental rotation abilities in children and elderly people using the same set of tasks and the same stimulus orientation.

An experiment designed to compare developmental differences in mental rotation is reported as a preliminary study. Four groups of subjects (five-year-olds, eight-year-olds, young adults and elderly people) were given mental rotation tasks. The tasks were borrowed or largely inspired from previously published studies. Performance (correct responses) was measured.

EXPERIMENT 1

METHOD

Subjects

Ninety six subjects participated in the experiment. Twenty four five-year-olds (mean age: 5;02 - range 4;09-5;03), 24 eight-year-olds (mean age: 7;11 - range 7;09-8;03), 24 young adults (mean age: 20;01, range 18;02-24;06) and 24 elderly people (mean age: 71;02, range

66;02-82;04) were recruited in the surroundings of Liège, Belgium. The children were from schools serving middle income communities in and around Liège, while the young adults were students or staff members at the University of Liège who participated as volunteers. Elderly people were members of the University Alumni Association or were recruited through personal contacts. Gender was not controlled, and all subjects were native French speakers.

General procedure

Subjects were tested individually in a session lasting approximately 40 minutes. Subjects performed the tasks in the following order: Cones, Mannequins and L-shape. Although the tasks were different, they were not systematically counter-balanced. It was assumed that they were identical in difficulty.

Mental Rotation Tasks

Material

Two stimuli were presented simultaneously on each trial (except for the L shape task). Three sets of stimuli were used in testing: the cones task (Marmor, 1977), the Mannequin task (Lejeune, 1994), and the L task (Farah & Hammond, 1988). The stimuli are presented in figure 2.

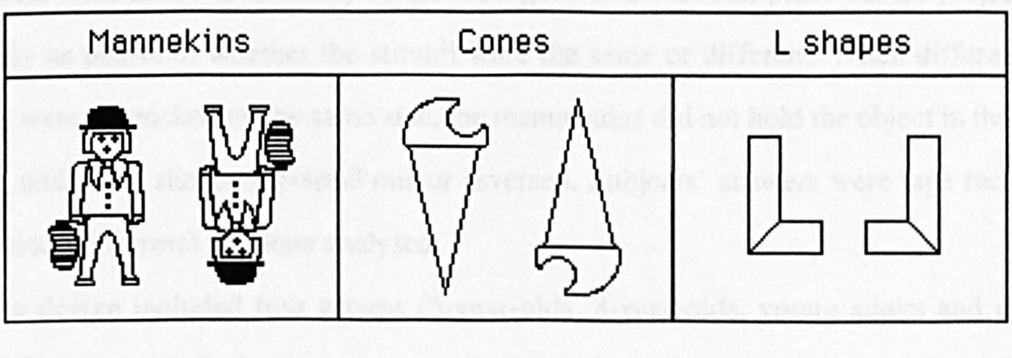


Figure 2: Stimuli used in the mental rotation tasks.

A slide projector was used to project the stimuli on a white screen (50 x 30 cm). Slide projection was controlled by the experimenter and stimuli were projected until the subject answered. The next stimulus was presented when the subject was ready.

Procedure

The experimental procedure consisted of two parts for children: (a) pretraining on same-different judgements, and (b) experimental tests. Adults and elderly people were introduced to the experimental tests without pretraining.

During the pretraining, children were taught through verbal instructions and demonstrations to discriminate between same and different pairs. The stimuli were pasted on pieces of cardboard that the child could manipulate. During the first phase of the pretraining, two stimuli were presented in the upright position. The subjects were required to say "same" when the stimuli were identical, and "different" when the stimuli were different. During the pretraining, the child could manipulate the pieces of cardboard; they could superimpose them to see whether they were identical.

Subjects were then given the experimental tests. In these tests, the stimulus on the subject's left side remained upright while the stimulus on the subject's right side appeared in one of four orientations: upright or 60°, 120°, 180° clockwise rotation from the upright.

Each subject was given three experimental tests (three sets of stimuli: Cones, Mannequins and L shapes). Each experimental test was composed of 32 trials randomly ordered. Subjects were asked to mentally rotate the figure in the frontal plane before judging (as quickly as possible) whether the stimuli were the same or different. When different, the cones were not nicked on the same side, the mannequins did not hold the object in the same hand, and the L shapes appeared mirror reversed. Subjects' answers were tape recorded. Performance (errors) was later analysed.

The design included four groups (5-year-olds, 8-year-olds, young adults and elderly people), three sets of stimuli (cones, mannequins and L shapes) and four orientations (0°, 60°, 120° and 180°). Orientations and stimuli were within-subjects factors while group was a between-subjects factor.

RESULTS

The number of correct trials for each subject in each mental rotation task was calculated. A repeated measures ANOVA was carried out on individual score with Age (5-yr-olds, 8-yr-olds, young adults and elderly people) and stimulus orientation (0°, 60°, 120° and 180°) as independent variables.

Cones task

In this task, Error rates were significantly different in the different age categories, $F(3,88) = 13.19$, $p < 0.0001$, and were affected by stimulus orientation, $F(3,264) = 28.97$, $p < 0.0001$. Moreover, a significant interaction between age and stimulus orientation, $F(9,264) = 7.29$, $p < 0.0001$, was observed. Error rates increased significantly as a function of stimulus orientation in the five-year-olds, $F(3,66) = 26.24$, $p < 0.0001$, in the eight-year-olds, $F(3,66) = 4.72$, $p < 0.005$ and in the elderly people, $F(3,66) = 9.11$, $p < 0.0001$, but not in the young adults, $F(3,66) = 0.82$, $p < 0.49$. Moreover, I tested the difference between the means for each orientation in comparison with the 0° condition in each age category. A Dunnett post-hoc analysis revealed significant differences for some orientations ($p < 0.05$). Significant differences are marked with an asterisk in figure 3. Error rates as a function of stimulus orientation for the four age categories are presented in figure 3.

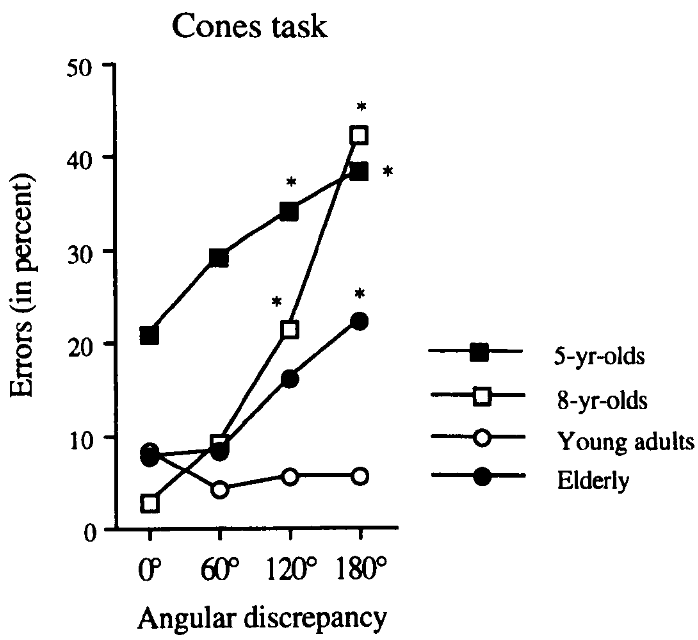


Figure 3: Error rates in the Cones task as a function of stimulus orientation and age.

Mannequin task

In this task, the age of the subjects and the stimulus orientation significantly affected performance, respectively, $F(3,88) = 15.08$, $p < 0.0001$, and $F(3,264) = 51.93$, $p < 0.0001$. However, the interaction between age and stimulus orientation was not significant, $F(9,264) = 0.84$, $p < 0.58$. Moreover, error rates increased in function of stimulus orientation in all age categories with $F(3,66) = 22.11$, $F(3,66) = 4.62$, $F(3,66) = 21.47$ and $F(3,66) = 15$ (all with $p < 0.005$), respectively in 5-, 8-yr-olds, young adults and elderly people. However, a Dunnett post hoc analysis revealed that the difference between the 0° and the other orientations was only significant (with $p < 0.05$) in some of the conditions (significant differences are reported with an asterisk in figure 4). Error rates are reported in figure 4.

L shapes task

Similar results were observed in the L shapes task: Age categories and stimulus orientation influenced significantly performance, respectively, $F(3,88) = 8.74$, $p < 0.0001$, and $F(3,624) = 27.05$, $p < 0.0001$. Moreover, the age variable interacted with stimulus orientation, $F(9,264) = 4.97$, $p < 0.0001$. Complementary ANOVAs revealed that orientation significantly affected the error rates in five-year-olds, $F(3,66) = 18.08$, $p < 0.0001$, in eight-year-olds, $F(3,66) = 8.05$, $p < 0.0001$, and in young adults, $F(3,66) = 2.94$, $p < 0.04$. A similar tendency was observed in elderly people, $F(3,66) = 2.37$, $p < 0.08$. Figure 5 presents the error rates as a function of stimulus orientation for the four age categories, and significant differences between the 0° and the other orientations (as revealed by a Dunnett post hoc analysis, with $p < 0.05$) are marked with an asterisk.

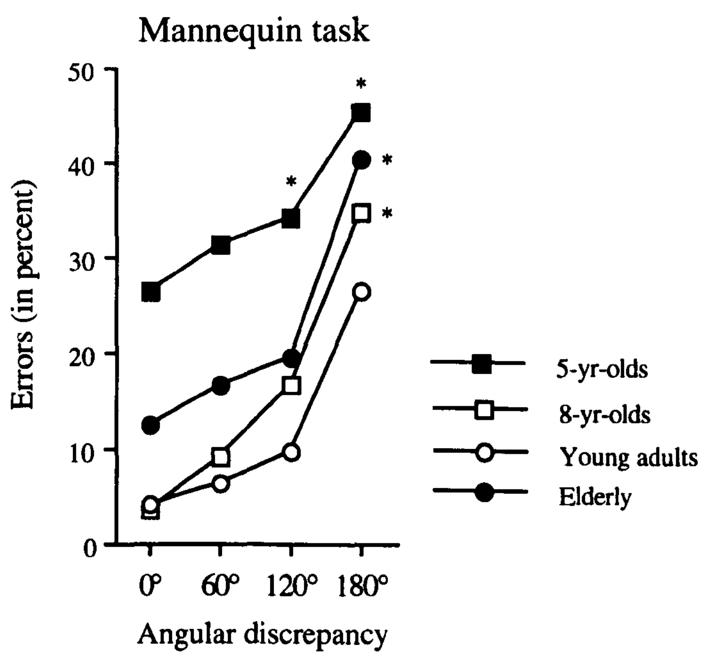


Figure 4: Error rates in the Mannequin task as a function of stimulus orientation and age.

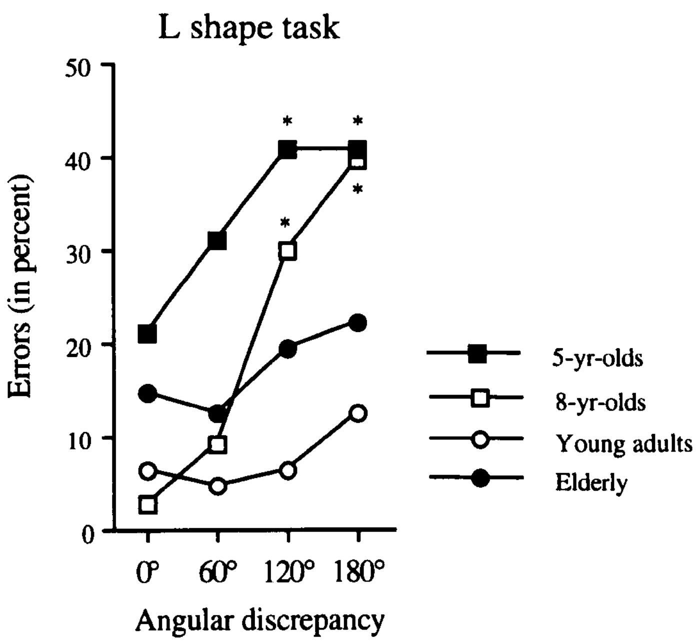


Figure 5: Error rates in the L shape task as a function of stimulus orientation and age.

Correlational analyses among mental rotation tasks

A global score (independent of stimulus orientation) for each mental rotation task was calculated. These global scores were used in correlational analyses among tasks for each age category. It was expected that good correlations would be observed between tasks as several studies have suggested that mental rotation is an automatic process (see, Kail, 1991, or Corballis, 1986). This theoretical assumption has not been observed in all age categories. A summary of the correlational analysis are reported in table 1. Interestingly, positive correlations between tasks are observed in young adults and in eight-year-olds - two age categories for which mental rotation is supposed to be mature. On the contrary, positive correlations are not observed between some tasks in the younger children and in the elderly.

Table 1 : Correlations between mental rotation tasks in the different age categories.

Five-year-olds :

	Cones	Mannequins	L-shape
Cones	1	0.44 ($p < 0.03$)	0.14 ($p < 0.52$)
Mannequins		1	-0.05 ($p < 0.83$)
L-shape			1

Eight-year-olds :

	Cones	Mannequins	L-shape
Cones	1	0.55 ($p < 0.005$)	0.69 ($p < 0.0002$)
Mannequins		1	0.63 ($p < 0.0008$)
L-shape			1

Young adults :

	Cones	Mannequins	L-shape
Cones	1	0.73 ($p < 0.0001$)	0.61 ($p < 0.001$)
Mannequins		1	0.52 ($p < 0.008$)
L-shape			1

Elderly people :

	Cones	Mannequins	L-shape
Cones	1	0.25 ($p < 0.24$)	0.44 ($p < 0.03$)
Mannequins		1	0.15 ($p < 0.49$)
L-shape			1

Performance for each mental rotation task was summed for each subject to get a general score. Due to the lack of positive correlation between tasks in some age categories, no inferential statistics analysis was performed; however, data are reported in scattergrams (figure 6) with general scores (in %) presented in ascending order in each age category (each black point represents an individual score).

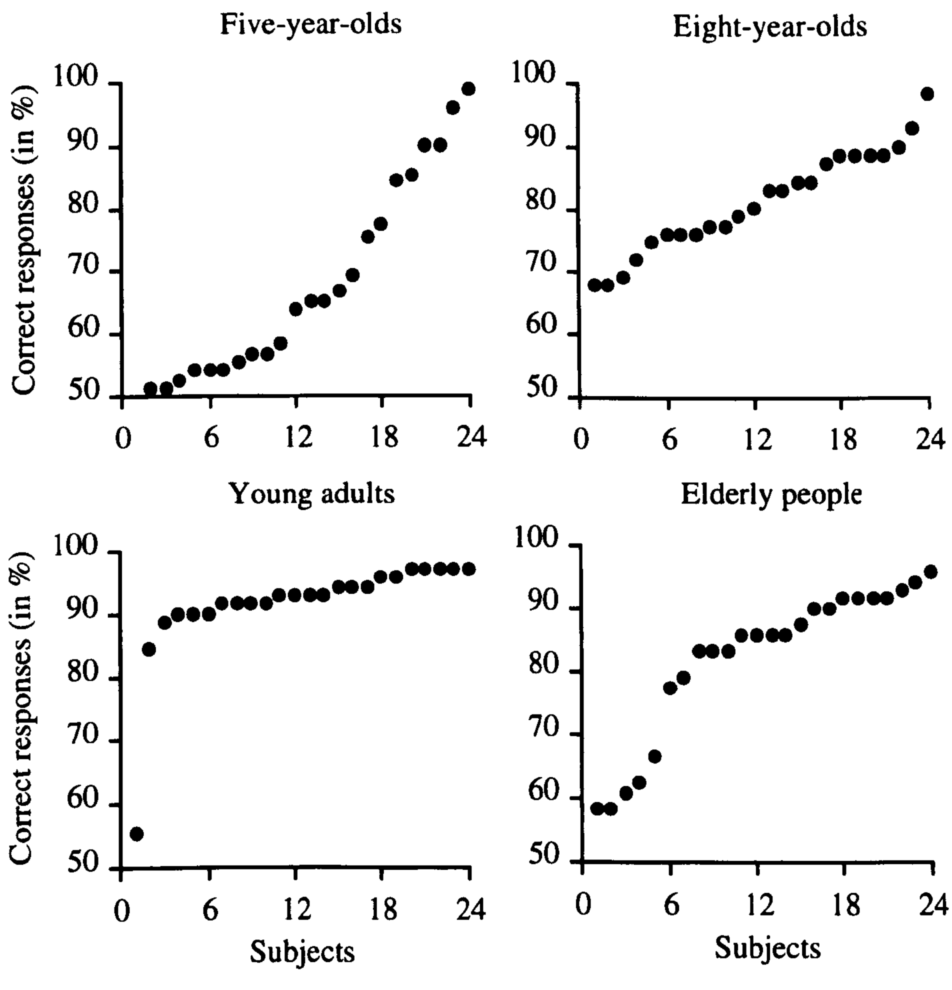


Figure 6 : Individual scores (in ascending order) for mental rotation tasks in five-year-olds, eight-year-olds, young adults and elderly people. General scores are expressed in percentages of correct responses. Twenty four subjects were assessed in each age category (each black point represents a subject).

Discussion

The aim of this study was to address the issue of the development of mental rotation in a life-span perspective. Similar tasks were used across ages (five-year-olds, eight-year-olds, young adults, and the elderly people). Mental rotation was supposed to be required to solve the tasks. Indeed, the cones task has been validated in young adults by Marmor (1977), the Mannequins task and the L shape task by Lejeune (1994, 1995 - the L shape task was inspired from Farah and Hammond (1988) who described this task as a mental rotation task in a neuropsychological study). In all these previous published papers, reaction times were linearly dependent on stimulus orientation in adults - a function which has been often used as an evidence for mental rotation. For these reasons, although we have no direct evidence that subjects carried out mental rotations (RTs were not measured in this study), it was assumed that they did.

An additional reason why subjects were supposed to carry out mental rotation can be found in the error distributions. When each task is considered separately, errors were observed to be significantly affected by stimulus orientation (with an exception) - a fact which is often observed in mental rotation tasks. Globally, errors increased with stimulus orientation with lower values for 0° presentation and higher values for 180° presentation [An exception to this general rule was observed for young adults in the cones task where errors were not affected by stimulus orientation].

As evidenced in figure 6, most of the young adults performed the mental rotation tasks quite well (90 % of correct response). It is however interesting to notice that one subject performed the mental rotation tasks very poorly. He was an undergraduate student in our Department but performed the tasks at chance level. General scores in eight-year-olds range from 70 % to more than 90 % correct responses. In five-year-olds, about half of the subjects got a general score between 50 % and 60 % correct responses, the other half of the subjects got a score range between 60 % and more than 90 % correct responses. Clearly, in this age category, there are huge individual differences and error rates are sometimes particularly high. In the elderly people, most of the subjects obtained rather good scores (ranged between 80 % and more than 90 % correct responses). However, some subjects (n = 5) performed the tasks very poorly with scores between about 60 % and 70 % correct responses.

These general scores confirm that at the age of eight (and in young adults), performance is good. It seems that at this age, mental rotation is mature. On the contrary, at five years of age, many children are still poor in mental rotation tasks. We can be particularly alerted by the poor performances observed in younger children when the comparison stimulus is not rotated. When the referent and the target are both presented at 0°, error rates reach values of about 20 % or more. Although children were trained to same-different judgments, their performance was still poor in such condition. Similarly, in the elderly people, the fact that some subjects get poor general scores suggests that ageing affects mental rotation ability. All these data are consistent with most of the studies published so far.

However, this global approach of subjects' performances has to be considered with caution. Indeed, correlational analysis between tasks within age category did not reveal significant positive correlation between all tasks in five-year-olds and in the elderly people. Moreover, when significant positive correlations were observed in young adults and in eight-year-olds, the values of the correlation were not particularly high. Such results question the role of stimulus characteristics in mental rotation tasks - a fact which is surprising since Kail (1991) has suggested that mental rotation is an automatic process. However, it should be noted that Kail (1991) assessed mental rotation ability in young adults and in young adolescents, i.e. at an age when mental rotation is mature. It might be that the nature of stimulus could influence performance when mental rotation is immature or has deteriorated with ageing.

Several hypotheses have been proposed to account for the difficulties young children and elderly people encounter while carrying out mental rotation. (see chapter two). Whatever the explanations are, it first appears that mental rotation is undoubtedly the product of complex processing. As mentioned earlier, Kosslyn (1994) suggests the existence of several processing subsystems. His model not only considers the constituent features of the object but also their location in space. It should allow a decomposition of the respective role of these two essential dimensions in visual cognition. Such a model is not only interesting in the understanding of object recognition *per se*, but is also probably valuable in establishing the relationships between object recognition and imaginal processes such as mental rotation. Mental rotation is a process strongly connected with the dorsal system described in the general introduction. Referred as the "ROTATE" unit in an earlier version of Kosslyn's (1980) theory, it would assist the usual dorsal routines in particular cases, and consequently, would benefit from the assistance of the ventral system as well.

Very few studies have strictly considered the development of the two major subsystems postulated in Kosslyn's model: (1) the ventral system and (2) the dorsal system. The intimate interconnection between both subsystems makes it difficult to find convincing behavioural effects. However, an explanation for the results of the present experiment could be sought in the development of these subsystems.

Explanations for the difficulties encountered by young children and elderly people while solving a mental rotation task should be sought both in the development of visuo-spatial short term memory and specifically in the development of the dorsal system. In a mental rotation task, subjects are not only required to analyse the spatial configuration of the rotated stimulus but also to *keep* it a longer time in short term memory (STM) - during the mental transformation (i.e. mental rotation) of the stimulus.

The next chapters of this thesis are devoted to these issues. Experiment two (in chapter four) considers the relationship between the development of visuo-spatial short term memory capacity (i.e. memory span), and mental rotation abilities. The major question addressed in this experiment is whether the development of mental rotation abilities is dependent on the development of STM capacity. Experiment three and the following experiment (in chapter five) attempt to decompose visuo-spatial STM into its two components: Visual and Spatial subsystems (see Logie & Marchetti, 1991), or in Kosslyn's (1994) parlance, Dorsal and Ventral subsystems.

Development of mental rotation ability and visuo-spatial short term memory span: Are they related ? [1]

We know now that it has been demonstrated several times that human adults are able to mentally rotate objects through space (see for a review: Shepard & Cooper, 1982). To identify what is the letter *p* when 180° rotated, they mentally rotate the stimulus to its upright position before judging that it is a *d*. The so-called "mental rotation" process allows them to transform a mental image of the stimulus and consequently to simulate a new position of the target stimulus.

Kosslyn, Flynn, Amsterdam and Wang (1990) have proposed that the mental rotation process can be activated when an image is kept in the visual buffer (i.e. the structure on which mental images are displayed in the cognitive system). This image is a short term memory (STM) representation formed either through a visual percept (e.g. Shepard & Metzler, 1971), or generated from long term memory (e.g. Kosslyn, Ball & Reiser, 1978). Once generated, the image has to be maintained until the transformation, i.e. mental rotation, has been accomplished.

Consequently, this model suggests that mental rotation could be based on the ability to keep visual information in STM for a certain period of time. In fact, humans have been

1 This study has been presented in an oral communication at the Second International Conference on Memory, Padova, Italy, 14th-19th July 1996.

shown to be able to keep visuo-spatial information in STM (Baddeley, 1986; Logie, 1986; Phillips, 1983). But, Wilson, Scott and Power (1987) showed that visuo-spatial STM capacity, i.e. the memory span, changes with age. This quantity is smaller in young children and in elderly people than in adolescents and young adults.

Does this mean that STM capacity (as revealed through the memory span) affects mental rotation abilities ? Should we search for developmental differences in mental rotation abilities considering the development of STM span ? The present study proposes a correlational analysis between mental rotation performances and visuo-spatial memory span across ages (from childhood to old age).

In fact, very few studies have considered this issue. A reason for this fact might be that Corballis (1986) as well as Kail (1991) have suggested that mental rotation is an *automatic* process. In these studies, subjects were asked to solve a classical mental rotation task (see for instance: Cooper & Shepard, 1973a) while increasing the memory load. Mental rotation of letters had to be carried out while retaining either digits or patterns in STM. Although the competing tasks slowed subjects while answering, the response times remained linearly dependent on the stimulus orientation. Mental rotation was not affected by an increase of the memory load. However, in both studies, subjects tested in the experiments presented well-developed mental rotation abilities. In Corballis's (1986) study, young adults were tested. In Kail's (1991) study, the youngest subjects were nine-years-old. If we refer to the developmental literature, there is no doubt that after the age of eight the mental rotation process is mature (see for a review: Dean, 1990). So, the question is: Is mental rotation independent of STM capacities before the age of eight ? Moreover, what about such independence when STM capacity has begun to deteriorate with age ? Indeed, several studies have suggested that the capacity of visuo-spatial STM is smaller in young children and elderly people than in young adults (see Van der Linden & Hupet, 1994; Wilson, Scott & Power, 1987).

Relevant to the present issue are both Kosslyn, Margolis, Barret, Goldknopf and Daly's (1990) and Dror and Kosslyn's (1994) studies. The first study considered mental rotation and image maintenance abilities in children, the second one considered the same issue in elderly people. Kosslyn *et al.* (1990) showed (among other things) that young children are relatively poor at rotating objects in images, but some of their data suggested that they are relatively good at maintaining images (at least for 3 seconds). On the contrary, Dror and Kosslyn (1994) showed that old age affects both mental rotation and image maintenance abilities. Consequently, it appears that different imagery subsystems are differentially affected by age.

In this study, five-year-olds, eight-year-olds, young adults and elderly people were presented with selected mental rotation tasks already used in experiment 1. In addition, their STM span for visuo-spatial information was measured. Correlational analyses between tasks were used to assess the interdependence of these cognitive abilities.

EXPERIMENT 2

METHOD

Subjects

Forty eight subjects participated in the experiment. Twelve five-year-olds (mean age: 5;01 - range 4;09-5;03), 12 eight-year-olds (mean age: 8;02 - range 7;09-8;03), 12 young adults (mean age: 21;03, range 19;06-25;10) and 12 elderly people (mean age: 75;03, range 68;05-83;11) were recruited in the area of Liège, Belgium. The children were from kindergartens and schools in and around Liège, while the young adults were undergraduate students at the Department of Psychology, University of Liège. Elderly people were recruited through personal contacts. All subjects participated as volunteers. Gender was not controlled, and all subjects were native French speakers.

General procedure

Subjects were tested individually in a session lasting approximately one hour. Subjects carried out two sets of tasks: Mental rotation tasks and Memory span tasks. All the subjects did the mental rotation tasks first followed by the memory tasks. Although the tasks within the two sets were somewhat different, they have not been systematically counter-balanced (which would have resulted in too large a combination of experimental conditions). It was assumed that mental rotation tasks were identical in difficulty. Each task was composed of 24 trials. Moreover, in the memory tasks, subjects were first tested on the easiest conditions, namely the conditions with the shortest retention interval (see description of tasks for further explanation).

Tasks

Mental Rotation Tasks

Material

Two stimuli were presented simultaneously on each trial (except for the L shape task). Three sets of stimuli were used in testing: the cones task (Marmor, 1977), the Mannequin task (Lejeune, 1994) and the L task (Farah & Hammond, 1988). The stimuli are presented in figure 7.

Stimuli were presented on A4 white sheets of paper. The next stimulus was presented after the subject responded to the previous item.

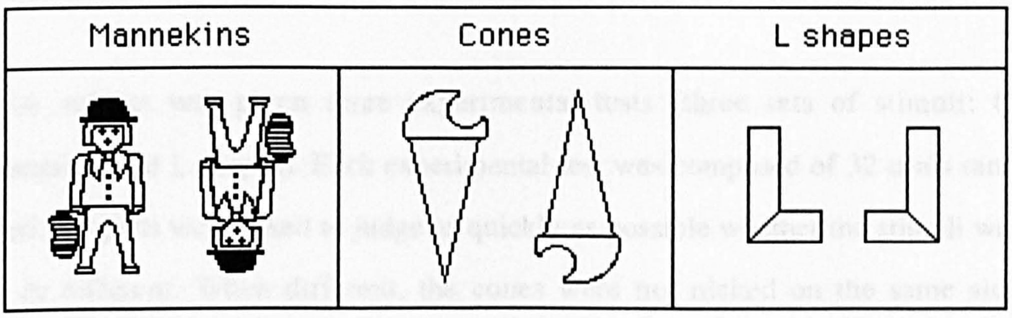


Figure 7: Stimuli used in the mental rotation tasks. For description of the tasks, see the procedure section.

Procedure

The experimental procedure consisted of three parts for children: (a) pretraining on same-different judgments, (b) criterion test, and (c) experimental tests. Adults and the elderly people undertook the experimental tests without pretraining or criterion tests.

During the pretraining, children were taught through verbal instructions and demonstrations to discriminate between same and different pairs (see experiment 1). This ability was then assessed with a criterion test in which equal numbers of same and different pairs were displayed in random order. The subjects were required to say "same" when the stimuli were identical, and "different" when the stimuli were different. On each trial, two stimuli were presented (except in the L shape task) in the upright position. The criterion used was the correct response on all of the first 10 trials or on any 20 of 24 trials.

Children who passed the criterion test, as well as adults and the elderly people, were given the experimental tests which were substantially similar to the criterion test except that the stimulus on the subject's left side remained upright while the stimulus on the subject's right side appeared in one of four orientations: upright or 60°, 120°, 180° clockwise rotation from upright.

Each subject was given three experimental tests (three sets of stimuli: Cones, Mannequins, and L shapes). Each experimental test was composed of 32 trials randomly ordered. Subjects were asked to judge as quickly as possible whether the stimuli were the same or different. When different, the cones were not nicked on the same side, the mannequins did not hold the object in the same hand, and the L shapes appeared mirror reversed.

The design included four groups (5-year-olds, 8-year-olds, young adults, and the elderly people), three sets of stimuli (Cones, Mannequins and L shapes) and four orientations (0°, 60°, 120° and 180°). Orientations and stimuli were within-subjects factors while group was a between-subjects factor.

Visuo-spatial STM tasks

Material

The memory tasks combined both Wilson *et al.*'s (1986) memory task and Kosslyn *et al.*'s (1990) image maintenance task. Stimuli were patterns composed of boxes which could be either filled or unfilled. Each box measured 1 cm X 1 cm. Filling the box produced a solidly illuminated rectangle. The first pattern presented consisted simply of two boxes, one below the other, with one box filled. Pattern complexity increased in steps of two boxes at a time. The last level of complexity was represented in a 6 X 5 matrix with 15 boxes filled. In each pattern exactly half of the boxes were illuminated at random. Four trials for each level of complexity were presented. Consequently, subjects could undertake at most 56 trials (14 levels of complexity X 4 trials).

Procedure

Each trial began with the presentation of an attentional signal. When ready, the subjects pressed the space bar, which caused the presentation of the stimulus. The stimulus was presented for 2000 msec. After this delay, the stimulus was removed and the subjects had to retain an image of the pattern for 500 msec (first condition), 1000 msec (second condition) or 5000 msec (third condition). Following this, two X marks appeared within the matrix. The subjects were asked to decide whether the stimulus shape (filled boxes) would have covered the X marks. If so, they pressed one key; if not, they pressed another one. Subjects were first presented with the first condition (500 msec), followed by the second (1000 msec) and the third (5000 msec) conditions. Figure 8 presents an example of a trial. The tasks were interrupted when subjects committed more than 2 errors in a set of 4 trials (corresponding to a particular level of complexity).

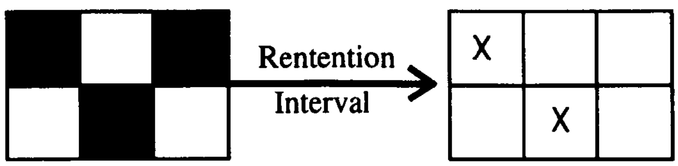


Figure 8 : Example of stimulus used in the Short term memory task. See procedure section for the description of the task.

Mental rotation tasks

The number of correct trials for each subject in each mental rotation task was calculated. A repeated measures ANOVA was carried out for each mental rotation task on individual scores with age (5-yr-olds, 8-yr-olds, young adults and elderly people) and stimulus orientation (0°, 60°, 120° and 180°) as independent variables.

In the Mannequin task, age, $F(3,44) = 7.03$, $p < 0.0006$, and stimulus orientation, $F(3,132) = 24.18$, $p < 0.0001$, significantly affected performance. As the interaction age X stimulus orientation was also significant [$F(9,132) = 6.63$, $p < 0.0001$], repeated measures ANOVAs were calculated for each age category considered separately. The stimulus orientation significantly affected performance in five-year-olds, $F(3,33) = 21.17$, $p < 0.0001$, in eight-year-olds, $F(3,33) = 3.58$, $p < 0.02$, and in the elderly people, $F(3,33) = 5.08$, $p < 0.005$. However, orientation did not affect performance in young adults, $F(3,33) = 1.72$, $p < 0.18$. Results are reported in figure 9.

Similar analyses were carried out for the Cone task. A global ANOVA revealed significant effects of age, $F(3,44) = 8.25$, $p < 0.0002$, orientation, $F(3,132) = 17.16$, $p < 0.0001$, and age X orientation, $F(9,132) = 6.29$, $p < 0.0001$. Complementary analyses showed that error rates were significantly affected in the five-year-olds, $F(3,33) = 15.16$, $p < 0.0001$, and in eight-year-olds, $F(3,33) = 5.48$, $p < 0.004$. In elderly people, the orientational effect almost reached significance, $F(3,33) = 2.37$, $p < 0.08$. This effect was not observed in young adults, $F(3,33) = 1$, $p < 0.41$. Error rates are reported in figure 10.

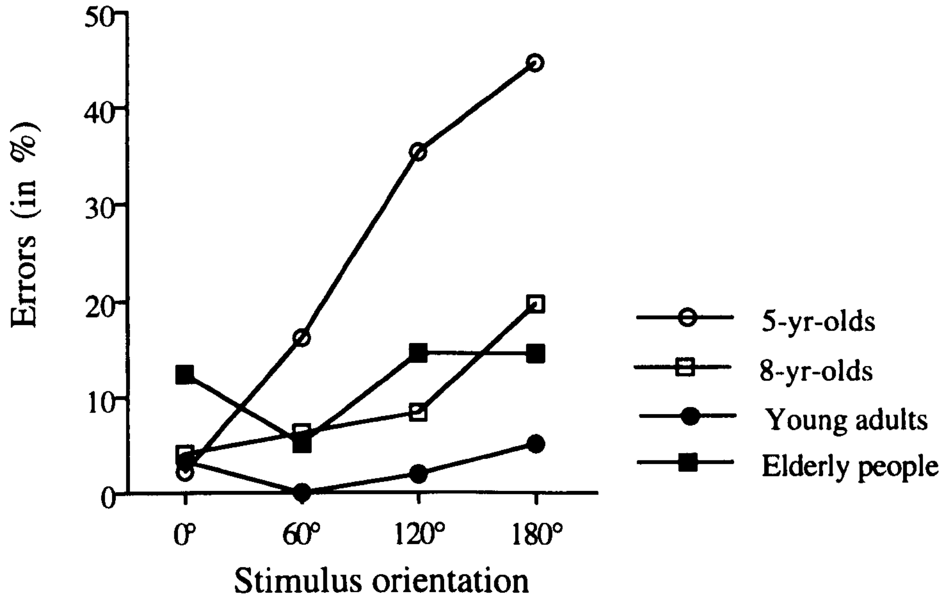


Figure 9: Mannequin task: Error rates as a function of stimulus orientation in five-year-olds, eight-year-olds, young adults and elderly.

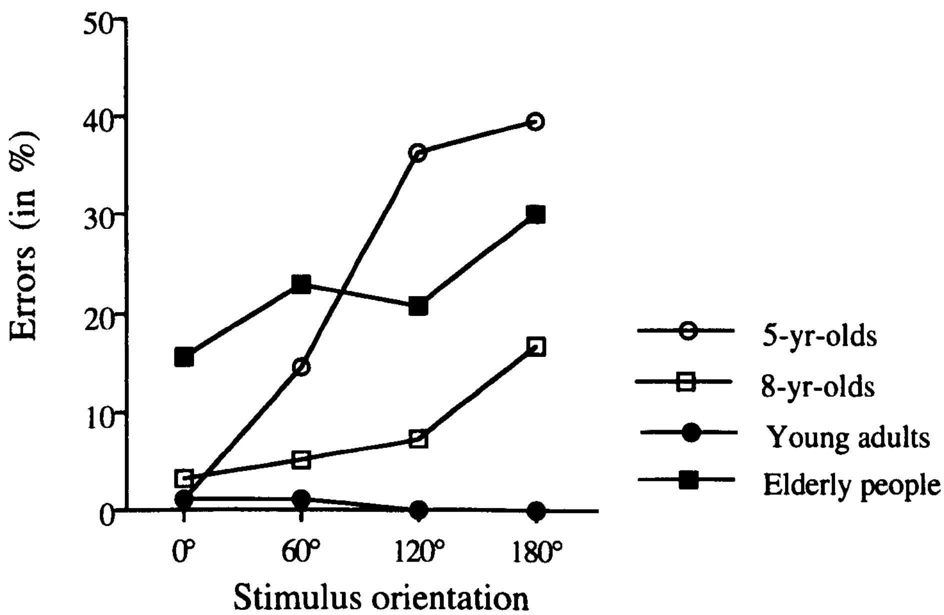


Figure 10 : Cone task: Error rates as a function of stimulus orientation in five-year-olds, eight-year-olds, young adults and elderly.

In the L shape task, age, $F(3,44) = 9.49$, $p < 0.0001$, orientation, $F(3,132) = 15.30$, $p < 0.0001$, and the interaction age X orientation, $F(9,132) = 3.24$, $p < 0.002$, were also shown to affect the scores significantly. Complementary ANOVAs revealed that the orientational effect was significant at the age of 5, $F(3,33) = 6.7$, $p < 0.001$, the age of 8, $F(3,33) = 3.06$, $p < 0.04$, and in elderly people, $F(3,33) = 8.4$, $p < 0.0003$. No effect was observed in young adults, $F(3,33) = 0.71$, $p < 0.55$. Error rates as a function of stimulus orientation in the four age categories are presented in figure 11.

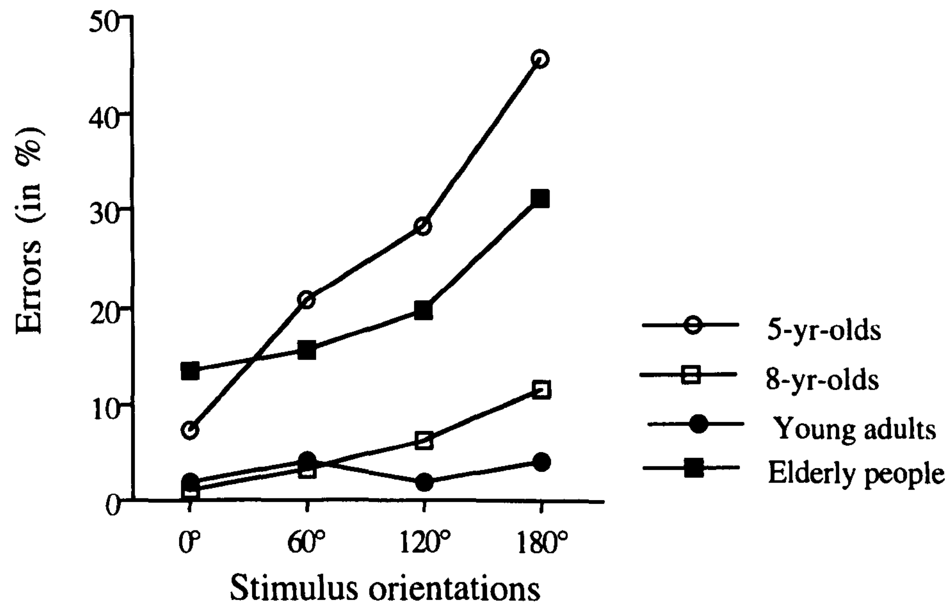


Figure 11 : L shape task: Error rates as a function of stimulus orientation in five-year-olds, eight-year-olds, young adults and elderly.

Visuo-spatial STM tasks

The memory span of each subject was determined as follows. The tasks comprised several levels of complexity, each corresponding to a particular memory span. For instance, the first level comprised two black squares, in other words two units to maintain, i.e. it corresponded to a memory span = 2. The next level corresponded to a memory span = 3, and so on until the last level which corresponded to a memory span of 15. The tasks were interrupted when the subject committed more than 2 errors for one level of complexity (i.e. equal to or worse than chance level: 50 %). The last level of complexity successfully completed by the subject determined his/her memory span. For instance, a subject who passed the task as far as level 6, i.e. gave the correct answers at least 3/4 trials, reached a memory span considered equivalent to 7. The same subject, at level 7, just passed 1/4 trials, i.e. failed more than half the time to give the correct answer. For each subject, this measure was computed in each retention interval condition (i.e. 500 msec, 1000 msec, and 5000 msec).

Repeated measures ANOVAs were calculated on the memory span value with Age (5-yr-olds, 8-yr-olds, young adults and elderly people) and Retention Interval (500, 1000 and 5000 msec) as independent variables. Age was a between variable and Retention a within variable. Table 2 shows the mean values and standard deviations observed in five, eight-year-olds, young adults and elderly people in the three retention interval conditions.

TABLE 2

	5-yr-olds	8-yr-olds	Yg Adults	Elderly
500 milliseconds	m: 2.75 s: 1.48	m: 5.33 s: 2.26	m: 6.83 s: 2.51	m: 4.5 s: 1.51
1000 milliseconds	m: 2.16 s: 0.93	m: 4.75 s: 1.76	m: 7 s: 2.41	m: 3.33 s: 1.07
5000 milliseconds	m: 1.83 s: 1.26	m: 4.5 s: 1.97	m: 6.66 s: 2.14	m: 3 s: 1.76

Table 2: Means (m) and standard deviations (s) for Memory span in five-year-olds, eight-year-olds, young adults and elderly people as a function of the retention interval (500 msec, 1000 msec and 5000 msec).

A global ANOVA revealed a significant effect of age, $F(3,44) = 17.33$, $p < 0.0001$, as well as of the retention interval, $F(2,88) = 8.31$, $p < 0.0005$. The interaction between age and retention interval was not significant, $F(6,88) = 1.11$, $p < 0.36$. Mean memory spans for each retention condition are reported in figure 12. However, a complementary ANOVA computed on memory span in each age category considered separately revealed only an effect of the retention interval in elderly people, $F(2,22) = 6.35$, $p < 0.0066$. No effect was observed in five-year-olds, $F(2,22) = 2.64$, $p < 0.09$, in eight-year-olds, $F(2,22) = 1.94$, $p < 0.17$, and in young adults, $F(2,22) = 0.32$, $p < 0.72$.

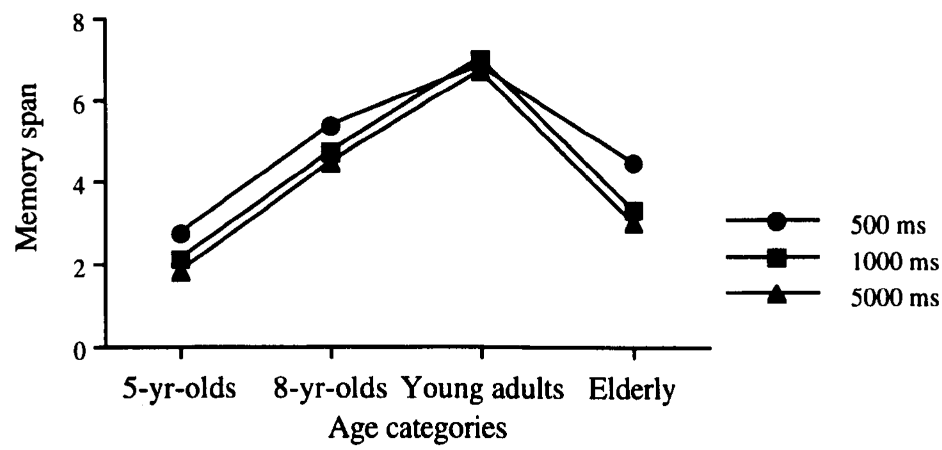


Figure 12: Changes in memory span as a function of age (five-year-olds, eight-year-olds, young adults and elderly people) and retention interval (black circle: 500 msec, black square: 1000 msec, and black triangle: 5000 msec).

Correlational analysis between mental rotation performances and visuo-spatial memory span

Global scores for mental rotation tasks and span tasks were calculated for each subject. Pearson correlations were computed on these global scores. Analysis within age group has been avoided since the sample size in each age category was relatively small (n = 12). Moreover, a cross-age analysis appeared to be more meaningful in the context of this developmental study. Correlation between error rates in mental rotation and memory span was observed to be relatively high (r = - 0.67, $p < 0.0001$). Values are reported in figure 13. When the three young adults scoring particularly high in memory span were removed (see figure 13, red squares), the correlation was -0.71 ($p < 0.0001$).

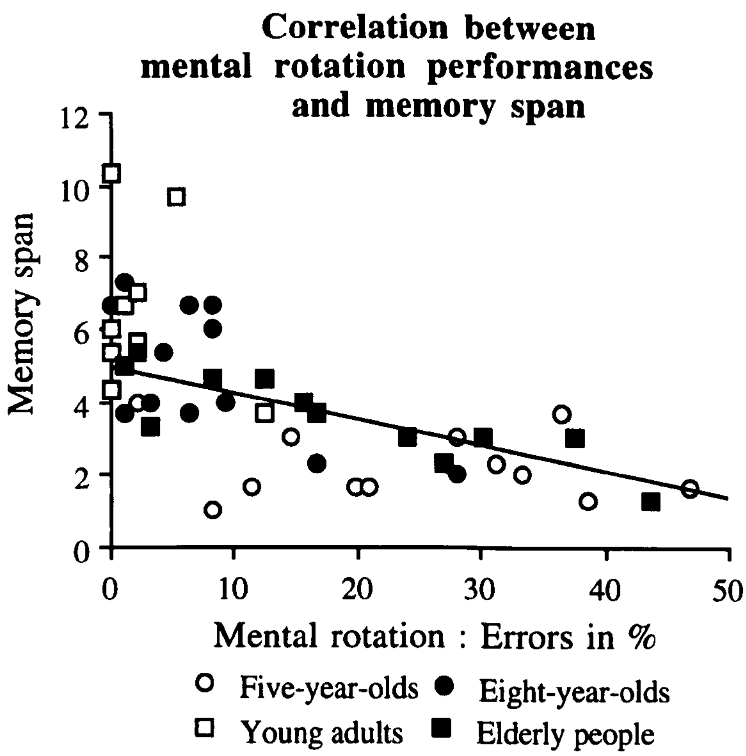


Figure 13 : Correlation between mental rotation performance (global score) and memory span for visual pattern. Each symbol represents an individual score.

The aim of this study was to investigate whether the development of mental rotation abilities is related to the development of visuo-spatial STM span. The answer is positive. A correlation between mental rotation performances and STM span computed across age categories revealed a relatively good association between scores. Consequently, it seems that both processes are related.

The first assessment carried out in this experiment concerned mental rotation abilities[1]. This study confirmed that mental rotation abilities are not yet fully developed in five-year-olds. At this age, young children performed very poorly in all three mental rotation tasks, especially when the stimuli were rotated by 180°. In this condition, answers were close to chance level. Such results confirm previously published studies with preoperational children (to use Piagetian parlance) (see: Dean, 1990). Similarly, in elderly people, poor performance was found in the three mental rotation tasks (with the exception of the mannequin task). It also confirms that mental rotation abilities are affected by ageing (e.g. Dror & Kosslyn, 1994).

This study also confirms that at the age of eight, mental rotation abilities are - roughly speaking - as well developed as in young adults. At eight-years-old, children perform mental rotation tasks as well as young adults. It seems that this part of the cognitive system is well developed. This is in agreement with the Piagetian conception of imagery development according to which transformational imagery (in this case: mental rotation) is developed after the onset of the operational stage (Piaget & Inhelder, 1966).

Young adults were particularly good at the three mental rotation tasks. Orientation did not affect their performances although it did in operational children. This reflects somehow a difference between these two last groups of subjects. It might be that the three mental

1 For the same reasons as those stated in experiment 1, although RTs have not been measured, I consider that subjects carried out mental rotations.

rotation tasks were really easy for young adults and/or the tested subjects were particularly good at these imagery tasks.

The second assessment carried out in this study concerned the visuo-spatial STM span. As reported by Wilson, Scott and Power (1987), STM span changes with age. The memory span in five, eight-year-olds, young adults and elderly as shown in table 2 reproduce Wilson *et al.*'s (1987) results. In younger children, the STM span was smaller than in the other groups. Moreover, the memory span decreases with ageing.

Correlational analysis between the two sets of tasks suggested that mental rotation abilities and STM span are related. Does this mean that we should immediately conclude that both cognitive processes are *totally* dependent ? In fact, I think that the memory tasks used in this experiment - although classical ones - are not sensitive enough to determine *in which way* both cognitive sub-systems are related.

In such tasks, visuo-spatial STM is considered as a single system. However, Logie and Marchetti (1991) have suggested that visuo-spatial STM - referred to in their theory as the VSSP (Visuo-spatial Sketch Pad) from Baddeley's (1986) working memory model - can be decomposed into two subsystems: (1) A visual and (2) a spatial subsystem. Similarly, Kosslyn (1994) has suggested that when studying visual cognition, we might consider the two main cortical pathways engaged in the analysis of a visual pattern. The first path, classically referred as the ventral system - or occipito-temporal path - analyses the structure of the stimulus, whilst the second path, referred as the dorsal system - or occipito-parietal path - considers the spatial dimensions of the stimulus. Consequently, both Logie and Marchetti (1991) and Kosslyn (1994) suggest that visuo-spatial STM should be decomposed into two subsystems.

If mental rotation abilities and visuo-spatial STM are somehow related, the assessment should consider the development of both memory subsystems as defined above.

Specifically, mental rotation abilities could be related to the spatial subsystem rather than the visual subsystem. It might be that some aspects of the spatial subsystem develop later than the visual subsystem, and also deteriorate earlier with age. This issue is considered in the next chapter.

Retention of spatial information in short term memory and mental rotation abilities from childhood to old age[1]

Cooper and Shepard (1973a) found that RTs increased linearly[2] with angular orientation of rotated letter stimuli. However, in a particular experimental condition, Cooper and Shepard (1973a) showed that providing subjects with information about the structure and the orientation of the to-be-compared target modifies the RT function. When young adults have enough information to generate an image of the target or can keep structural and spatial information about the target in visual short term memory (VSTM), they respond with identical speed whatever the stimulus orientation. Reaction times become independent of stimulus orientation.

In addition, Kosslyn *et al.* (1990) have suggested that the mental rotation process can be activated when an image is kept in the visual buffer (i.e. the structure in which mental images are generated). This image is a STM representation formed either through a visual percept, or generated from long term memory. Once constituted, the image has to be maintained until the transformation, i.e. mental rotation, has been carried out. Consequently, the ability to maintain visual information in STM for enough time is essential for a successful mental rotation. Similarly, a visual STM trace exempts subjects from the activation of the mental rotation subsystem (e.g. Cooper & Shepard, 1973).

1 Part of this research has been presented at the Annual Meeting of the Belgian Psychological Society, May 12, 1995, Louvain-la-Neuve, Belgium.

2 In fact, to be precise, the RTs function was curvilinear. However, for the purpose of this experiment, it is not necessary to consider this difference. These effects were probably due both to the experimental procedure and the stimulus characteristics (see for instance: Lejeune, M. & Parmentier, F., *in press*, for a discussion of this issue).

Visuo-spatial short term memory: Visual and Spatial

In the following experiments, visuo-spatial short term memory is considered in the context of two theories: (1) Kosslyn's (1994) theory of high level vision, and (2) Baddeley's (1986) working memory model. These models were presented in the general introduction.

Considering both models, it seems that visuo-spatial short term memory is not to be considered as a single system but rather as - at least - a dual system with a visual (*cf.* ventral system) and a spatial (*cf.* dorsal system) subsystem. These two subsystems would process different but related information from a visual pattern.

What do we know about the development of visuo-spatial short term memory ?

Studies of children: Memory capacity

There have not been many studies on the development of visuo-spatial short term memory. Most of the studies of children - just as studies of young adults - have mostly considered the development of verbal working memory. Dempster (1981) reported that verbal memory span (i.e. verbal memory capacity) goes from about two items (digits) at the age 2 $^1/_2$ to about five items at age 7. In young adults, the verbal memory span value is about seven.

Wilson, Scott and Power (1987) studied visual memory span in five, seven, eleven-year-olds and young adults. A pattern (black and white grid cells) was presented for two seconds (i.e. memorisation time). Then, the stimulus was removed for a period of 2 or 10 seconds (i.e. retention interval). During the 10-second retention interval, subjects were either given an interfering task (a counting task) or were not. Following the retention interval, the pattern was displayed again but with one black cell replaced by a white one. The stimuli were increased in complexity by adding cells to the pattern, i.e. increasing the memory span. Subjects were required to point at the position of the missing black cell. The longer the retention interval was, the more the memory span decreased in all age categories except in the five-year-olds where it remained identical between the 2- and 10-second interval conditions (without an interfering task). The mean memory spans in the 2-second interval conditions were 3.7, 8.2, 14.1 and 14.3 units, and in the 10-second interval condition were about 2.8, 6.9, 11 and 11.2 units, respectively in the 5, 7, 11-year-olds and adults.

Similarly, Kosslyn, Margolis, Barrett, Goldknopf and Daly (1990) have shown that children of five years of age are able to retain visual information for at least three seconds. Five, eight and fourteen-year-olds and young adults were asked to memorise grids that contained a pattern created by filling in grid cells. After the memorisation period, a key had to be depressed and the pattern was removed from the computer screen. Two conditions were studied: (1) A 4 items pattern - i.e. a pattern where one-fifth of the cells of a 4x5 grid were filled in - had to be maintained for 500 msec, and (2) a 7 items pattern - i.e. a pattern where one-fifth of the cells of a 5x7 grid were filled in - had to be maintained for 3000 msec. After the retention interval, two X marks appeared either in or out of a previously filled square. Subjects were required to judge whether both X marks appeared in or out of the memorised pattern. In the heavy load and long retention interval condition, errors were about 35 %, 25 %, 15 % and 7 % respectively in the 5-, 8-, 14-year-olds and young adults. These results suggest that young subjects can *partially* keep visual information in STM for at least 3 seconds. However, since error rates increased between the two conditions in the three younger groups, it appeared also that young children encounter more difficulty in the heavy load and long retention interval condition. The percentages of errors (35%) in the five-year-olds in the second experimental condition are particularly high. However, Kosslyn *et al.* 's (1990) study does not make clear whether the increase in error rates is due to the increase in memory load or due to the increase in the retention interval as the amount of information to be kept in STM was not the same in both conditions.

To answer this question, I (see chapter four) combined Wilson *et al.*'s (1987) and Kosslyn *et al.*'s (1990) tasks: Wilson's stimuli were used but Kosslyn's methodology was applied. The patterns (presented for 2 seconds) became more complex over trials, and subjects had to judge whether two X marks had been displayed in previously filled in squares. The retention intervals used in this study were 500 msec, 2000 msec and 5000 msec. Subjects were tested successively on all three conditions. Interestingly enough, the retention interval did not affect young adults, or children. These results suggest that the reduction of efficiency in young children observed in Kosslyn et al's (1990) study can be explained by the higher memory load in the second condition rather than by the retention interval itself.

Studies of children: Evidence for a dissociation between the spatial and visual subsystems ?

To my knowledge, no study has explicitly tested the dissociation between the spatial and visual subsystems in short term memory. However, a reinterpretation of some published studies might provide us with some information on this issue.

Koenig, Reiss and Kosslyn (1990) showed in a study assessing several subsystems composing the dorsal system, that young children are highly impaired in assessing the metrical distance between objects and parts of objects but are well able to categorise objects. Such data would suggest - although not demonstrate - that the spatial subsystem within the dorsal system develops later than the other subsystem.

Two studies on mental rotation abilities in children could also be considered with interest in this context: Childs and Polich (1979) and Waber, Carlson and Mann (1982). The first authors applied the Cooper and Shepard (1973b) paradigm (*cf. supra*) to young children and adults. Nine, eleven and twenty-year-olds were required to judge as quickly as possible whether rotated letters were normal or mirror-reversed versions. Two experimental conditions were compared: (1) Subjects received no information on the target before the test, and (2) subjects received information about the structure and the orientation of the target 1000 msec before its presentation; concretely, they were shown the forthcoming target in its normal form (i.e. not in the mirror-reversed version) in a particular orientation (similar to that of the forthcoming target). Without advance information, RTs were linearly dependent on stimulus orientation in *all* subjects. However, in the advance information condition, younger children's RTs functions remained linearly dependent on stimulus orientation. Children had to carry out mental rotations despite the information provided. They behaved as if they did not use the information provided. Childs and Polich (1979) interpreted these results as evidence that children have difficulty in keeping visual information in short term memory for 1000 msec.

Waber, Carlson and Mann (1982) reproduced Childs and Polich's (1979) findings in other age categories. Fifth- (about 10-yr-olds) and seventh- (about 12-yr-olds) grade children were presented with rotated letters and were required to judge whether they were normal or mirror-reversed versions. Globally, quantitative analysis showed that RTs increased linearly with stimulus orientation either in an advance or no advance information condition. However, qualitative analysis revealed that the frequency of an adult-like profile (i.e. flat slope in the advance information condition) increased substantially between age 10 and 12 (although only 41 % of the older subjects showed an adult-like profile). Consequently, it appeared that manipulations of visual images and visual short term memory would still be poor in early adolescence. Subjects at the age of the puberty could hardly retain visual information in memory for 1000 msec (which was also the retention interval used in this study).

As already mentioned in chapter two, I think that the interpretation of these two studies should be reformulated in the light of more recently published works. Indeed, can we really conceive that young children cannot retain a visual pattern in STM for one second ? One second is such a short period of time that such a hypothesis does not seem to be seriously valid. Indeed, as mentioned above, Kosslyn *et al.* (1990) showed that children of five years of age are able to retain visual information for at least three seconds. In addition, Wilson *et al.* (1987) showed that the retention interval can reach values of 10 seconds in children of similar age.

A fundamental difference between Kosslyn's and Wilson's studies and Childs and Polich's and Waber *et al.*'s studies on mental rotation is the *orientation* of the to-be-memorised stimulus. In the two first studies, the patterns are presented in an orientation basically defined by horizontal and vertical axes. No stimulus appears in an oblique orientation. In contrast, in the mental rotation studies, the orientation is an important component of the task: The stimuli are presented in several orientations - often in an oblique orientation. Would it mean that the orientation of the memory representation makes the difference ? Would it be more difficult to keep an oblique pattern in STM ? It would mean that the *spatial characteristics* of the stimuli are lost during the 1000 msec interval used in Childs and Polich's (1979) and Waber, Carlson and Mann's (1982) studies.

In conclusion, the reinterpretations of the previous studies - if correct - would suggest that the spatial subsystem (or dorsal system) - at least part of it - is developed later than the visual subsystem (or ventral system). This issue is considered in this chapter.

Studies with elderly people: Memory capacity

Although several studies (see: Craik, 1977) have suggested that no differences can be observed between young adults and elderly people in memory span tasks, others reported opposite results (see: Salthouse, 1991). However, among these studies, very few considered visuo-spatial short term memory.

An effect of ageing has been observed while using the block-tapping test to measure spatial memory span in elderly people (Feyereisen & Van der Linden, 1992). Memory span values were 6.54 and 4.96, respectively in young adults and elderly people. Moreover, in chapter four, similar effects of ageing were reported with another visuo-spatial memory task. Although the memory span in young adults was equal to 6.83 (mean between the different retention interval conditions), it was reduced to 3.61 in 65- to 80-year-olds. Both studies suggest that old age reduces visual memory capacity.

Dror and Kosslyn (1994) observed a similar reduction of visual image maintenance ability in elderly people. They used a task also used with children (see Kosslyn *et al.*, 1990). Subjects age 63 were submitted to an image maintenance task. They had to study a pattern, and after the removal of the pattern, an X mark appeared after 2500 msec. Subjects had to decide whether the memorised shape would have covered the X mark. The patterns became more complex over the trials. Error rates increased with the complexity of the pattern. Although no significant differences appeared between elderly people and young adults, an overall analysis suggested that the elderly may have a deficit in maintaining images. The absence of significant differences makes accurate conclusions difficult.

Studies with elderly people: Evidence for a dissociation between the spatial and visual subsystems ?

There are no more studies on the effects of ageing on the different visuo-spatial memory subsystems other than in children. However, Hoyer (1990) reviewed the literature on the effect of ageing on visual memory and argued that published studies suggest an effect of ageing on the localisation process (i.e. dorsal system) but not on the identification subsystem (i.e. ventral system).

In fact, Grady *et al.* (1992) reported clear evidence for a reduction of efficiency of the dorsal system in the elderly. In a PETscan study, they showed that different cortical areas were activated whilst subjects were submitted to a pattern recognition or pattern localisation task. In the first task, the ventral path, i.e. occipito-temporal areas, was activated, while in the second task, the dorsal path, i.e. occipito-parietal areas, was activated. However, although this dissociation between the two cortical paths was observed in young adults, the distinction was less obvious in elderly people. According to the authors, this would reflect a reduction of efficiency of these structures (or processes) with age.

The present study

The "mental rotation paradigm" might be particularly useful in assessing the development of both visual and spatial short term memory. To study this issue, I have used a methodology inspired by Cooper and Shepard (1973a). Simple characters were used as stimuli to reduce as much as possible the amount of information to be kept in memory. The assessment was realised in a life-span perspective: Young children, young adults and elderly people were tested.

EXPERIMENT 3a

Experiment 3a is largely inspired from Childs and Polich's (1979) and Waber, Carlson and Mann's (1981) studies. The ability of five-year-olds, eight-year-olds, young adults and elderly people was tested in a mental rotation task using three experimental conditions. In the first condition (see figure 14, A), subjects were presented with the letter L. The letter could be presented upright or 60° or a multiple of 60° rotation from the upright. Subjects were required to mention whether the presented stimulus was the normal or mirror-reversed version of an L. It was expected that in *all* age categories, RTs would increase linearly with stimulus orientation just as in classical work.

In the second condition (see figure 14, B), subjects were first provided both with structural and orientational information about the target. As in Childs and Polich (1979) and Waber *et al.* (1981) studies, the target appeared 1000 msec after the removal of this information. In other words, subjects had to keep the information in short term memory for one second. The RT function was expected to be independent of orientation in eight-year-olds and in young adults since no mental rotation is required in this condition. On the contrary, at the age of 5 and in the elderly, the RT function was expected to be dependent on stimulus orientation despite the information provided (and consequently, despite the fact that no mental rotation is really required in this condition). The hypothesis was based on the fact that it appeared in previously published studies (see chapter two) that young children and elderly people are poor at maintaining spatial information in short term memory.

The third condition (see figure 14, C) tested whether a reduction of the time interval between the information provided and the target (as defined in the second condition) would modify the RT functions. Let us suppose that RT functions are dependent on orientation in the second condition in five-year-olds and elderly people and that these results are due to the fact that these subjects cannot retain spatial information for 1000 msec (as postulated in my hypothesis). Reducing the retention interval should allow subjects to benefit from the provided information. They could possibly maintain the information in short term memory for a shorter period of time. If they can retain this information, they should easily solve the mental rotation task, and the RT function should become independent of stimulus orientation since no mental rotation is required. In the third condition, the retention interval was reduced to 500 msec.

Subjects

Four age categories of subjects were tested: 36 five-year-olds (mean age: 5;02 [5 years 2 months] range 4;09 to 5;03), 36 eight-year-olds (mean age: 7;10, range 7;09-8;03), 36 young adults (mean age: 20, range 18-26) and 36 elderly subjects (mean age: 71, range 65-78). All subjects were volunteers. Children were attending public and private schools in the surroundings of Liège. Young adults were undergraduate students at the University of Liège. The elderly subjects were recruited through personal contacts or in leisure clubs in Liège. According to self-reports, all subjects were completely healthy and were not taking any medication that might have affected their cognitive performance.

Subjects from each age category were distributed among three experimental groups, each receiving a different version of the mental rotation task. Consequently, each experimental group was composed of 12 subjects from each age category ($\sum n = 48$).

Material

The stimulus for the task was the same used in Farah and Hammond (1988). The shape used in the task looks like the letter L (size : 3.5 cm x 2 cm). The stimuli were presented at the centre of a computer screen placed at about 50 cm from the subject. The stimuli were presented in six orientations: 0°, 60°, 120°, 180°, 240° or 300°. The letter L could be presented in its normal or mirror-reversed version. Two keys on a keyboard were used to respond.

The task comprised 48 trials, 8 at each level of orientation; half of the stimuli at each level of orientation were normal, half were mirror-reversed.

Procedure

Three experimental conditions were tested. In the first condition, subjects had to depress the space bar when they were ready. Following this, a stimulus was presented. The subjects were instructed to mentally reorient the shape to its upright position, and then to decide as quickly as possible whether it was a normal or mirror-reversed version of the letter L. They depressed one of two keys to answer (left hand on the W key of an AZERTY keyboard for "different" answer, i.e. mirror-reversed, and right hand on the + key of an AZERTY keyboard for "same" answer).

In the second condition, when subjects had depressed the space bar, they were provided with structural and orientational information about the target, i.e. they could see the letter L in its normal format *in the orientation* of the forthcoming target. This information was presented for 2000 msec. Following this, the information was removed from the screen. One thousand msec later, the target was displayed. It could be a normal or mirror-reversed version of an L presented in the same orientation as the provided information. Subjects had to depress a key as quickly as possible (same as in the first condition) to indicate whether the target was identical to the provided information.

Finally, the third condition was similar to the second condition except that the target appeared 500 msec after the removal of the information. Figure 14 illustrates the three experimental conditions.

Before the experimental tests as described above, the two groups of children underwent a training session to teach them through verbal instructions and demonstrations the difference between the normal and mirror-reversed version of the letter L. When the children had understood the instructions, the training session began. During the training session, the stimuli were always presented on the centre of a computer screen in the upright position but could be normal or backward. Children were asked to depress a specific key on the keyboard when the stimuli were the same, and another key when they were different. This training task was made up of 24 trials. The training was continued until the child reached a score of 80% or more of correct responses.

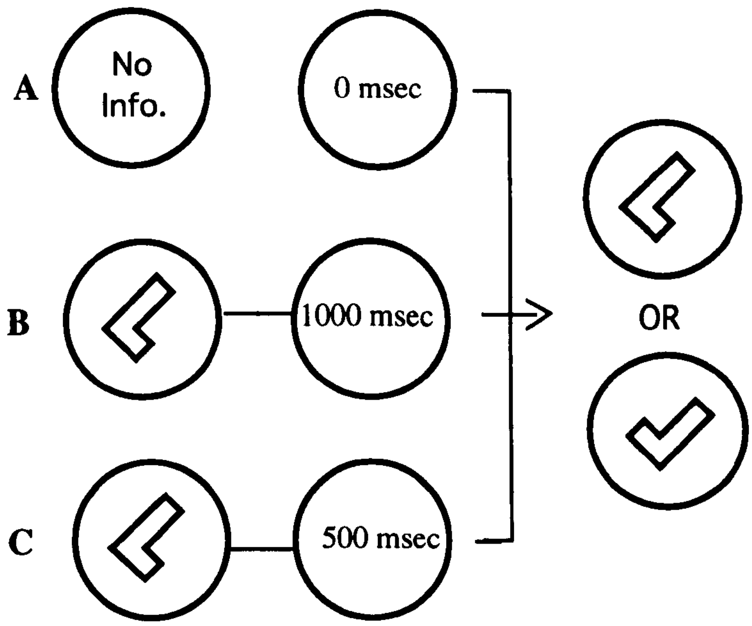


Figure 14 : Schematic representation of the three experimental conditions. A : No information. B: Advanced information followed by a 1000 msec retention interval before the target. C: Advanced information followed by a 500 msec retention interval before the target. The target was *always* presented in the same orientation as the advanced information (B & C) but was the normal or mirror-reversed version of the advanced information.

Reaction times

Reaction time functions are presented in figures 15 A, 15 B, and 15 C. Means and standard deviations are presented extensively in appendix 3.

A global repeated measures ANOVA was carried out on individual RT means for *correct* responses. Age, stimulus orientation and experimental conditions were considered as independent variables. Age, $F(3,132) = 28.2$, $p < 0.0001$, and experimental conditions, $F(2,132) = 3.95$, $p < 0.02$, had a significant effect on RTs. Similarly, stimulus orientation which had an overall significant effect on RT, $F(5,660) = 13.21$, $p < 0.0001$, also interacted with the age variable, $F(15,660) = 1.75$, $p < 0.04$, and the experimental conditions, $F(10,660) = 3.37$, $p < 0.0003$. However, age did not interact significantly with the experimental condition, $F(6,132) = 0.94$, $p < 0.47$. Similarly, the triple interaction between age, experimental conditions and stimulus orientation was not significant, $F(30,660) = 1.00$, $p < 0.47$.

Complementary ANOVAs were computed on each age category considered separately. In the five-year-olds, there was a significant effect of the experimental condition, $F(2,33) = 7.4$, $p < 0.002$, and of stimulus orientation, $F(5,165) = 11.31$, $p < 0.0001$. Both variables interacted significantly, $F(10,165) = 2.28$, $p < 0.02$. In fact, stimulus orientation significantly affected RTs in younger children when they were not provided with information, $F(5,55) = 4.6$, $p < 0.001$, and when the information was provided 1000 msec before the presentation of the target, $F(5,55) = 8.25$, $p < 0.0001$. When the retention interval was 500 msec, stimulus orientation had no effect on RTs, $F(5,55) = 1.78$, $p < 0.13$.

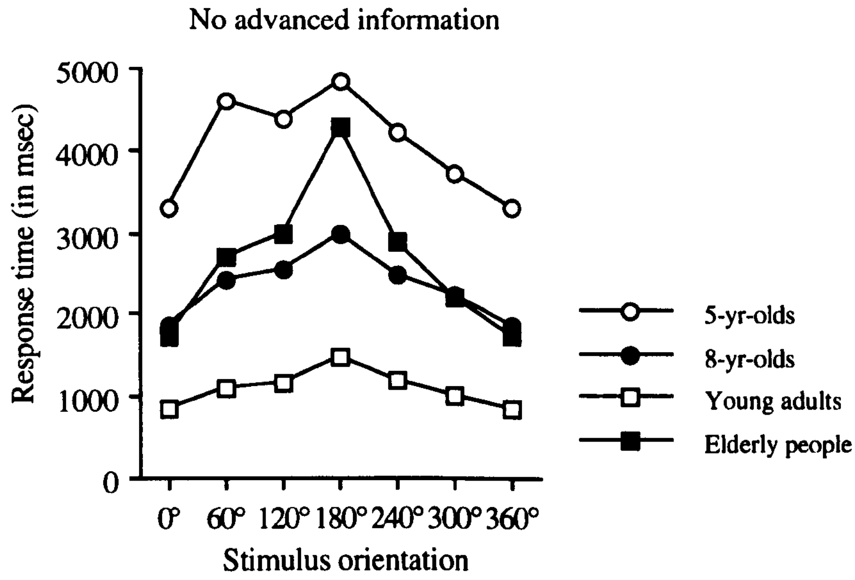


Figure 15 A : Reaction times (in msec) as a function of stimulus orientation for the "No advanced information" condition in the four age categories.

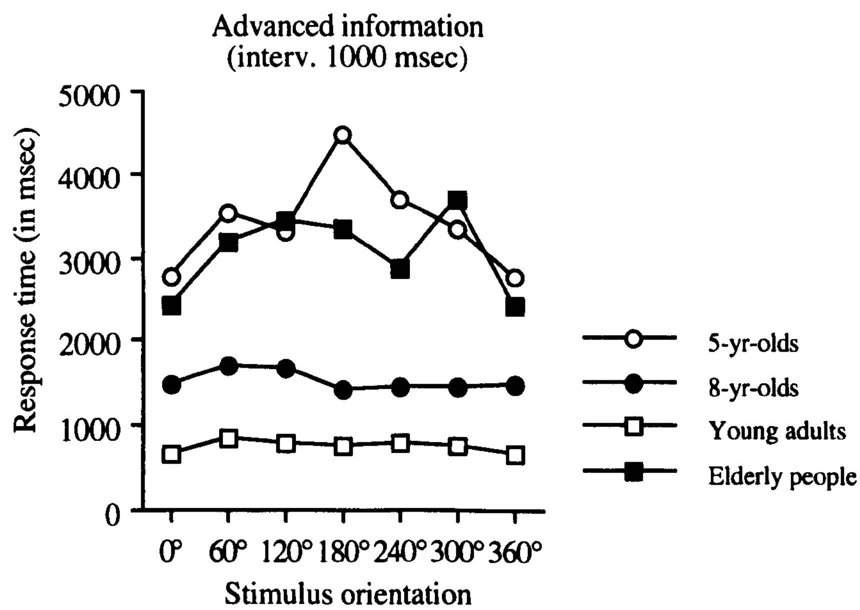


Figure 15 B : Reaction times (in msec) as a function of stimulus orientation for the "Advanced information : 1000 msec" condition in the four age categories.

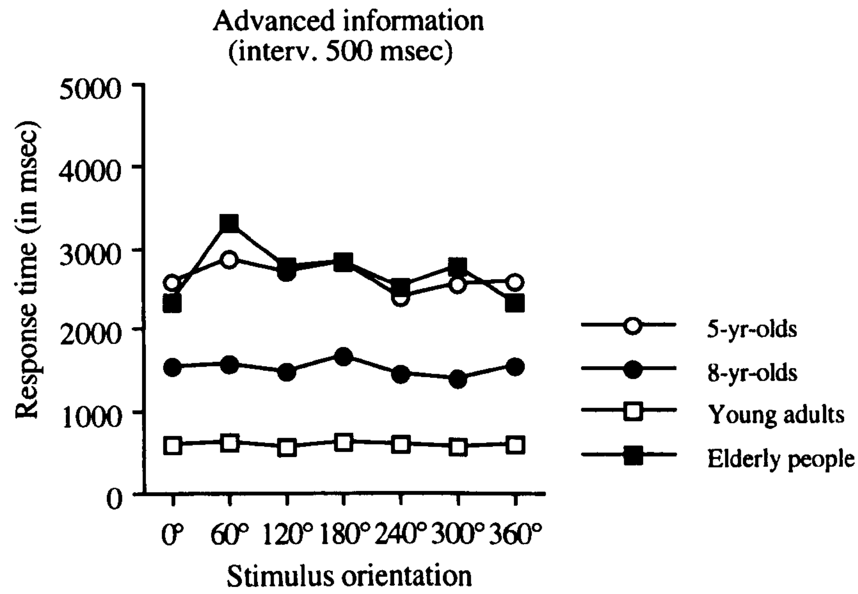


Figure 15 C : Reaction times (in msec) as a function of stimulus orientation for the "Advanced information : 500 msec" condition in the four age categories.

In the eight-year-olds, similar results were observed. Experimental conditions, $F(2,33) = 7.65$, stimulus orientation, $F(5,165) = 6.74$, and the interaction experimental condition X stimulus orientation, $F(10,165) = 5.19$, had a significant effect on RTs, all with $p < 0.0001$. However, the orientational effect was only significant in the first condition (No information), $F(5,55) = 7.33$, $p < 0.0001$, and in the second condition (1000 msec retention interval), $F(5,55) = 3.14$, $p < 0.01$. Stimulus orientation did not affect RTs in the 500 msec retention interval condition, $F(5,55) = 1.82$, $p < 0.12$.

In young adults, complementary ANOVAs revealed a significant effect of experimental conditions, $F(2,33) = 16.35$, stimulus orientation, $F(5,165) = 15.17$, all with $p < 0.0001$, on RTs. The interaction between these two variables was also found to be significant, $F(10,165) = 9.9$, $p < 0.0001$. Other analyses showed that stimulus orientation affected RTs when subjects were not provided with information, $F(5,55) = 23.58$, $p < 0.0001$, and when the information was provided 1000 msec before the target, $F(5,55) = 2.66$, $p < 0.03$. In the last condition, i.e. when the retention interval was 500 msec, RTs function was independent of stimulus orientation, $F(5,55) = 0.8$, $p < 0.56$.

Finally, in the elderly, the overall ANOVA showed only a significant effect of stimulus orientation on RTs, $F(5,165) = 2.98$, $p < 0.01$. However, neither the experimental condition, $F(2,33) = 0.1$, $p < 0.9$, nor the interaction between stimulus orientation and the experimental conditions, $F(10,165) = 1.21$, $p < 0.29$, was significant. In fact, the orientational effect was only significant when subjects were not provided with information, $F(5,55) = 5$, $p < 0.0008$. In the 1000 msec retention interval condition, the stimulus orientation did not affect RTs, $F(5,55) = 0.57$, $p < 0.73$. Similar results were observed in the 500 msec retention interval condition, $F(5,55) = 1.35$, $p < 0.26$.

Error rates

Error rates are reported in figures 16 A, 16 B, and 16 C, and mean values and standard deviations are presented in appendix 3.

A global repeated measures ANOVA was carried out on errors. Age (5-, 8-year-olds, young adults and elderly) and the experimental conditions (without advanced information, with advanced information 1000 msec and 500 msec before the target) were between variables, while stimulus orientation (0°, 60° and multiple of 60°) served as a within variable.

A global effect of age, $F(3,60) = 3.29$, $p < 0.03$, and of stimulus orientation, $F(5,300) = 5.45$, $p < 0.0001$, was observed. However, the experimental conditions did not yield significantly different performance, $F(2,60) = 0.35$, $p < 0.7$. No interaction between variables significantly affected the performance (orientation x age :

F(15,300) = 1.33, $p < 0.18$; age x experimental condition : F(6,60) = 0.45, $p < 0.84$; orientation x experimental condition, F(10,300) = 0.52, $p < 0.87$; and orientation x experimental condition x age : F(30,300) = 0.99, $p < 0.48$).

Complementary ANOVAs on each age category considered separately confirmed a significant effect of stimulus orientation only in five-year-olds, F(5,75) = 2.64, $p < 0.03$, and in the elderly, F(5,75) = 3.4, $p < 0.008$. No effect of stimulus orientation was observed in the eight-year-olds, F(5,75) = 0.61, $p < 0.69$, and in the young adults, F(5,75) = 1.95, $p < 0.09$.

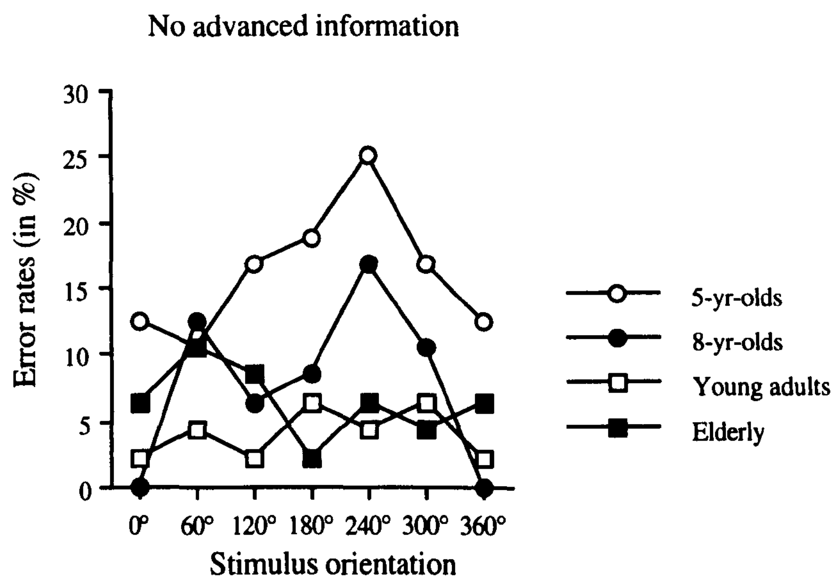


Figure 16 A : Errors (in percent) as a function of stimulus orientation for the "No advanced information" condition in the four age categories.

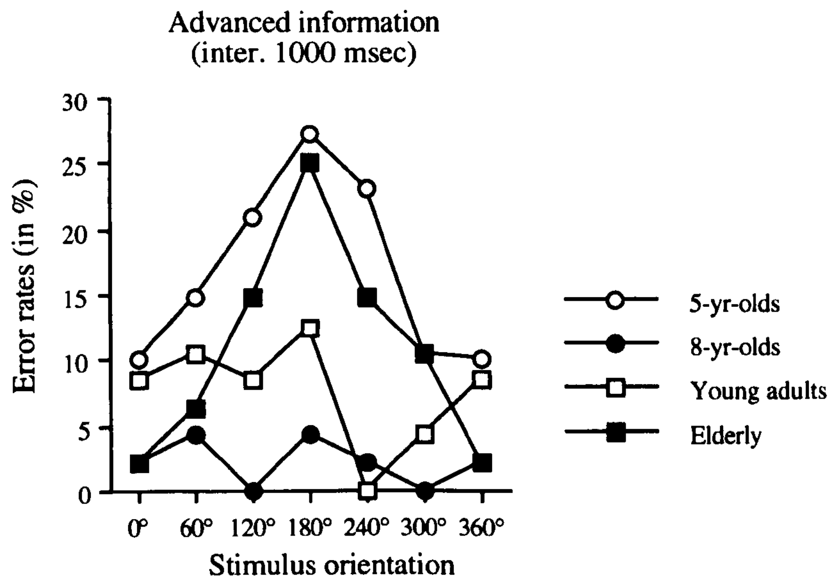


Figure 16 B : Errors (in percent) as a function of stimulus orientation for the "Advanced information : 500 msec" condition in the four age categories.

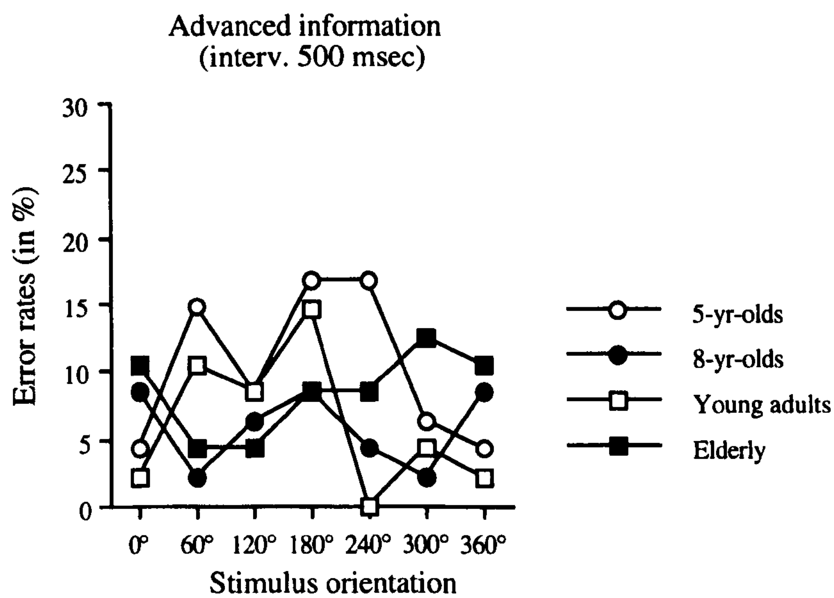


Figure 16 C : Errors (in percent) as a function of stimulus orientation for the "Advanced information : 500 msec" condition in the four age categories.

Error rates did not differ in the experimental conditions in the five-year-olds, $F(2,15) = 0.3$, $p < 0.75$, in the eight-year-olds, $F(2,15) = 1.37$, $p < 0.28$, in the young adults, $F(2,15) = 1.46$, $p < 0.26$, and in the elderly people, $F(2,15) = 0.2$, $p < 0.82$. Moreover, the experimental conditions never interacted significantly with stimulus orientation (in the five-year-olds: $F(10,75) = 0.44$, $p < 0.92$; in the eight-year-olds: $F(10,75) = 1.21$, $p < 0.3$; in the young adults: $F(10,75) = 0.55$, $p < 0.84$; and in the elderly people: $F(10,75) = 1.52$, $p < 0.15$).

Discussion

Three experimental conditions were compared in experiment 3a. When subjects were not provided with structural and orientational information on the forthcoming stimulus, and had to judge whether the stimulus - which could be rotated - was a normal or mirror-reversed version of the letter L, RT functions were significantly dependent on stimulus orientation in *all* age categories. These results suggest that at all ages, subjects were using an analogue transformational process before judging the identity of the stimuli. However, it should be also noticed that error rates were relatively high in children (between 15 and 20 % for most stimulus orientations in five-year-olds). These results suggest that, although young children exhibit the same RT functions when they answer correctly, they are relatively poor in mental rotation tasks.

The most interesting results of experiment 3a are found in the second and third conditions. When provided with information 1000 msec before the presentation of the target, eight-year-olds and young adults answered uniformly rapidly whatever the stimulus orientation. The orientational effect observed in both age categories for this experimental condition should not be interpreted as evidence for mental rotation. Indeed, the RT slope is too slight to reflect the mental rotation processes (see chapter two). It seems that they could keep the provided information in short term memory and consequently did not need to carry out a mental rotation of the target before responding.

In contrast, younger children did not seem to keep such information for one second as revealed by the RT function. Indeed, in the second experimental condition, when provided with structural and orientational information 1000 msec before the target presentation, five-year-olds' RTs depended on stimulus orientation. Moreover, their error rates were quite high (more than 20 % of errors) for the larger stimulus orientations. These results confirmed Childs and Polich's (1979) and Waber *et al.*'s (1981) results.

Similarly, in elderly people, although RTs were not significantly affected by stimulus orientation, the RT pattern suggested that their information-processing was not similar to that of young adults, but not yet identical to that of younger children. There was a hint that their RTs tended to be affected by stimulus orientation (see figure 16 B). As in younger children, their performance was poor for larger stimulus disorientation; error rates reached 15 to 25 % of errors for the 120°, 180° and 240° orientations. Although provided with information on the forthcoming target, elderly people performed poorly in mental rotation tasks.

The results are even more interesting in the third condition. In this condition, RTs were independent of stimulus orientation in *all* age categories. It seems that at any age, subjects can keep structural *and* orientational information in short term memory for 500 msec. However, despite short interval and target priming, error rates were still high (10-15 %) in the younger children and in the elderly people.

In conclusion, experiment 3a seems to confirm that five-year-olds are particularly poor at maintaining spatial information (the stimulus orientation) for 1 second but that they can retain it for 500 msec. Similarly, experiment 3a suggests that such ability is poor in the elderly. In contrast, eight-year-olds as well as young adults have no difficulty in keeping information in short term memory and benefit from this information while solving a mental rotation task.

The difference observed between the younger children and the other subjects might be found in the difficulty that they have mentally rehearsing the information during the retention interval. Indeed, several authors (e.g. Cuvo, 1975; Ornstein, Nauss & Liberty, 1975) have suggested that young children do not spontaneously use rehearsal strategies. This topic will be reconsidered later.

EXPERIMENT 3b

The hypothesis that spatial information is particularly difficult to maintain in short term memory in children age 5 and in the elderly is tested in experiment 3b. To test this hypothesis, the second and third conditions of experiment 3a were replicated, introducing an interfering mask during the retention interval.

Consequently, in experiment 3b, subjects were provided with structural and orientational information 1000 msec or 500 msec before the presentation of the target, but during this retention interval, an interfering mask was presented. Figure 17 presents the experimental conditions. It is assumed that the interfering mask would prevent subjects from mentally rehearsing the information provided. Indeed, in such a condition, they should be mainly busy with an inhibition of the irrelevant information.

It was expected that in this condition, both five-year-olds and elderly people would be particularly impaired in the task. As a consequence, RTs in five-year-olds and in elderly people should be dependent on stimulus orientation in each condition, or in other words, younger children and elderly people would need to carry out mental rotations despite the advanced information.

Subjects

Twenty four five-year-olds (mean age: 4;11, range 4;09-5;03), 24 eight-year-olds (mean age: 8;01, range 7;09-8;03), 24 young adults (mean age: 19, range 18-24) and 24 elderly people (mean age: 69, range 65-80) took part in the experiment. They were recruited through the same channels as in experiment 3a.

Subjects from each age category were distributed among two experimental groups. Each experimental group was consequently composed of 12 subjects from each age category ($\sum$ n = 48).

Material

Basically, the material was identical to experiment 3a except that only four orientations were used: 0°, 60°, 120° and 180°. Moreover, an interfering mask was displayed during the retention interval (see figure 17 for an illustration of the stimuli). The tasks were composed of 32 trials, 8 at each level of orientation; half of the stimuli at each level of orientation were normal, half were mirror-reversed.

Procedure

Two experimental conditions were tested. In the first condition, subjects were required to press on the space bar when they were ready. Following this, structural and orientational information about the target was displayed for 2 seconds. The information was removed from the computer screen and replaced by an interfering mask (see figure 17). The mask was presented for 1000 msec. After this, the target was presented. It was a normal or mirror-reversed version of the letter L. Subjects had to decide as quickly as possible whether the target was identical to the provided information. When the target was identical to the provided information, they depressed a key, and when different, they depressed another key on the keyboard (see experiment 3a).

The second condition was basically the same as the first condition except that the mask was presented for 500 msec.

Children were presented with a training session as in experiment 3a (see above for details on the procedure).

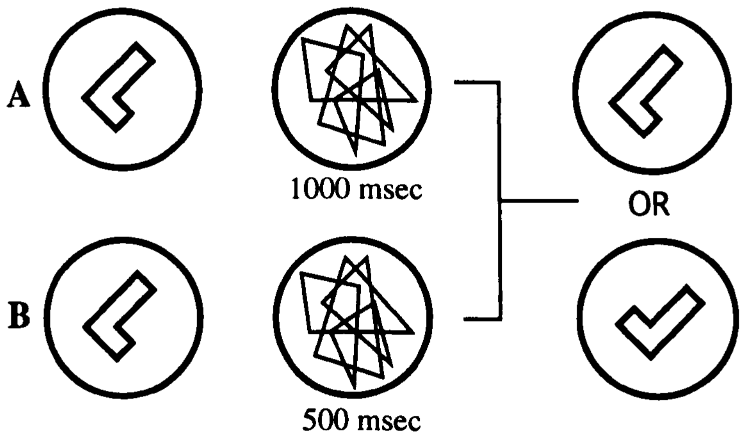


Figure 17 : Schematic representation of the experimental conditions. A: with a 1000 msec interval, and B: with a 500 msec interval during which an interfering mask was displayed.

Reaction times

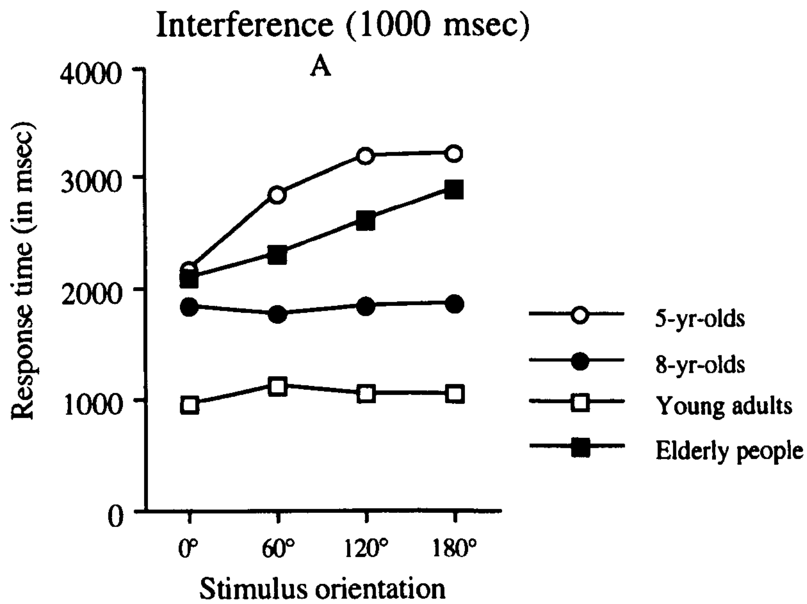
Reaction times functions are presented in figures 18 A and 18 B. Means and standard deviations are reported in appendix 4.

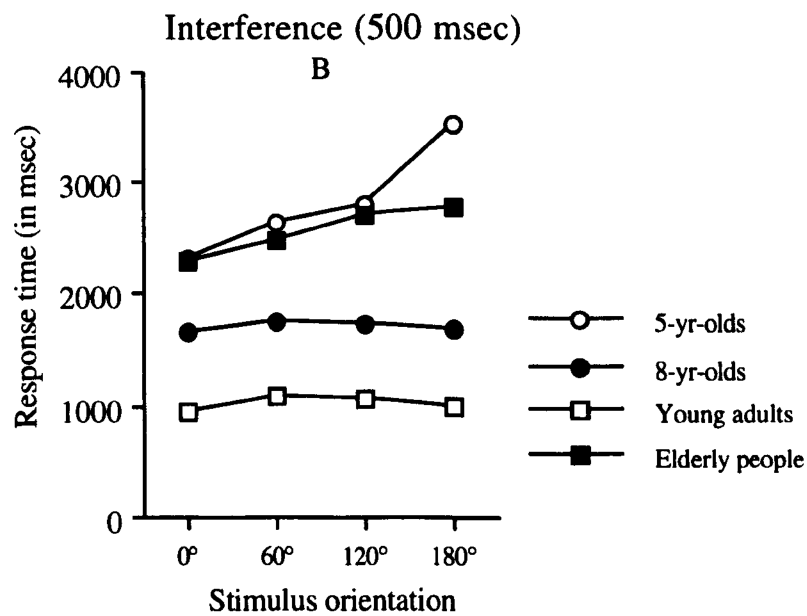
A global repeated measures ANOVA was calculated on reaction times for correct responses. Significant effects of age, $F(3,87) = 94.91$, and of stimulus orientation, $F(3,261) = 19.75$, were observed, all with $p < 0.0001$. Similarly, the interaction stimulus orientation X age was also significant, $F(9,261) = 6.25$, $p < 0.0001$. A Tukey post-hoc analysis revealed that the 5-year-olds and the elderly people obtained similar RT means ($p < 0.05$). However, neither the experimental condition, $F(1,87) = 0.01$, $p < 0.91$, nor the other interactions between variables affected significantly the reaction times [age X experimental condition, $F(3,87) = 0.3$, $p < 0.82$; experimental condition X stimulus orientation, $F(3,261) = 0.12$, $p < 0.95$; and stimulus orientation X age X experimental condition, $F(9,261) = 0.84$, $p < 0.58$].

As an effect of age was observed in the global ANOVA, several analyses were carried out on each age category considered separately. When subjects had to keep structural and orientational information for 500 msec before the presentation of the target, RTs were significantly dependent on stimulus orientation in the five-year-olds, $F(3,33) = 6.17$, $p < 0.002$, and in the elderly people, $F(3,33) = 5.31$, $p < 0.004$. No effect of stimulus orientation was observed in the eight-year-olds, $F(3,33) = 0.47$, $p < 0.71$, and in the young adults, $F(3,33) = 2.76$, $p < 0.07$.

When subjects had to retain the information for 1000 msec, similar results were observed. Stimulus orientation significantly affected RTs in the five-year-olds, F(3,30) =

3.82, $p < 0.02$, and in the elderly, $F(3,33) = 8.77$, $p < 0.0002$, but not in the eight-year-olds, $F(3,33) = 0.47$, $p < 0.7$, and in the young adults, $F(3,33) = 2.35$, $p < 0.09$.





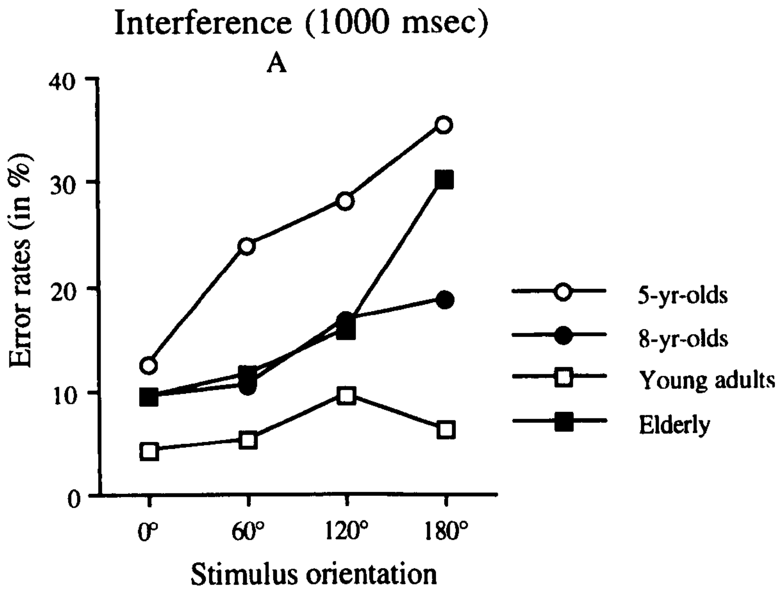
Figures 18 A and B : Reaction times (in msec) as a function of stimulus orientation in five-year-olds, eightyear-olds, young adults and elderly people (see symbols on the right side of each graph). Results for the "1000 msec retention interval" are presented in part A of the figure, whilst results for the "500 msec retention interval" are presented in part B.

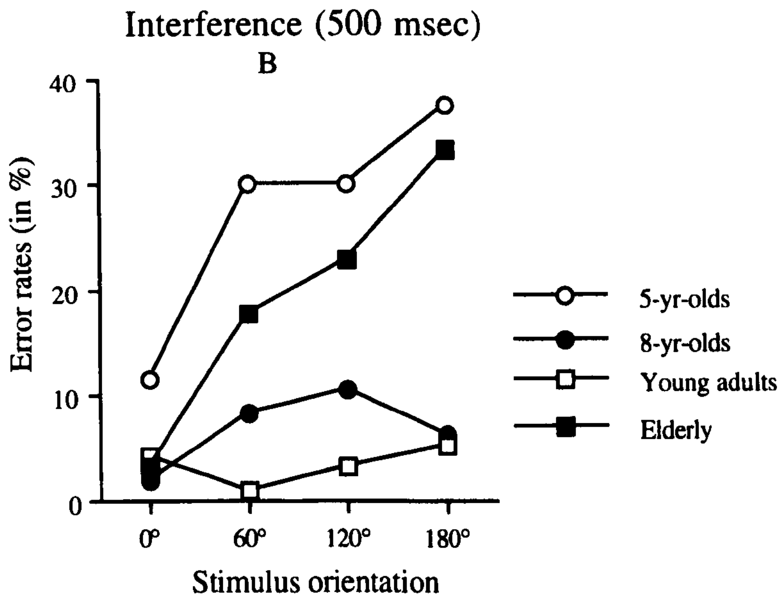
Error rates

Error rates are presented in figures 19 A and 19 B. Error means and standard deviations are reported in appendix 4.

Similar analyses were computed on error rates. A global repeated measures ANOVA revealed significant effects of age, $F(3,88) = 32.92$, and stimulus orientation, $F(3,264) = 21.95$, with $p < 0.0001$. The interaction stimulus orientation X age was also significant, $F(9,264) = 3.99$, $p < 0.0001$. No effect of the experimental condition, $F(1,88) = 0.58$, $p < 0.45$, and of the other interactions between variables could be observed [age X experimental condition, $F(3,88) = 2.02$, $p < 0.12$; stimulus orientation X experimental condition, $F(3,264) = 0.7$, $p < 0.55$; and stimulus orientation X age X experimental condition, $F(9,264) = 0.65$, $p < 0.75$].

ANOVAs calculated on each age category considered separately revealed a significant effect of stimulus orientation both in the five-year-olds, $F(3,33) = 4.29$, $p < 0.01$, $F(3,33) = 2.74$, $p < 0.06$, in the 500 and 1000 msec conditions respectively, and in the elderly people, $F(3,33) = 18.14$, $p < 0.0001$, $F(3,33) = 9.26$, $p < 0.0001$, in the 500 and 1000 msec conditions respectively. No effect of stimulus orientation could be observed in the eight-year-olds in the 500 msec condition, $F(3,33) = 1.73$, $p < 0.18$, and in the 1000 msec condition, $F(3,33) = 1.59$, $p < 0.21$. Similar results were observed in the young adults in the 500 msec condition, $F(3,33) = 1.14$, $p < 0.35$, and in the 1000 msec condition, $F(3,33) = 0.81$, $p < 0.49$.





Figures 19 A and B : Errors (in percent) as a function of stimulus orientation in five-year-olds, eight-year-olds, young adults and elderly people (see symbols on the right side of each graph). Results for the "1000 msec retention interval" are presented in part A of the figure, whilst results for the "500 msec retention interval" are presented in part B.

The purpose of experiment 3b was to confront subjects with an interfering mask while solving a mental rotation task. It was hypothesised that an interfering mask should affect the ability of younger children and elderly people to maintain visuo-spatial information in short term memory.

Experiment 3a showed that five-year-olds are poor at maintaining the orientation of the stimulus for 1000 msec in short term memory. It appeared in experiment 3a that the maximum time for which they can keep spatial information in short term memory seems to be around 500 msec. Indeed, when provided with orientational information about the target 500 msec before the test, younger children respond at the same speed whatever the target orientation.

Experiment 3b indicates that this 500 msec limit holds good only when subjects have no other information processing to carry out during the retention interval. When an interfering mask is displayed during the retention interval, it was found again in the five-year-olds that the linear RTs trend classically observed when subjects are carrying out mental rotations occured. In the 500 msec and 1000 msec retention interval conditions, younger children seem to be particularly impaired at maintaining spatial information in short term memory. This is also confirmed by the high error rates observed for the 60° to 180° orientations.

Similar results were observed in elderly people. In experiment 3a, RTs were not influenced by stimulus orientation in the 1000 msec retention interval condition, which suggested that elderly people are well able to keep spatial information for such a period. Such conclusions however have to be revised in the light of experiment 3b.

Indeed, in this experiment, the introduction of an interfering mask during the retention interval modified RT functions in elderly people. It appeared that they are highly impaired in maintaining spatial information in short term memory even for 500 msec. Their RT functions are similar to those observed in younger children (except maybe in the 500 msec retention interval where the effect of stimulus orientation is less pronounced - but still significant). In addition, error rates were also relatively high in both retention interval conditions, especially for the larger stimulus disorientations.

It should also be noticed that, although no statistical analysis has been carried out between experiments 3a and 3b, the graphs suggest that error rates increased in five-year-olds and in the elderly people when an interfering mask is displayed during the retention interval. Such results confirm the negative effect of the interfering mask on young children and elderly performances; it suggests how poor these subjects are in solving such tasks.

How should the effect of the interfering mask be interpreted ? When provided with information on the forthcoming target, subjects have to keep it in short term memory. It is well known that to maintain auditory information, subjects use the so-called articulatory loop (at least if we refer to Baddeley's working memory model). In some way, they sub-vocally rehearse the information. In case of visual information, it seems that a similar processes could exist. Kosslyn (1980) refers to a REGENERATE unit. This subsystem would allow subjects to mentally rehearse the information to keep it in the visual buffer, i.e. in short term memory.

When an interfering mask is used, subjects are confronted with irrelevant information during the period when logically they should be mentally rehearsing the pattern to be kept in short term memory. However, it might be that the mask interferes with the rehearsal processes. Subjects have to allocate resources for the inhibition of the irrelevant information. Consequently, it might be that their ability to rehearse the relevant information is affected by the necessity to inhibit the interfering mask.

On the one hand, several studies (e.g. Cuvo, 1975; Flavell, Beach & Chinsky, 1966; Ornstein, Nauss & Liberty, 1975; Ornstein, Nauss & Stone, 1977) have suggested that before the age of 7, children do not use rehearsal strategies. Prior to age 7, children typically are not strategic. It is only after this age that they begin to use the simplest rehearsal strategies, i.e. overt or covert repetition of items to be remembered. This could account for the difficulties young children have in keeping spatial information in memory. In fact, the debate on young children's ability to mentally rehearse information is going on. It seems that young children can rehearse and spontaneously choose to do so for auditory speech material. However, when the memory material is presented in pictorial form, similar cognitive processing is not observed (Hitch & Halliday, 1983; See Gathercole, Adams & Hitch (1994) for a recent study on this issue).

On the other hand, some studies (e.g. Zacks & Hasher, 1988) have reported the difficulty elderly people have in inhibiting irrelevant information during task solving. Hasher and Zacks (1988) have suggested that ageing would be associated with a reduction of efficiency of the inhibitory attentional processes which control the access and the temporary maintenance of irrelevant information in a task in progress. The existence of distracting information in working memory would be the expression of this deficit. It would interfere with the resolution of a particular problem. Such a deficit could explain why elderly people's RT functions became dependent on stimulus orientation in experiment 3b.

In conclusion, although similar patterns of responses have been observed in five-year-olds and elderly people, the responsibility could be shared between two different subsystems: A poor rehearsal ability in young children *versus* a lack of inhibition of irrelevant information in elderly (or both).

The interfering mask did not affected either eight-year-olds or young adults. In both groups, RTs remained independent of stimulus orientation. These facts confirm that at these ages, both short term memory and mental rotation processes are mature.

EXPERIMENT 3c

Through experiments 3a and 3b, the reasoning has been that five-year-olds and elderly people are very poor at maintaining *spatial* information in short term memory. However, no experiment tested whether *structural* information, i.e. the information processed by the ventral or visual subsystem, is preserved in memory. Experiment 3c is designed to assess this ability.

The experimental procedure is similar to that used in the two previous experiments. Subjects were provided with structural and orientational information on the forthcoming target. Two experimental conditions were used, i.e. a 500 msec and a 1000 msec retention interval. The provided information was the letter L or C in different orientations. The target could be the same letter or the other one, always presented in the same orientation as the provided information. Subjects could be presented with the letter L in its normal version, the letter L in its mirror-reversed version, or the letter C as targets (the exact shapes are represented in figure 20). In the case where the provided information was an L in its normal version followed by an L in its normal version as the target, the two stimuli were structurally equivalent. The situation was identical when both the provided information and the target were the letter C. In the cases where the letter L in its mirror-reversed version was displayed after an L in its normal version, or when an L in its normal version followed the letter C, there was a structural difference between the information provided and the target.

If younger children and elderly people can keep *structural information* in short term memory, when the provided information and the target are structurally different, they should immediately notice that there is a mismatch between both stimuli. This is particularly the case when the provided information is the letter C and the target is the letter L. Consequently, it was hypothesised that in such situation, subjects' RTs should not be affected by stimulus orientation. They should immediately perceive the difference between the information kept in memory and the target.

However, when the letter L, normal or mirror-reversed, serves as target after an L in its normal format, the results reported in experiment 3a (second and third experimental conditions) should be replicated in experiment 3c. Indeed, in such situation, if they do not keep the provided information in short term memory, they have to identify through a mental rotation process which version of the letter L is presented as a target. Indeed, as Simion, Bagnara, Roncato and Umiltà (1982) mentioned : "same" and "different" judgments are mediated by the same holistic processor in the case of visual images. As a consequence, orientation functions for "different" or negative responses are like those for "same" or positive responses in showing a linear or quasi-linear relationship between latency and angular difference of the comparison stimuli.

In showing a difference in RT functions in the two situations, i.e. same structure *versus* different structure, a differential development of the visual and spatial components of STM for visual patterns would be partly evidenced in five-year-olds and elderly people.

METHOD

Subjects

Ninety six subjects completed the experiment. Twenty four were children aged five (mean age: 5;02, range 4;09-5;03), 24 were eight-years-old (mean age: 8;01, range 7;09-8;04), 24 were young adults (mean age: 22, range 18-29) and 24 were elderly people (mean age: 78, range: 71-80).

Children were from kindergartens and schools in the surroundings of Liège and Huy, Belgium. Young adults were undergraduate students or staff members at the University of Liège. Elderly people were recruited from personal contacts or attended a leisure club in the area of Liège.

Material

The shapes used in the task were the letters L and C (size : 3.5 cm x 2 cm). The stimuli were presented at the center of a computer screen placed at about 50 cm from the subject. The stimuli were presented in four orientations : 0°, 60°, 120° or 180°. The letter L could be presented in its normal or mirror-reversed version. The letter C was always presented in its normal version.

Subjects completed 64 trials : 12 times the letter L in its normal version followed by the letter L in its normal version (4 trials for each orientation); 12 times the letter L in its normal version followed by the letter L in its mirror-reversed version (4 trials for each orientation); 12 times the letter C in its normal version followed by the letter L in its normal version (4 trials for each orientation); and 12 times the letter C in its normal version followed by the letter C in its normal version (4 trials for each orientation). Trials were displayed in random order. Two keys on a keyboard were used to indicate responses.

Procedure

Two experimental conditions were tested. In the first condition, when subjects had depressed the space bar, they were provided with structural and orientational information on the target, i.e. they saw the letter L or C in its normal format in the orientation of the forthcoming target. Subjects were instructed that the provided information would be *always* an L or a C in its normal version. This information was presented for 2000 msec. Following this, the information was removed from the screen. One thousand msec later, the target was displayed. It could be a normal or mirror-reversed version of an L, or the normal version of the letter C. Subjects had to decide as quickly as possible whether the target corresponded to the information provided. They depress one of two keys to answer (left hand on the W key of an AZERTY keyboard for "different" answer, i.e. mirror-reversed, and right hand on the + key of an AZERTY keyboard for "same" answer).

The second condition was similar to the first condition except that the target appeared 500 msec after the removal of the information. Figure 20 illustrates the two experimental conditions, and the possible combination of stimuli for the 60° orientation.

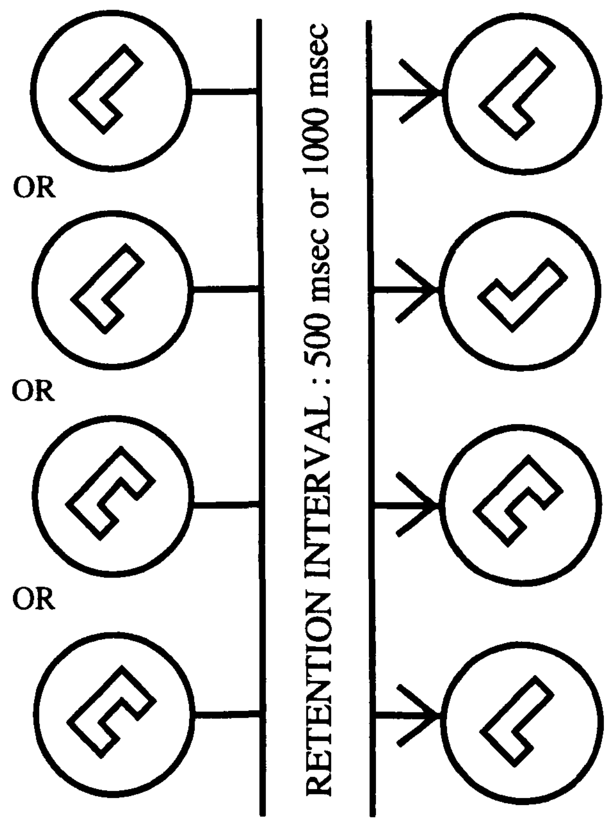


Figure 20 : Schematic representation of the experimental conditions. The provided information are represented on the left side with targets represented on the right side. In between : retention interval of 500 msec or 1000 msec. The provided information and the target were always presented in the same orientation.

In contrast to the young adults and the elderly people, children were first submitted to a training period as defined in the two previous experiments, i.e. discrimination learning of "same" and "different" judgments. A criterion test was also used to select subjects as in experiments 3a and 3b.

RESULTS

Reaction times

In experiment 3c, there were two experimental conditions : the retention interval for the provided information was 500 msec or 1000 msec. Subjects could be presented with four trial categories : L normal followed by L normal (L > L), L normal followed by L mirror-reversed (L > LM), C normal followed by L normal (C > L), or C normal followed by C normal (C > C). Stimuli could be presented at 0°, 60°, 120° or 180°.

A first global mixed ANOVA was calculated on RT means for correct responses with Age and Experimental conditions as between factors, and Trial category and Stimulus orientation as within factors. Results of this global ANOVA are presented in table 3. As all the interactions between independent variables but one were significant, several complementary analyses have been carried out to understand these complex significant effects.

Complementary analyses on RTs : Trial categories

A first set of analyses was carried out on RTs for correct responses on each trial category considered separately. Age and experimental conditions were between factors and stimulus orientation was a within factor. RT means are reported in figures 21 A to 24 B. Data are also reported extensively in appendix 5.

TABLE 3

Results of the global mixed ANOVA on RTs for correct responses

Independent variables and interactions	F(df) = value	*p* value
Age	F(3,88) = 24.65	$p < 0.0001$
Experimental condition (Retention)	F(1,88) = 0.52	$p < 0.47$: NS
Age x Experimental condition	F(3,88) = 0.28	$p < 0.84$: NS
Trial category	F(3,264) = 50.8	$p < 0.0001$
Trial category x Age	F(9,264) = 8.62	$p < 0.0001$
Trial category x Experimental condition	F(3,264) = 10.24	$p < 0.0001$
Trial category x Age x Exp. condition	F(9,264) = 3.96	$p < 0.0001$
Stimulus orientation	F(3,264) = 42.52	$p < 0.0001$
Stimulus orientation x Age	F(9,264) = 8.9	$p < 0.0001$
Stimulus orientation x Exp. condition	F(3,264) = 7.45	$p < 0.0001$
Stim. orientation x Age x Exp. condition	F(9,264) = 3.91	$p < 0.0001$
Trial category x Stimulus orientation	F(9,792) = 14.57	$p < 0.0001$
Trial cat. x Stim. orientation x Age	F(27,792) = 3.49	$p < 0.0001$
Trial cat. x Stim. orient. x Exp. condition	F(9,792) = 5.63	$p < 0.0001$
Trial cat. x Stim. or. x Age x Exp. cond.	F(27,792) = 3.1	$p < 0.0001$

L normal > L normal

The results are reported in figure 21 A for the 1000 msec condition, and in figure 21 B for the 500 msec retention interval condition.

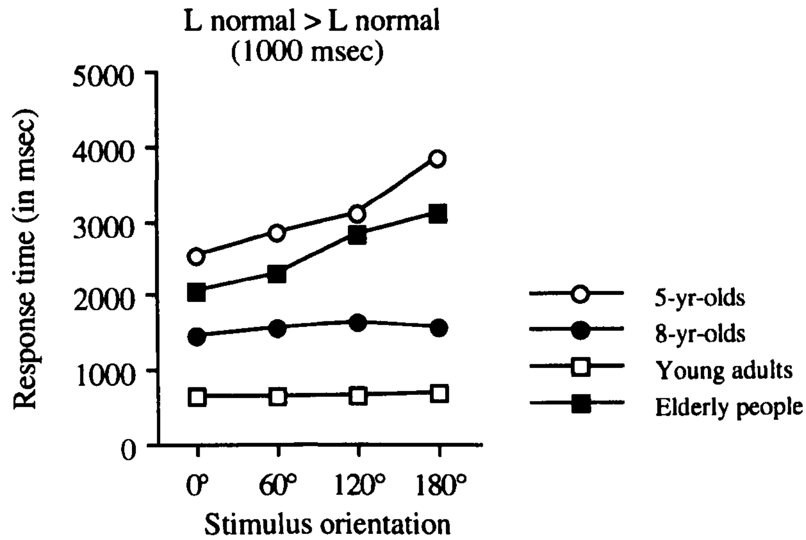


Figure 21A : Response times (in msec) as a function of stimulus orientation and age, for the trial category L > L, the 1000 msec retention interval condition.

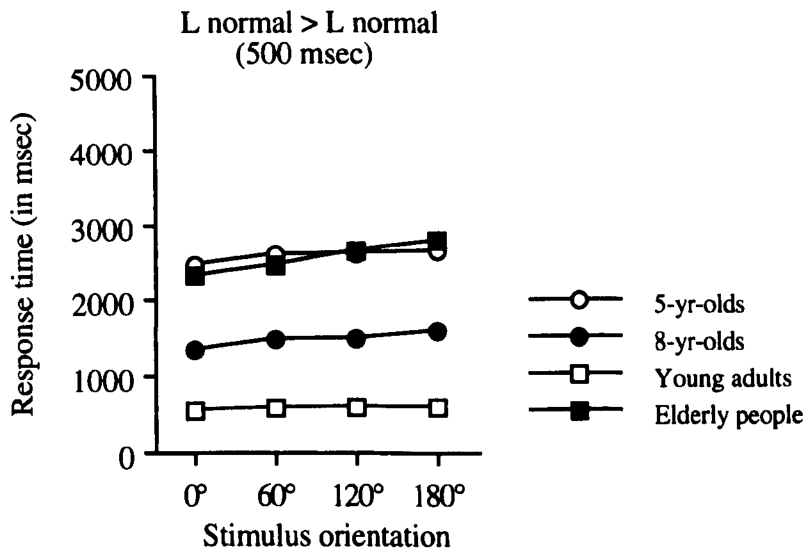


Figure 21B : Response times (in msec) as a function of stimulus orientation and age, for the trial category L > L, the 500 msec retention interval condition.

In the first trial category (L > L), a global repeated measures ANOVA was carried out on RT means for correct responses. Age, $F(3,88) = 26.16$, $p < 0.0001$, and stimulus orientation, $F(3,264) = 40.04$, $p < 0.0001$, significantly affected RTs. In addition, Stimulus orientation interacted significantly with age, $F(9,264) = 8.85$, and with the retention interval, $F(3,264) = 10.14$, both with $p < 0.0001$. The triple interaction orientation x age x retention, $F(9,264) = 5.05$, $p < 0.0001$, was also significant. The retention interval did not affect the RTs by itself, $F(1,88) = 0.76$, $p < 0.38$, and did not interact significantly with age, $F(3,88) = 0.33$, $p < 0.8$.

The analysis was carried on one step further. Repeated measures ANOVAs were calculated on each age category considered separately to assess the effect of stimulus orientation.

In the five-year-olds, RTs significantly increased as a function of stimulus orientation in the 1000 msec retention interval condition, $F(3,33) = 22.02$, $p < 0.0001$, but not in the 500 msec retention interval condition, $F(3,33) = 2.44$, $p < 0.08$. Similar results were found in the elderly people: Stimulus orientation significantly affected RTs when the information was presented 1000 msec before the target, $F(3,33) = 13.44$, $p < 0.0001$, but not - although results were almost significant - when the information was presented 500 msec before the target, $F(3,33) = 2.7$, $p < 0.06$.

In the eight-year-olds and the young adults, stimulus orientation significantly affected the RTs in both experimental condition [Eight-year-olds : 1000 msec retention interval : $F(3,33) = 3$, $p < 0.04$; 500 msec : $F(3,33) = 5.45$, $p < 0.004$; and Young adults : 1000 msec retention interval : $F(3,33) = 4.52$, $p < 0.009$; 500 msec : $F(3,33) = 3.46$, $p < 0.03$].

L normal > L mirror-reversed

The results are reported in figure 22 A for the 1000 msec condition, and in figure 22 B for the 500 msec retention interval condition.

Similar results were observed for this trial category. A global ANOVA on RTs for correct responses showed that age, $F(3,88) = 25.28$, and stimulus orientation, $F(3,264) = 27.39$, both with $p < 0.0001$, significantly affected the RTs. Moreover, stimulus orientation interacted significantly with age, $F(9,264) = 5.97$, $p < 0001$, and with retention interval, $F(3,264) = 6.55$, $p < 0.0003$. The orientation x age x retention interval interaction was also significant, $F(9,264) = 3.57$, $p < 0.0003$. On the contrary, retention interval itself did not affect the RTs, $F(1,88) = 2.33$, $p < 0.13$, and did not interact with age, $F(3,88) = 0.75$, $p < 0.52$.

ANOVAs were then computed on RTs for each age category considered separately. In the five-year-olds, an effect of stimulus orientation was observed both in the 500 msec condition, $F(3,33) = 0.05$, $p < 0.05$, and in the 1000 msec condition, $F(3,33) = 15.1$, $p < 0.0001$. Similar results were observed in the eight-year-olds [500 msec : $F(3,33) = 4.77$, $p < 0.007$; 1000 msec : $F(3,33) = 3.2$, $p < 0.04$], and in the elderly [500 msec : $F(3,33) = 3.17$, $p < 0.04$; 1000 msec : $F(3,33) = 7.09$, $p < 0.0008$]. In the young adults, the orientational effect was only observed in the 1000 msec retention interval condition, $F(3,33) = 7.64$, $p < 0.0005$, and not in the 500 msec condition, $F(3,33) = 1.04$, $p < 0.39$.

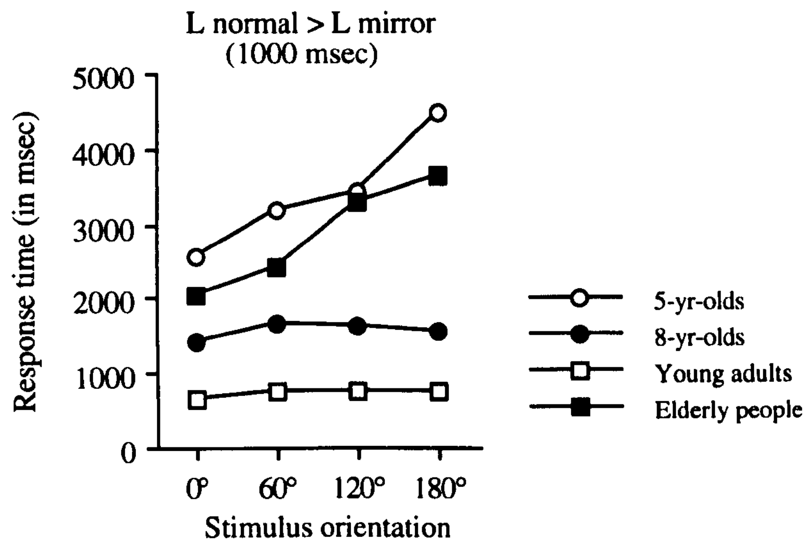


Figure 22A : Response times (in msec) as a function of stimulus orientation and age, for the trial category L > LM, the 1000 msec retention interval condition.

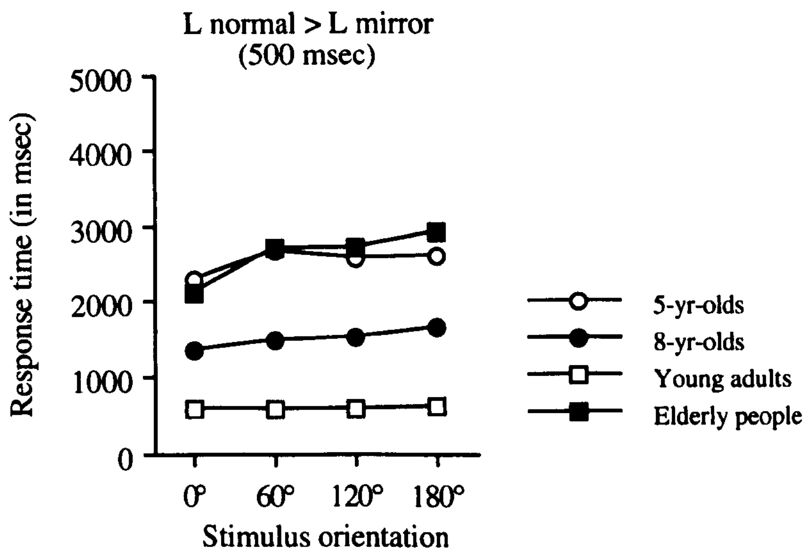


Figure 22B : Response times (in msec) as a function of stimulus orientation and age, for the trial category L > LM, the 500 msec retention interval condition.

C normal > L normal

The results are reported in figure 23 A for the 1000 msec condition, and in figure 23 B for the 500 msec retention interval condition.

A global repeated measure ANOVA was carried out on RTs for correct responses. The RTs were significantly affected by age, F(3,88) = 19.93, $p < 0.0001$, and by stimulus orientation, F(3,264) = 4.7, $p < 0.003$. No other variable or interaction between variables was observed in this trial category [retention interval : F(1,88) = 0, $p < 0.97$; age x retention interval, F(3,88) = 0.25, $p < 0.86$; stimulus orientation x age : F(9,264) = 1.29, $p < 0.24$; stimulus orientation x retention interval : F(3,264) = 0.49, $p < 0.68$; stimulus orientation x age x retention interval : F(9,264) = 1.07, $p < 0.38$].

The orientational effect was assessed for each age category considered separately. Stimulus orientation affected RTs in the 1000 msec retention interval in the five-year-olds, F(3,33) = 3.11, $p < 0.04$, in young adults, F(3,33) = 3.38, $p < 0.03$, and in the elderly people, F(3,33) = 2.93, $p < 0.05$, but not in the eight-year-olds, F(3,33) = 1.2, $p < 0.23$.

In the 500 msec retention interval condition, stimulus orientation did not affect significantly RTs [Five-year-olds : F(3,33) = 2.75, $p < 0.06$ (almost significant); Eight-year-olds : F(3,33) = 2.39, $p < 0.09$; Young adults : F(3,33) = 1.51, $p < 0.23$; and Elderly people : F(3,33) = 1.38, $p < 0.27$].

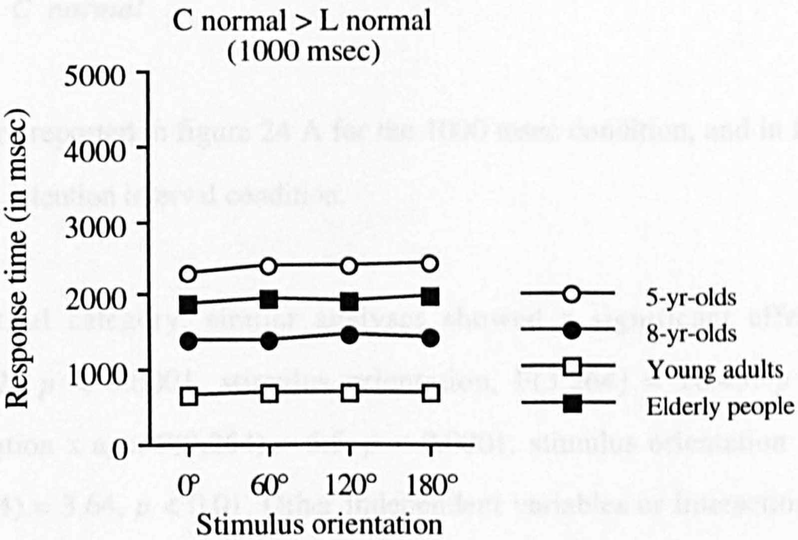


Figure 23A : Response times (in msec) as a function of stimulus orientation and age, for the trial category C > L, the 1000 msec retention interval condition.

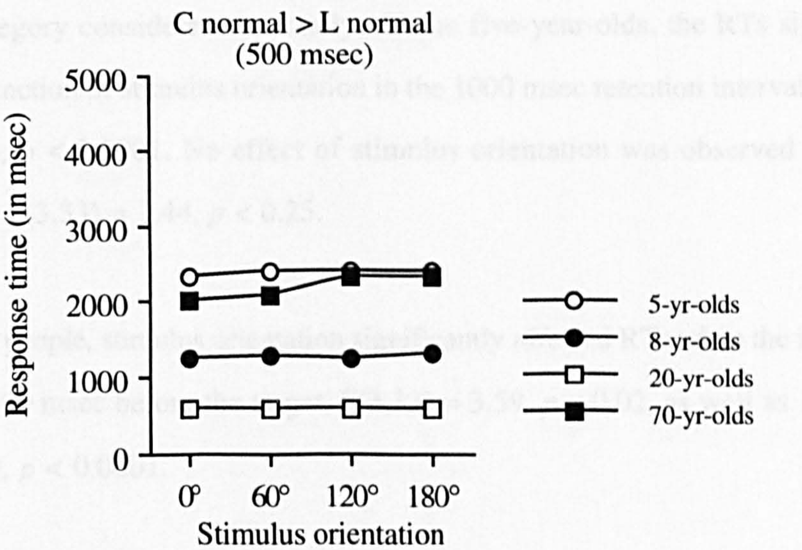


Figure 23B : Response times (in msec) as a function of stimulus orientation and age, for the trial category C > L, the 500 msec retention interval condition.

C normal > C normal

The results are reported in figure 24 A for the 1000 msec condition, and in figure 24 B for the 500 msec retention interval condition.

In the last trial category, similar analyses showed a significant effect of age, $F(3,88) = 23.42$, $p < 0.0001$, stimulus orientation, $F(3,264) = 28.45$, $p < 0.0001$, stimulus orientation x age, $F(9,264) = 5.5$, $p < 0.0001$, stimulus orientation x retention interval, $F(3,264) = 3.64$, $p < 0.01$. Other independent variables or interactions between variables did not significantly affect RTs [Retention interval : $F(1,88) = 0.08$, $p < 0.77$; age x retention interval : $F(3,88) = 0.28$, $p < 0.84$; stimulus orientation x age x retention interval : $F(9,264) = 1.63$, $p < 0.11$].

The analysis was carried one step further. Repeated measures ANOVAs were calculated on each age category considered separately. In the five-year-olds, the RTs significantly increased as a function of stimulus orientation in the 1000 msec retention interval condition, $F(3,33) = 10.24$, $p < 0.0001$. No effect of stimulus orientation was observed in the 500 msec condition, $F(3,33) = 1.44$, $p < 0.25$.

In the elderly people, stimulus orientation significantly affected RTs when the information was presented 500 msec before the target, $F(3,33) = 3.59$, $p < 0.02$, as well as 1000 msec, $F(3,33) = 14.99$, $p < 0.0001$.

In eight-year-olds, a stimulus orientation effect was observed in the 1000 msec condition, $F(3,33) = 4.69$, $p < 0.008$, but not in the 500 msec condition, $F(3,33) = 2.34$, $p < 0.09$. In contrast, in young adults, opposed results were observed : Stimulus orientation influenced significantly RTs in the 500 msec retention interval condition, $F(3,33) = 5.22$, $p > 0.005$, but not in the 1000 msec condition, $F(3,33) = 1.73$, $p < 0.18$.

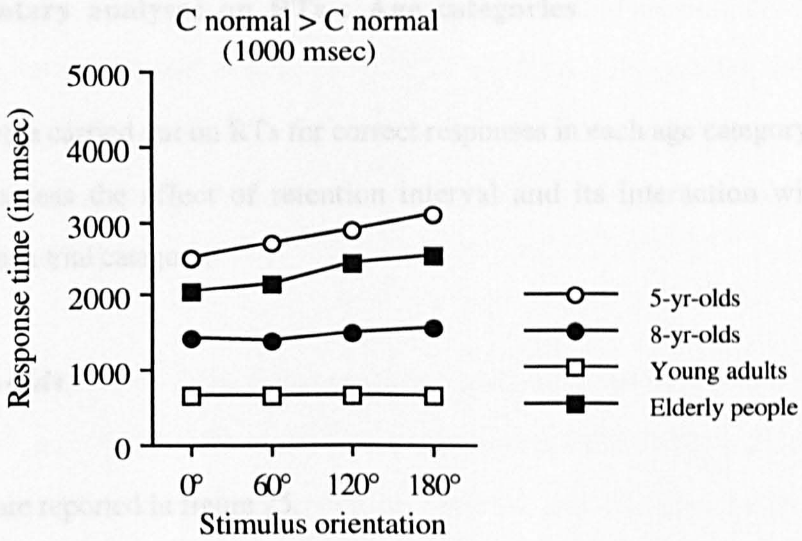


Figure 24A : Response times (in msec) as a function of stimulus orientation and age, for the trial category C > C, the 1000 msec retention interval condition.

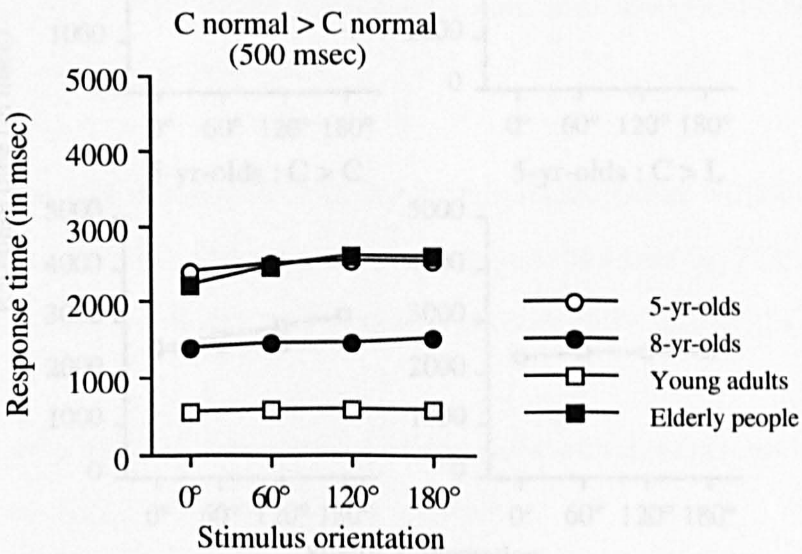


Figure 24B : Response times (in msec) as a function of stimulus orientation and age, for the trial category C > C, the 500 msec retention interval condition.

Complementary analyses on RTs : Age categories

ANOVAs were carried out on RTs for correct responses in each age category considered separately to assess the effect of retention interval and its interaction with stimulus orientation in each trial category.

Five-year-olds

The results are reported in figure 25.

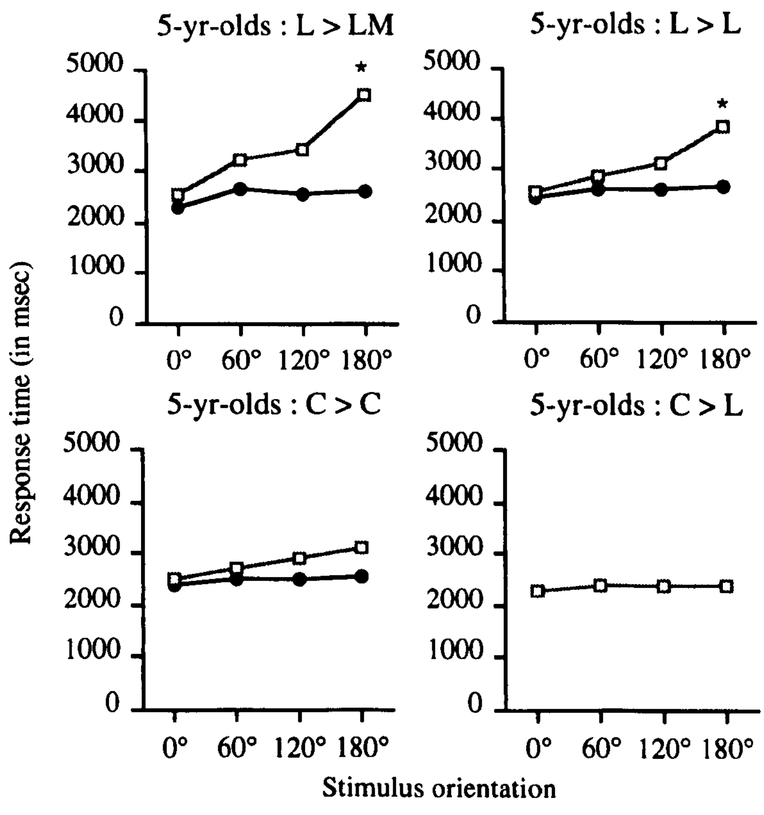


Figure 25 : Response times (in msec) as a function of stimulus orientation, trial category (L > LM, L > L, C > C, C > L) and retention interval (grey line : 1000 msec; black line : 500 msec) in five-years-old children.

For the trial category L > LM, significant effects of retention interval, $F(1,22) = 5.41$, $p < 0.03$, stimulus orientation, $F(3,66) = 16.25$, $p < 0.0001$, and stimulus orientation x retention interval, $F(3,66) = 9.52$, $p < 0.0001$, were observed. A Tukey test ($p < 0.05$) showed that the difference between the retention interval conditions was only present for the 180° orientation.

For the trial category L > L, the RTs were significantly affected by stimulus orientation, $F(3,66) = 23.03$, $p < 0.0001$, but not by the retention interval, $F(1,22) = 2.15$, $p < 0.16$. However, the interaction between retention interval and stimulus orientation was significant, $F(3,66) = 14.59$, $p < 0.0001$. A Tukey test ($p < 0.05$) showed a significant difference between RT means for the 180° orientation.

When children were presented with a C followed by an L, RTs were only significantly affected by the stimulus orientation, $F(3,66) = 5.67$, $p < 0.002$. Neither the retention interval, $F(1,22) = 0$, $p < 0.98$, nor the interaction retention interval x stimulus orientation, $F(3,66) = 0.25$, $p < 0.86$, was significant.

Finally, for the trial category C > C, the stimulus orientation, $F(3,66) = 10.69$, $p < 0.0001$, and the interaction stimulus orientation x retention interval, $F(3,66) = 4.92$, $p < 0.004$, were significant, but not the retention interval itself, $F(1,22) = 0.84$, $p < 0.37$.

The interactions between trial category and stimulus orientation are presented in table 4 for both the 500 msec and 1000 msec retention intervals.

TABLE 4

Interaction between trial category and stimulus orientation. Retention interval : 500 msec

	L > L	C > C	C > L
L>LM	F(3,33) = 1.21, $p < 0.32$	F(3,33) = 1.64, $p < 0.2$	F(3,33) = 1.68, $p < 0.19$
L > L		F(3,33) = 0.25, $p < 0.86$	F(3,33) = 0.71, $p < 0.55$
C > C			F(3,33) = 0.23, $p < 0.88$

Interaction between trial category and stimulus orientation. Retention interval : 1000 msec

	L > L	C > C	C > L
L>LM	F(3,33) = 2.79, $p < 0.06$	F(3,33) = 8.04, $p < 0.0004$	F(3,33) = 13.3, $p < 0.0001$
L > L		F(3,33) = 6.01, $p < 0.002$	F(3,33) = 19, $p < 0.0001$
C > C			F(3,33) = 6.43, $p < 0.002$

Eight-year-olds

The RT values are reported in figure 26.

In eight-year-olds, neither the retention interval [L > LM : F(1,22) = 0.16, $p < 0.69$; L > L : F(1,22) = 0.38, $p < 0.55$; C > L : F(1,22) = 1.07, $p < 0.31$; and C > C : F(1,22) = 0.01, $p < 0.91$], nor the interaction between retention interval and stimulus orientation [L > LM : F(3,66) = 2.10, $p < 0.11$; L > L : F(3,66) = 1.58, $p < 0.20$; C > L : F(3,66) = 1.06, $p < 0.45$; and C > C : F(3,66) = 0.9, $p < 0.45$] significantly affected the RTs.

However, RTs were significantly affected by the stimulus orientation in the trial category L > LM, F(3,66) = 5.92, $p < 0.001$, L > L, F(3,66) = 6.51, $p < 0.0006$, C > L, F(3,66) = 2.07, $p < 0.01$, and C > C, F(3,66) = 5.69, $p < 0.002$.

The interactions between trial category and stimulus orientation are presented in table 5 for both the 500 msec and 1000 msec retention intervals.

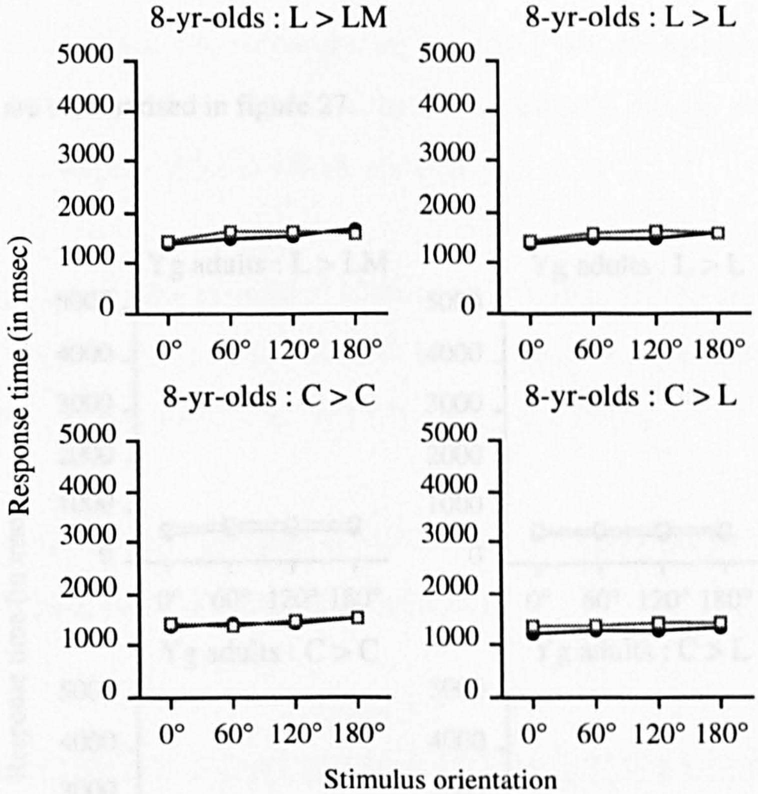


Figure 26 : Response times (in msec) as a function of stimulus orientation, trial category (L > LM, L > L, C > C, C > L) and retention interval (grey line : 1000 msec; black line : 500 msec) in eight-years-old children.

TABLE 5

Interaction between trial category and stimulus orientation. Retention interval : 500 msec

	L > L	C > C	C > L
L>LM	F(3,33) = 0.72, $p < 0.55$	F(3,33) = 1.19, $p < 0.33$	F(3,33) = 2.9, $p < 0.05$
L > L		F(3,33) = 0.47, $p < 0.71$	F(3,33) = 2.04, $p < 0.13$
C > C			F(3,33) = 0.8, $p < 0.5$

Interaction between trial category and stimulus orientation. Retention interval : 1000 msec

	L > L	C > C	C > L
L>LM	F(3,33) = 0.15, $p < 0.71$	F(3,33) = 3.65, $p < 0.02$	F(3,33) = 2.9, $p < 0.12$
L > L		F(3,33) = 2.68, $p < 0.06$	F(3,33) = 1.32, $p < 0.29$
C > C			F(3,33) = 1.36, $p < 0.27$

Young adults

The results are summarised in figure 27.

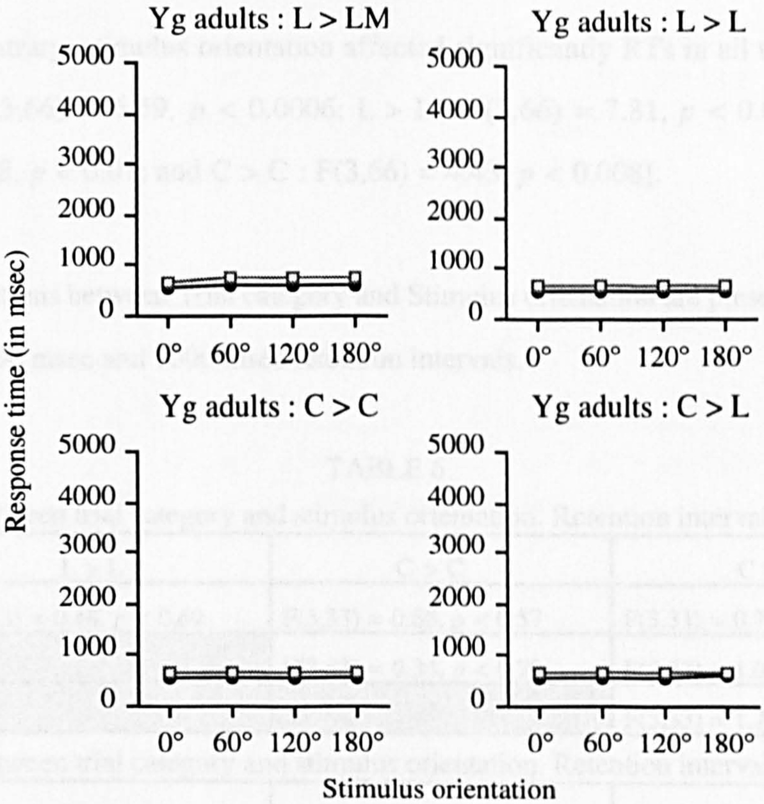


Figure 27 : Response times (in msec) as a function of stimulus orientation, trial category (L > LM, L > L, C > C, C > L) and retention interval (grey line : 1000 msec; black line : 500 msec) in young adults.

As in eight-year-olds, the retention interval did not affect the RTs in young adults [L > LM : $F(1,22) = 4.08$, $p < 0.06$; L > L : $F(1,22) = 1.56$, $p < 0.22$; C > L : $F(1,22) = 1.67$, $p < 0.21$; and C > C : $F(1,22) = 1.48$, $p < 0.24$], and interacted significantly with stimulus orientation only in the trial category L > LM, $F(3,66) = 3.65$, $p < 0.02$. In fact, a Tukey test showed that RT means were different in the 60° and 120° orientation.

The stimulus orientation x retention interval interaction was not significant in the L > L trial category, F(3,66) = 0.52, $p < 0.22$, in the C > L category, F(3,66) = 1.93, $p < 0.13$, and in the C > C category, F(3,66) = 0.18, $p < 0.91$.

On the contrary, stimulus orientation affected significantly RTs in all trial categories [L > LM : F(3,66) = 6.59, $p < 0.0006$; L > L : F(3,66) = 7.81, $p < 0.0002$; C > L : F(3,66) = 3.98, $p < 0.01$; and C > C : F(3,66) = 4.43, $p < 0.008$].

The interactions between Trial category and Stimulus orientation are presented in table 6 for both the 500 msec and 1000 msec retention intervals.

TABLE 6

Interaction between trial category and stimulus orientation. Retention interval : 500 msec

	L > L	C > C	C > L
L>LM	F(3,33) = 0.48, $p < 0.69$	F(3,33) = 0.68, $p < 0.57$	F(3,33) = 0.71, $p < 0.55$
L > L		F(3,33) = 0.34, $p < 0.79$	F(3,33) = 1.05, $p < 0.38$
C > C			F(3,33) = 1.78, $p < 0.17$

Interaction between trial category and stimulus orientation. Retention interval : 1000 msec

	L > L	C > C	C > L
L>LM	F(3,33) = 4.47, $p < 0.01$	F(3,33) = 5.87, $p < 0.003$	F(3,33) = 4.72, $p < 0.008$
L > L		F(3,33) = 0.73, $p < 0.54$	F(3,33) = 0.28, $p < 0.84$
C > C			F(3,33) = 0.74, $p < 0.53$

Elderly people

The results are reported in figure 28.

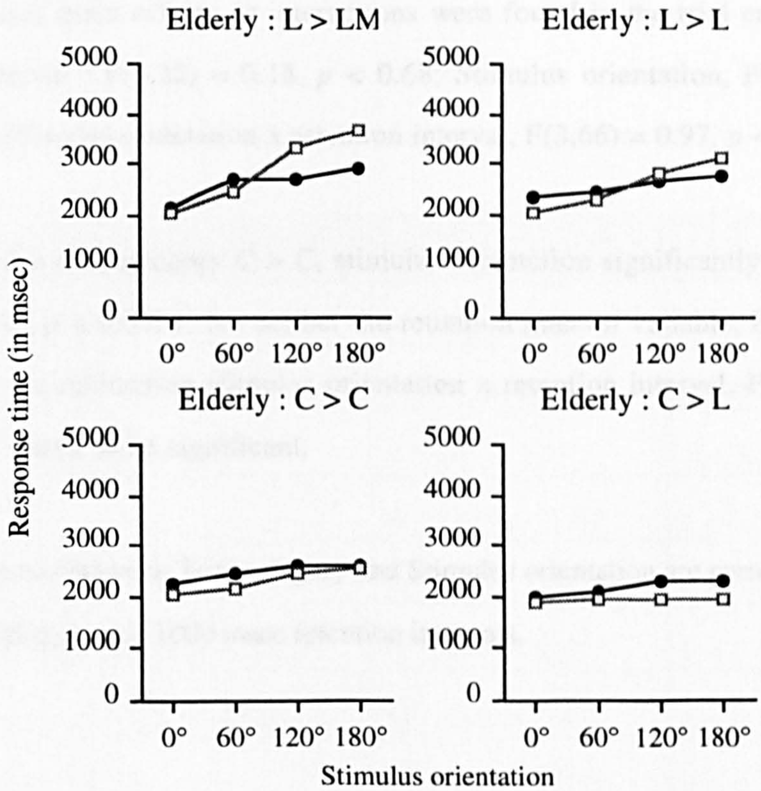


Figure 28 : Response times (in msec) as a function of stimulus orientation, trial category (L > LM, L > L, C > C, C > L) and retention interval (grey line : 1000 msec; black line : 500 msec) in the elderly people.

In the trial category L > LM, RTs were affected only by stimulus orientation, F(3,66) = 9.51, $p < 0.1$. Retention interval, F(1,22) = 0.1, $p < 0.75$, and the interaction retention interval x stimulus orientation, F(3,66) = 2.17, $p < 0.1$, did not significantly affect the results.

In the trial category L > L, similar results were observed : The stimulus orientation, F(3,66) = 14.45, $p < 0.0001$, was the only variable to affect the RTs. Retention interval, F(1,22) = 0, $p < 0.99$, and stimulus orientation x retention interval, F(3,66) = 2.47, $p < 0.07$, were not significant, although the interaction almost reached significance.

No significant main effects or interactions were found in the trial category C > L [Retention interval : F(1,22) = 0.18, $p < 0.68$; Stimulus orientation, F(3,66) = 0.14, $p < 0.14$; and Stimulus orientation x retention interval, F(3,66) = 0.97, $p < 0.41$].

Finally, in the trial category C > C, stimulus orientation significantly affected RTs, F(3,66) = 12.66, $p < 0.0001$, but neither the retention interval variable, F(1,22) = 0.07, $p < 0.79$, nor the interaction stimulus orientation x retention interval, F(3,66) = 0.61, $p < 0.61$, was found to be significant.

The interactions between Trial category and Stimulus orientation are presented in table 7 for both the 500 msec and 1000 msec retention intervals.

TABLE 7

Interaction between trial category and stimulus orientation. Retention interval : 500 msec

	L > L	C > C	C > L
L>LM	F(3,33) = 1.68, $p < 0.19$	F(3,33) = 1.89, $p < 0.15$	F(3,33) = 1.77, $p < 0.17$
L > L		F(3,33) = 0.4, $p < 0.75$	F(3,33) = 0.26, $p < 0.86$
C > C			F(3,33) = 0.2, $p < 0.89$

Interaction between trial category and stimulus orientation. Retention interval : 1000 msec

	L > L	C > C	C > L
L>LM	F(3,33) = 2.07, $p < 0.12$	F(3,33) = 4.12, $p < 0.01$	F(3,33) = 6.67, $p < 0.001$
L > L		F(3,33) = 4.89, $p < 0.006$	F(3,33) = 12.7, $p < 0.0001$
C > C			F(3,33) = 11.6, $p < 0.0001$

Error rates

A first global mixed ANOVA was carried out on errors with age and experimental conditions as between factors, and trial category and stimulus orientation as within factors. The results of this global ANOVA are presented in table 8. Several complementary analyses were carried out to understand the significant effects.

TABLE 8

Results of the global mixed ANOVA on errors

Independent variables and interactions	F(df) = value	p value
Age	F(3,88) = 16.24	$p < 0.0001$
Experimental condition (Retention)	F(1,88) = 23.03	$p < 0.0001$
Age x Experimental condition	F(3,88) = 5.28	$p < 0.002$
Trial category	F(3,264) = 16.07	$p < 0.0001$
Trial category x Age	F(9,264) = 1.9	$p < 0.05$
Trial category x Experimental condition	F(3,264) = 8.37	$p < 0.0001$
Trial category x Age x Exp. condition	F(9,264) = 1.45	$p < 0.17$: NS
Stimulus orientation	F(3,264) = 17.19	$p < 0.0001$
Stimulus orientation x Age	F(9,264) = 1.67	$p < 0.09$: NS
Stimulus orientation x Exp. condition	F(3,264) = 4.02	$p < 0.008$
Stim. orientation x Age x Exp. condition	F(9,264) = 0.78	$p < 0.64$: NS
Trial category x Stimulus orientation	F(9,792) = 0.94	$p < 0.49$: NS
Trial cat. x Stim. orientation x Age	F(27,792) = 0.23	$p < 1$: NS
Trial cat. x Stim. orient. x Exp. condition	F(9,792) = 0.95	$p < 0.48$: NS
Trial cat. x Stim. or. x Age x Exp. cond.	F(27,792) = 0.45	$p < 0.99$: NS

Complementary analyses on error rates : Trial categories

A first set of analyses were carried out on errors on each trial category considered separately. Age and experimental conditions were between factors and stimulus orientation was a within factor. Error rates (in %) are reported in figures 29 A to 32 B. Data are also reported extensively in appendix 6.

L normal > L normal

The results are reported in figure 29 A for the 1000 msec condition, and in figure 29 B for the 500 msec retention interval condition.

In the first trial category (L > L), a global repeated measures ANOVA was carried out on errors. Error rates were significantly affected by age, $F(3,88) = 16.7$, $p < 0.0001$, retention interval, $F(1,88) = 24.01$, $p < 0.0001$, and stimulus orientation, $F(3,264) = 6.87$, $p < 0.0002$. In addition, the retention interval significantly interacted with age, $F(3,88) = 4.56$, $p < 0.005$, and with stimulus orientation, $F(3,264) = 3.15$, $p < 0.03$. However, stimulus orientation did not interact significantly with age, $F(9,264) = 1.06$, $p < 0.39$, and the triple interaction orientation x age x retention, $F(9,264) = 0.44$, $p < 0.91$, did not significantly affect the performance.

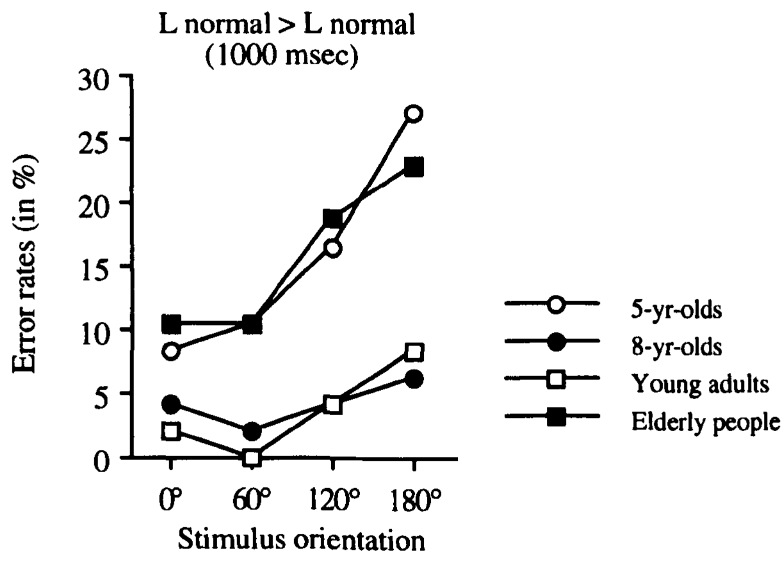


Figure 29A : Errors (in %) as a function of stimulus orientation and age, for the trial category L > L, the 1000 msec retention interval condition.

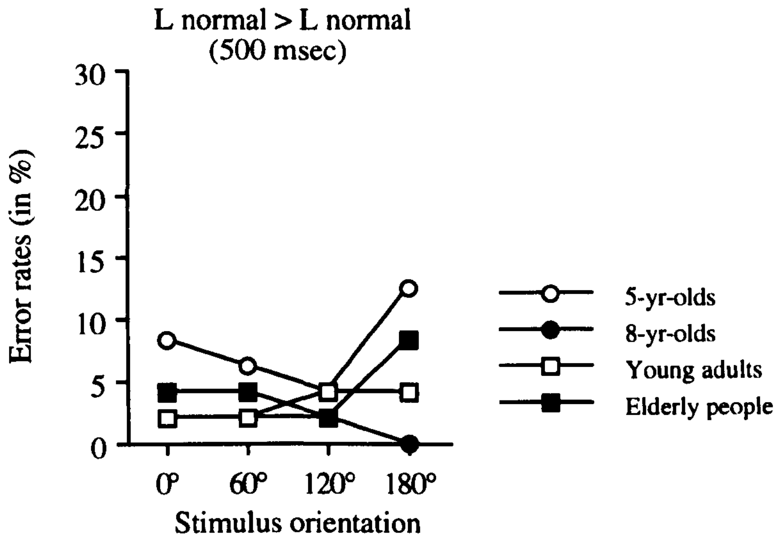


Figure 29B : Errors (in %) as a function of stimulus orientation and age, for the trial category L > L, the 500 msec retention interval condition.

Repeated measures ANOVAs tested the effect of stimulus orientation on each age category considered separately.

In the five-year-olds, error rates increased significantly as a function of stimulus orientation in the 1000 msec retention interval condition, $F(3,33) = 5.04$, $p < 0.006$, but not in the 500 msec retention interval condition, $F(3,33) = 0.67$, $p < 0.58$. Similar results were found in the elderly people: Stimulus orientation significantly affected error rates when the information was presented 1000 msec before the target, $F(3,33) = 3.19$, $p < 0.04$, but not when the information was presented 500 msec before the target, $F(3,33) = 0.9$, $p < 0.45$.

Stimulus orientation did not significantly affect error rates in eight-year-olds and young adults, [Eight-year-olds : 1000 msec retention interval : $F(3,33) = 0.29$, $p < 0.83$;

500 msec : F(3,33) = 0.31, $p < 0.81$; and Young adults : 1000 msec retention interval : F(3,33) = 1.6, $p < 0.21$; 500 msec : F(3,33) = 0.21, $p < 0.89$].

L normal > L mirror-reversed

The results are reported in figure 30 A for the 1000 msec condition, and in figure 30 B for the 500 msec retention interval condition.

Similar results were observed for this trial category. A global ANOVA on errors showed that error rates were significantly affected by age, F(3,88) = 9.35, retention interval, F(1,88) = 27.8, stimulus orientation, F(3,264) = 8.53, all with $p < 0.0001$, and by the interaction retention interval x age, F(3,88) = 5.06, $p < 0.003$. On the contrary, the interactions retention interval x stimulus orientation, F(3,264) = 2.2, $p < 0.09$, stimulus orientation x age, F(9,264) = 0.55, $p < 0.84$, and stimulus orientation x age x retention interval, F(9,264) = 0.72, $p < 0.69$, had no significant impact on performance.

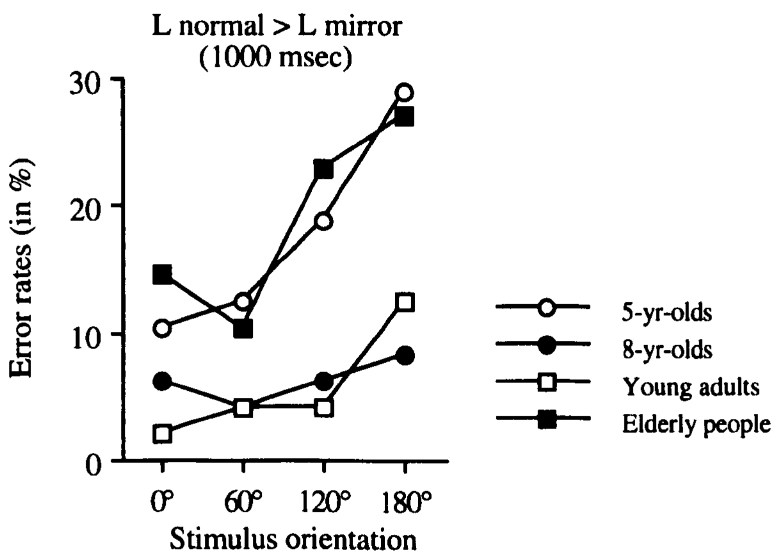


Figure 30A : Errors (in %) as a function of stimulus orientation and age, for the trial category L > LM, the 1000 msec retention interval condition.

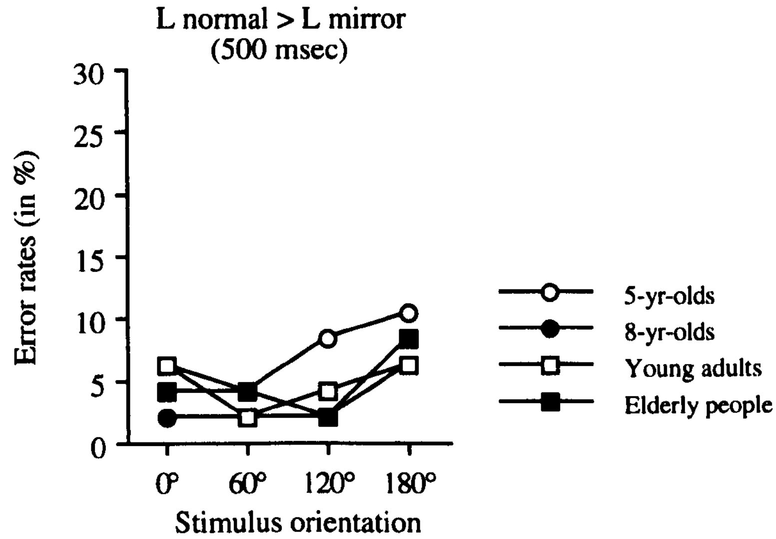


Figure 30B : Errors (in %) as a function of stimulus orientation and age, for the trial category L > LM, the 500 msec retention interval condition.

ANOVAs were then computed for error rates for each age category considered separately. In the five-year-olds, an effect of stimulus orientation was observed in the 1000 msec condition, $F(3,33) = 5.04$, $p < 0.006$, but not in the 500 msec condition, $F(3,33) = 0.41$, $p < 0.74$. Similar results were observed in the elderly [500 msec : $F(3,33) = 0.81$, $p < 0.49$; 1000 msec : $F(3,33) = 3.61$, $p < 0.02$]. In contrast, in the eight-year-olds and in young adults, stimulus orientation did not affect performance [8-year-olds: 500 msec : $F(3,33) = 0.52$, $p < 0.67$; 1000 msec : $F(3,33) = 0.21$, $p < 0.89$; young adults: 500 msec : $F(3,33) = 0.46$, $p < 0.71$; 1000 msec : $F(3,33) = 2.25$, $p < 0.10$].

C normal > L normal

The results are reported in figure 31 A for the 1000 msec condition, and in figure 31 B for the 500 msec retention interval condition.

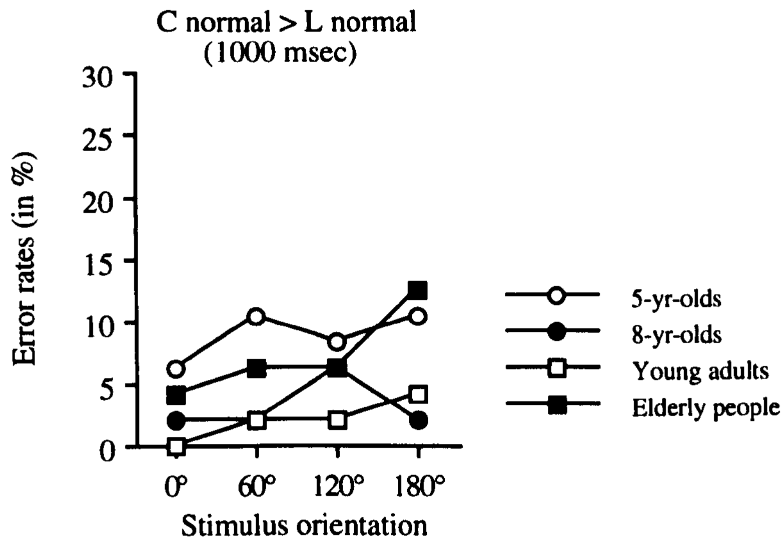


Figure 31A : Errors (in %) as a function of stimulus orientation and age, for the trial category C > L, the 1000 msec retention interval condition.

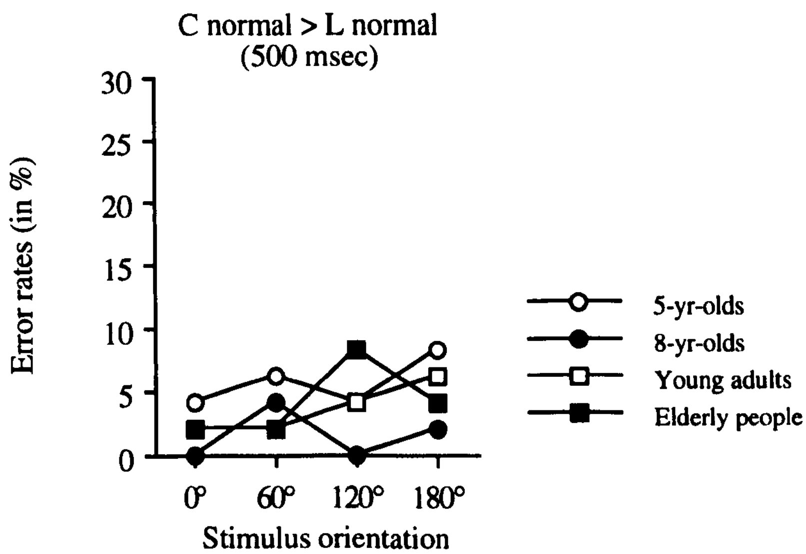


Figure 31B : Errors (in %) as a function of stimulus orientation and age, for the trial category C > L, the 500 msec retention interval condition.

A global repeated measure ANOVA was carried out on Errors. Errors were only significantly influenced by age, $F(3,88) = 5.25$, $p < 0.002$. No effect of other variables or interaction between variables was observed in this trial category [Retention interval : $F(1,88) = 2.32$, $p < 0.13$; Age x retention interval, $F(3,88) = 1.16$, $p < 0.33$; Stimulus orientation, $F(3,264) = 2.06$, $p < 0.11$; Stimulus orientation x Age : $F(9,264) = 0.36$, $p < 0.95$; Stimulus orientation x retention interval : F(3,264) = 0.0.04, $p < 0.99$; Stimulus orientation x age x retention interval : $F(9,264) = 0.63$, $p < 0.77$].

Unsurprisingly, when age categories were considered separately, the stimulus orientation did not affect error rates [5-year-olds: 500 msec: $F(3,33) = 0.31$, $p < 0.81$; 1000 msec: $F(3,33) = 0.28$, $p < 0.84$; 8-year-olds: 500 msec: $F(3,33) = 1.25$, $p < 0.31$; 1000 msec: $F(3,33) = 0.52$, $p < 0.67$; Young adults: 500 msec: $F(3,33) = 0.42$, $p < 0.74$; 1000 msec: $F(3,33) = 0.65$, $p < 0.59$; and Elderly people: 500 msec: $F(3,33) = 1.22$, $p < 0.32$; 1000 msec: $F(3,33) = 1.14$, $p < 0.35$].

C normal > C normal

The results are reported in figure 32 A for the 1000 msec condition, and in figure 32 B for the 500 msec retention interval condition.

In the last trial category, similar analyses showed a significant effect of age, $F(3,88) = 12.2$, $p < 0.0001$, of retention interval, $F(1,88) = 10.09$, $p < 0.002$, and of the interaction between these variables, $F(3,88) = 3.72$, $p < 0.01$, on performance. The effect of stimulus orientation on errors almost reached significance, $F(3,264) = 2.38$, $p < 0.07$. However, the other interactions between variables did not significantly affect error rates [Stimulus orientation x age: $F(9,264) = 0.42$, $p < 0.92$; Stimulus orientation x retention interval: $F(3,264) = 1.3$, $p < 0.27$; and Stimulus orientation x age x retention interval: $F(9,264) = 0.38$, $p < 0.95$].

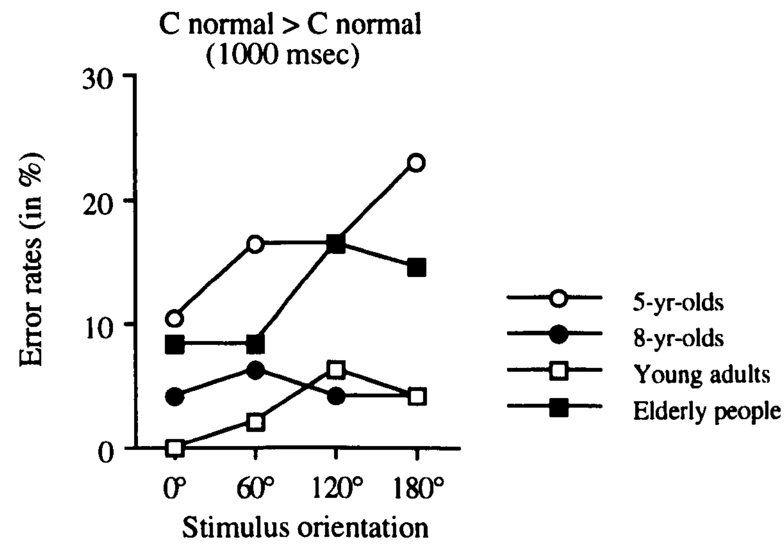


Figure 32A : Errors (in %) as a function of stimulus orientation and age, for the trial category C > C, the 1000 msec retention interval condition.

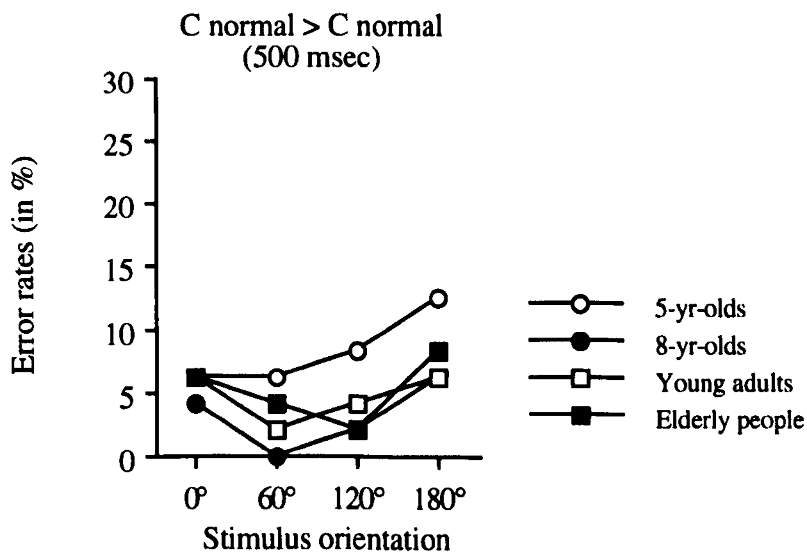


Figure 32B : Errors (in %) as a function of stimulus orientation and age, for the trial category C > C, the 500 msec retention interval condition.

The analysis was carried one step further. Repeated measures ANOVAs were calculated on each age category considered separately to test the effect of stimulus orientation. This latter variable did not affect error rates [5-year-olds: 500 msec: $F(3,33) = 0.5$, $p < 0.68$; 1000 msec: $F(3,33) = 1.03$, $p < 0.39$; 8-year-olds: 500 msec: $F(3,33) = 1$, $p < 0.41$; 1000 msec: $F(3,33) = 0.08$, $p < 0.97$; Young adults: 500 msec: $F(3,33) = 0.28$, $p < 0.84$; 1000 msec: $F(3,33) = 1.28$, $p < 0.29$; and Elderly people: 500 msec: $F(3,33) = 1$, $p < 0.41$; 1000 msec: $F(3,33) = 1.27$, $p < 0.3$].

Complementary analyses on errors : Age categories

ANOVAs were carried out on errors in each age category considered separately to assess the effect of retention interval and its interaction with stimulus orientation in each trial category.

Five-year-olds

The results are reported in figure 33.

For the trial category L > LM, a significant effect of retention interval, $F(1,22) = 9.82$, $p < 0.005$, and stimulus orientation, $F(3,66) = 3.76$, $p < 0.01$, was observed. However, the interaction stimulus orientation x retention interval, $F(3,66) = 1.19$, $p < 0.32$, was not significant. A Tukey test ($p < 0.05$) showed that the difference between the retention interval condition was only present for the 180° orientation.

For the trial category L > L, errors were significantly affected by the retention interval, $F(1,22) = 8.87$, $p < 0.007$, and stimulus orientation, $F(3,66) = 3.62$, $p < 0.02$. However, the interaction between retention interval and stimulus orientation was not significant, F(3,66) = 1.43, $p < 0.24$. A Tukey test ($p < 0.05$) showed a significant difference between RT means for the 120° and 180° orientations.

When children were presented with a C followed by an L, errors were not significantly affected by the retention interval, F(1,22) = 2.08, $p < 0.16$, the stimulus orientation, F(3,66) = 0.54, $p < 0.65$, and the interaction retention interval x stimulus orientation, F(3,66) = 0.05, $p < 0.98$.

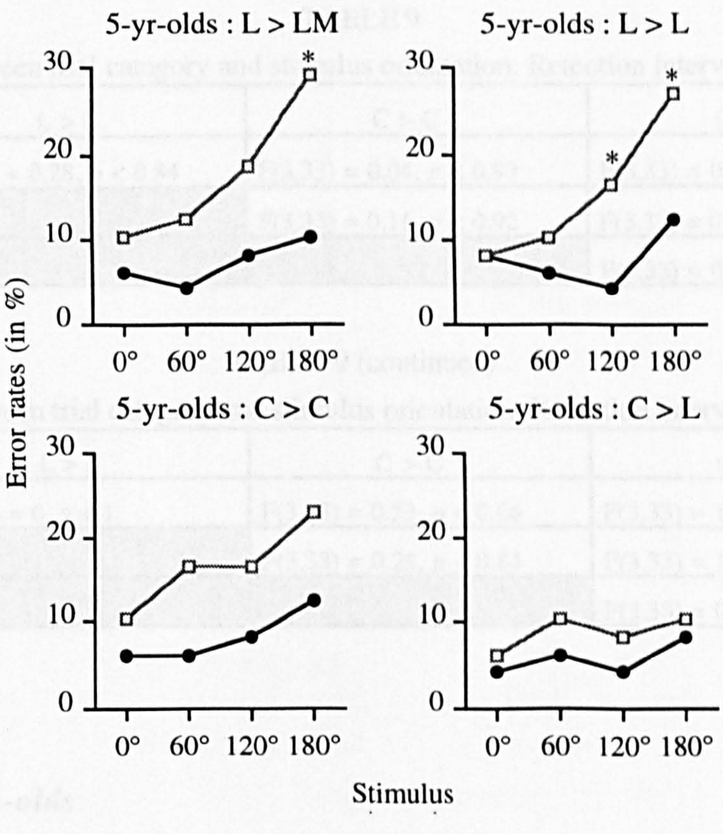


Figure 33 : Errors (in %) as a function of stimulus orientation, trial category (L > LM, L > L, C > C, C > L) and retention interval (grey line : 1000 msec; black line : 500 msec) in five-years-old children.

Finally, for the trial category C > C, only the retention interval, F(1,22) = 9.26, $p < 0.006$, significantly affected performance. Neither the stimulus orientation, F(3,66) = 1.43, $p < 0.24$, nor the interaction stimulus orientation x retention interval, F(3,66) = 0.2, $p < 0.89$, had a significant effect on error rates.

The interactions between Trial category and Stimulus orientation are presented in table 9 for both the 500 msec and 1000 msec retention intervals.

TABLE 9

Interaction between trial category and stimulus orientation. Retention interval : 500 msec

	L > L	C > C	C > L
L>LM	F(3,33) = 0.28, $p < 0.84$	F(3,33) = 0.04, $p < 0.99$	F(3,33) = 0.38, $p < 0.77$
L > L		F(3,33) = 0.16, $p < 0.92$	F(3,33) = 0.15 $p < 0.93$
C > C			F(3,33) = 0.16, $p < 0.92$

TABLE 9 (continued)

Interaction between trial category and stimulus orientation. Retention interval : 1000 msec

	L > L	C > C	C > L
L>LM	F(3,33) = 0, $p < 1$	F(3,33) = 0.53, $p < 0.66$	F(3,33) = 1.77, $p < 0.17$
L > L		F(3,33) = 0.28, $p < 0.84$	F(3,33) = 1.48, $p < 0.24$
C > C			F(3,33) = 0.28, $p < 0.83$

Eight-year-olds

The RT values are reported in figure 34.

In eight-year-olds, neither the retention interval [L > LM : F(1,22) = 2.2, $p < 0.15$; L > L : F(1,22) = 2.1, $p < 0.16$; C > L : F(1,22) = 0.89, $p < 0.36$; and C > C : F(1,22) = 0.43, $p < 0.52$], the stimulus orientation [L > LM, F(3,66) = 0.59, $p < 0.63$, L > L, F(3,66) = 0.08, $p < 0.97$, C > L, F(3,66) = 0.35, $p < 0.79$, and C > C, F(3,66) = 0.19, $p < 0.9$], nor the interaction between retention interval and stimulus orientation [L > LM : F(3,66) = 0.59, $p < 0.97$; L > L : F(3,66) = 0.51, $p < 0.68$; C > L : F(3,66) = 1.10, $p < 0.35$; and C > C : F(3,66) = 0.6, $p < 0.61$] significantly affected error rates.

The interactions between trial category and stimulus orientation are presented in table 10 for both the 500 msec and 1000 msec retention intervals.

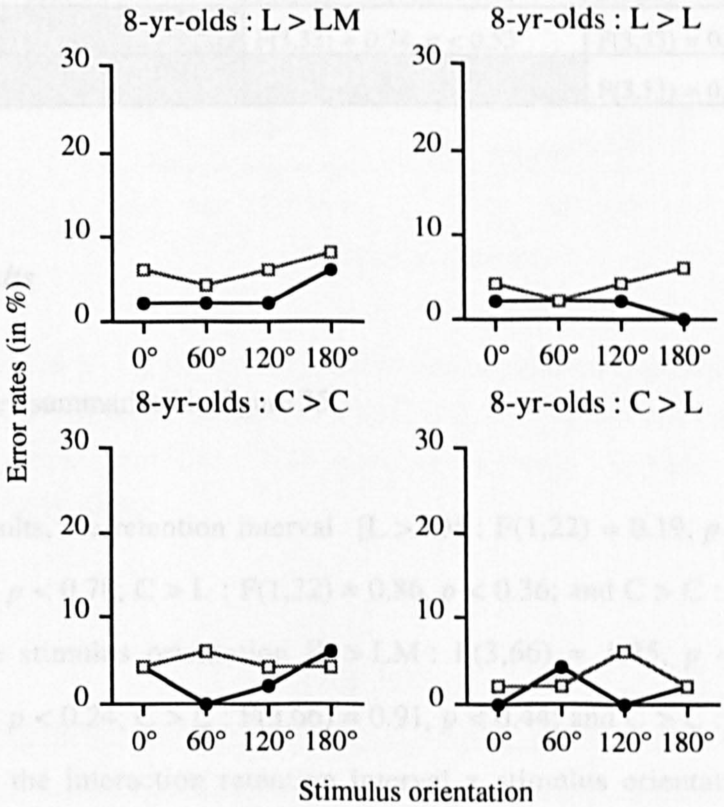


Figure 34 : Errors (in %) as a function of stimulus orientation, trial category (L > LM, L > L, C > C, C > L) and retention interval (grey line : 1000 msec; black line : 500 msec) in eight-years-old children.

TABLE 10

Interaction between trial category and stimulus orientation. Retention interval : 500 msec

	L > L	C > C	C > L
L>LM	F(3,33) = 0.67, $p < 0.57$	F(3,33) = 0.14, $p < 0.94$	F(3,33) = 0.74, $p < 0.53$
L > L		F(3,33) = 1.18, $p < 0.33$	F(3,33) = 0.79, $p < 0.51$
C > C			F(3,33) = 1.18, $p < 0.33$

Interaction between trial category and stimulus orientation. Retention interval : 1000 msec

	L > L	C > C	C > L
L>LM	F(3,33) = 0, $p < 1$	F(3,33) = 0.37, $p < 0.78$	F(3,33) = 0.41, $p < 0.74$
L > L		F(3,33) = 0.74, $p < 0.53$	F(3,33) = 0.57, $p < 0.64$
C > C			F(3,33) = 0.74, $p < 0.53$

Young adults

The results are summarised in figure 35.

In young adults, the retention interval [L > LM : F(1,22) = 0.19, $p < 0.66$; L > L : F(1,22) = 0.08, $p < 0.78$; C > L : F(1,22) = 0.86, $p < 0.36$; and C > C : F(1,22) = 0.62, $p < 0.44$], the stimulus orientation [L > LM : F(3,66) = 1.75, $p < 0.17$; L > L : F(3,66) = 1.43, $p < 0.24$; C > L : F(3,66) = 0.91, $p < 0.44$; and C > C : F(3,66) = 0.49, $p < 0.69$] and the interaction retention interval x stimulus orientation [L > LM, F(3,66) = 1.03, $p < 0.38$; L > L, F(3,66) = 0.46, $p < 0.71$, C > L, F(3,66) = 0.08, $p < 0.97$, and C > C, F(3,66) = 0.64, $p < 0.59$] did not significantly affect the performances.

The interactions between trial category and stimulus orientation are presented in table 11 for both the 500 msec and 1000 msec retention intervals.

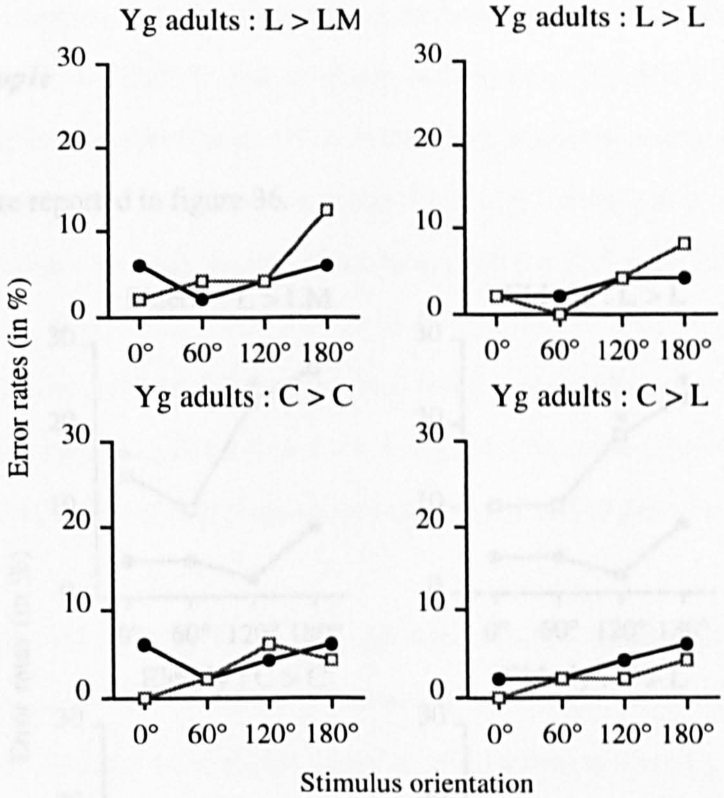


Figure 35 : Errors (in %) as a function of stimulus orientation, trial category (L > LM, L > L, C > C, C > L) and retention interval (grey line : 1000 msec; black line : 500 msec) in young adults.

TABLE 11

Interaction between trial category and stimulus orientation. Retention interval : 500 msec

	L > L	C > C	C > L
L>LM	F(3,33) = 0.21, $p < 0.89$	F(3,33) = 0, $p < 1$	F(3,33) = 0.23, $p < 0.87$
L > L		F(3,33) = 0.24, $p < 0.86$	F(3,33) = 0.12, $p < 0.95$
C > C			F(3,33) = 0.24, $p < 0.86$

Interaction between trial category and stimulus orientation. Retention interval : 1000 msec

	L > L	C > C	C > L
L>LM	F(3,33) = 0.36, $p < 0.78$	F(3,33) = 2.25, $p < 0.1$	F(3,33) = 0.67, $p < 0.57$
L > L		F(3,33) = 0.3, $p < 0.83$	F(3,33) = 0.64, $p < 0.59$
C > C			F(3,33) = 0.3, $p < 0.83$

Elderly people

The results are reported in figure 36.

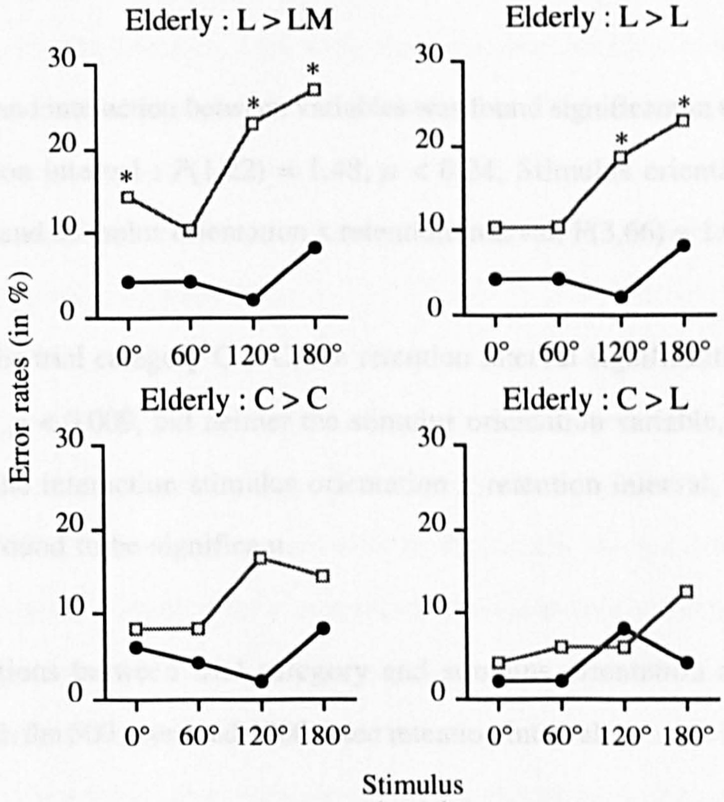


Figure 36 : Errors (in %) as a function of stimulus orientation, trial category (L > LM, L > L, C > C, C > L) and retention interval (grey line : 1000 msec; black line : 500 msec) in the elderly people.

In the trial category L > LM, errors were significantly affected by the retention interval, $F(1,22) = 23.65$, $p < 0.0001$, and the stimulus orientation, $F(3,66) = 3.35$, $p < 0.02$. The interaction retention interval x stimulus orientation, $F(3,66) = 1.93$, $p < 0.13$, did not significantly affect performance. A Tukey test ($p < 0.05$) showed a difference between the retention intervals for the 0°, 120° and 180° orientations.

In the trial category L > L, similar results were observed : Retention interval, $F(1,22) = 19.02$, $p < 0.0002$, and stimulus orientation, $F(3,66) = 3.11$, $p < 0.03$, significantly affected performance. The interaction stimulus orientation x retention interval, $F(3,66) = 1.51$, $p < 0.22$, was not significant. A Tukey test ($p < 0.05$) revealed a significant difference between the retention intervals for the 120° and 180° orientations.

No variable and interaction between variables was found significant in the trial category C > L [Retention interval : $F(1,22) = 1.48$, $p < 0.24$; Stimulus orientation, $F(3,66) = 1.33$, $p < 0.27$; and Stimulus orientation x retention interval, $F(3,66) = 1.01$, $p < 0.39$].

Finally, in the trial category C > C, the retention interval significantly affected RTs, $F(3,66) = 8.34$, $p < 0.009$, but neither the stimulus orientation variable, $F(1,22) = 0.98$, $p < 0.41$, nor the interaction stimulus orientation x retention interval, $F(3,66) = 1.38$, $p < 0.26$, was found to be significant.

The interactions between trial category and stimulus orientation are presented in table 12 for both the 500 msec and 1000 msec retention intervals.

TABLE 12

Interaction between trial category and stimulus orientation. Retention interval : 500 msec

	L > L	C > C	C > L
L>LM	$F(3,33) = 0$, $p < 1$	$F(3,33) = 0.06$, $p < 0.98$	$F(3,33) = 1.12$, $p < 0.35$
L > L		$F(3,33) = 1.35$, $p < 0.27$	$F(3,33) = 1.17$, $p < 0.33$
C > C			$F(3,33) = 1.35$, $p < 0.28$

Interaction between trial category and stimulus orientation. Retention interval : 1000 msec

	L > L	C > C	C > L
L>LM	$F(3,33) = 0.18$, $p < 0.91$	$F(3,33) = 0.54$, $p < 0.66$	$F(3,33) = 1.12$, $p < 0.35$
L > L		$F(3,33) = 0.54$, $p < 0.66$	$F(3,33) = 0.55$, $p < 0.65$
C > C			$F(3,33) = 0.54$, $p < 0.66$

In experiment 3c, subjects were confronted with four different situations. In the first situation, they had to keep in short term memory the letter L in a particular orientation, and they were then (after a retention interval of 500 msec or 1000 msec) presented with the same stimulus. In the second situation, they were first presented with the letter L and after the retention interval, they were presented with the letter L in its mirror-reversed version. In the third situation, they were presented with the letter C followed, after the retention interval, by the letter C. Finally, in the fourth situation, they were presented with the letter C, and after the retention interval, by the letter L.

Results of experiments 3a were replicated in the first and second situations, i.e. L > L and L > L mirror-reversed. When five-year-olds and elderly people had to keep the provided information in STM before the presentation of the target, the RTs were dependent on stimulus orientation. Although they received information before the presentation of the target, they had to activate a mental rotation process to discriminate between a normal versus a mirror-reversed version of the letter. In contrast, when the retention interval was reduced to 500 msec, flat functions were observed. Reducing the retention interval made them able to keep the spatial characteristics of the provided information in STM. Globally, although no statistical analyses have been carried out to compare experiments 3a and 3c, error rates were equivalent in both experiments for these experimental conditions. Younger children and the elderly performed the task poorly, especially for the larger stimulus disorientations.

Results of experiments 3a were also replicated in eight-year-olds and young adults. An effect of stimulus orientation was observed in both retention interval conditions. However, the RT slope was too slight to interpret these data as evidence for the use of a mental rotation process (see chapter two). Whatever the retention interval, they can keep the information in STM which makes mental rotations unnecessary.

It was hypothesized in the two previous experiments that these results suggest poor maintenance of spatial (orientational) information in STM before the age 5 and in elderly people.

If the orientational effects observed in experiments 3a and 3b were due to the difficulty younger children and the elderly had in keeping *spatial* information in STM, these effects should disappear when the information to be kept in STM is structurally different from the target. In fact, in this later condition, subjects should immediately notice the mismatch between the information provided and the target. The structural difference between the two stimuli makes the decision easier and, whatever the stimulus orientation, the responses should be uniformly rapid. Subjects, whatever their age, can keep the stimulus structure in STM and consequently do not need to activate a transformational process to compare the stimuli. In this condition, the stimuli are immediately recognised as being different. Indeed, it has been shown that mental rotation is not required to identify rotated letters (e.g. Eley, 1982; Corballis, Zbrodoff, Schetzer & Butler, 1978), but mental rotation is required to discriminate between normal versus mirror-reversed versions of rotated letters (Corballis, 1988). This situation corresponds to the fourth one in experiment 4b where the provided information was the letter C and the forthcoming target was the letter L.

The results tend to confirm this hypothesis. Let us first consider the performance of five-year-olds and elderly people. When the information provided and the target were structurally different, i.e. the letter C was followed by the letter L, whatever the retention interval, the RTs never reflected the use of mental rotation. The RT functions were the same in *all* subjects. Although the RTs were dependent on stimulus orientation, the RT slope was too low to provide evidence for the mental rotation process. Moreover, performances were better in this situation (C > L) than in the other situations whatever the stimulus orientation.

In eight-year-olds and in young adults, similar results were observed. They did not use mental rotation to solve the task, a fact which is not surprising since no mental rotation is required to solve such a task !

In such conditions, it seems that *all* subjects, whatever the age, immediately noticed the mismatch between the information provided and the target. As a consequence, subjects answered uniformly rapidly whatever the stimulus orientation. The very first visual processing of the target would be sufficient to observe a structural difference between the simultaneously presented stimuli. The segments composing the two letters are different: (1) The letter L is composed of one long bar and a shorter bar with a right angle at one of their extremities, (2) the letter C is composed of one long bar but *two* shorter bars also connected through right angles at their extremities with the two shorter bars pointing in the same direction. The analysis of the stimulus structure during initial visual processing allows the subjects to recognise that the presented stimuli are different in structure. In other words, these results suggest that young children and elderly people can keep structural information in STM.

CONCLUSION

Several studies have assessed mental rotation abilities in young children and in the elderly (see chapter two for a review of the literature). Although contradictory results are reported, most of the authors agree that mental rotation ability is poor in young children (usually referred as preoperational children) and in the elderly. They can carry out mental rotations but their performance is usually poorer than that of older children (older than about 8 years of age) and young adults. Several explanations have been suggested but none of them is at present completely satisfactory.

However, when the successive steps subjects have to take when confronted with a mental rotation task are considered, it seems that young children and the elderly people already encounter some difficulties during the very first steps. They are particularly poor at encoding and maintaining visuo-spatial information in short term memory. But to understand this issue, it seems that visuo-spatial short term memory should not be considered as a single system but rather as a dual system (although a correlation has been observed between memory span for visual patterns and mental rotation ability - when performance is considered across age categories - [see chapter three]).

Kosslyn (1994) and Logie and Marchetti (1991) have suggested two different but related models of visuo-spatial STM. Both of them suggest that visuo-spatial STM can be decomposed into - at least - two subsystems. Kosslyn (1994) refers to a ventral and a dorsal subsystem while Logie and Marchetti (1991) refer to a visual and a spatial subsystem (see also, Logie & Reisberg, 1992). The first subsystem (ventral or visual) would process, roughly speaking, the structural characteristics of the stimuli, while the second (dorsal or spatial) would process the spatial characteristics. The distinction between these two subsystems has been supported by neuropsychological studies (e.g. Farah, Hammond, Levine & Calvanio, 1988) as well as by connectionist modelling (Rueckl, Cave & Kosslyn, 1989).

The present experiments suggest that both young children and elderly people are poor at maintaining the spatial characteristics of a visual pattern in short term memory. Specifically, they seem to be poor at maintaining the orientation of the stimulus. If we consider both Kosslyn's (1994) and Logie's (1995) theoretical models, we might suggest that the spatial component of these models is not yet developed in young children and is affected by ageing. These results are probably related to other data reported by other authors. Koenig *et al.* (1990) have reported that young children are poor at assessing metrical distances between objects, and Hoyer (1990) has suggested that the localisation processes engaged in visual processing might be affected by ageing. However, other authors (see Ellis *et al.*, 1987) have reported that the localisation of objects would be automatically encoded and would emerge early in cognition.

Consequently, this suggests that in the domain of spatial cognition, some spatial processes could be more affected by age than others. The dorsal system - if engaged in the processing assessed in the experiments as hypothesized - should probably be decomposed into other subsystems. However, other studies are necessary to understand the genesis of the spatial analysis involved in visual processing.

Mental scanning: A life-span study[1]

While navigating in town, we sometimes have the impression of visualising the route to reach a particular shop, for instance. In such situations, we generate images and scan them to "observe" some important characteristics of the route so that we can anticipate our actions. Subjects often report the use of a mental scanning process while reading a map, navigating in complex environments, remembering details on some of Rodin's sculptures seen in the Hotel Biron during a last trip to Paris.

With the emergence of research on mental imagery in the 1970s, mental scanning began to be studied in young adults using mental chronometry as a paradigm. Classical cognitive psychology studies have been presented in the general introduction. These classical chronometrical studies have been criticised but, again, cognitive neuroscience can help to interpret the data in mental scanning.

As mentioned in chapter 1, Kosslyn (1994) recently reformulated his theory of mental imagery in the context of recent cognitive neuroscience. In his theory, image scanning has to be considered as an image transformation process.

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1 This study was done in collaboration with Dr Yannick Courbois, University Charles de Gaulle, Lille, France. It is part of a research program assessing the development of imagery abilities in normal and mentally retarded children. Normal populations are considered in our laboratory in Liège, while the French laboratory specializes in mental handicap. Several studies have been presented at different international conferences (see Courbois & Lejeune, 1994; Courbois, Lejeune & Aslani, 1995).

Experiment 4a and 4b will appear in : Lejeune, M. & Courbois, Y. L'inspection mentale de l'enfance au grand âge: données empiriques récentes. In J. Bideaud and Y. Courbois (in press), *L'image mentale et son développement*. Paris: Presses Universitaires de France.

Brandt, Stark, Hacisalihzade, Allen and Tharp (1989) showed that eye movements always accompany the visualisation of objects, and that subjects also tend to move their eyes when scanning visual images internally (Kosslyn, 1973, collected similar unpublished data - reported in Kosslyn, 1994, p. 366). Kosslyn (1994, p. 366) suggests that "most image scanning consists of recalling what one saw when actually scanning along an object, but such processing may be more common than one might suspect; people usually have the opportunity to scan an object at the time it is initially perceived".

Image scanning would then be akin to imaged saccades (although imaged saccades are not clearly defined in Kosslyn's (1994) theory, they would correspond functionally to real saccades but without any physical eye movements). However, in the classical studies mentioned before, a more continuous process was suggested by RT patterns. Kosslyn (1994) suggests that such a process might mimic what we would actually see after a head or body rotation rather than after eye movements.

Image scanning may involve two mechanisms: One that shifts the attention window (see description of Kosslyn's (1994) model in the general introduction) and one that transforms the contents of the visual buffer. This latter mechanism may rely on motor programs that ordinarily move the eyes, head or body. It replaces the contents of the visual buffer with a new representation of material that is contiguous to that in the previous representation. In this case the image would "slide" across the visual buffer.

Studies of children

If many studies have considered the development of mental rotation abilities in children (see chapter 2), very little research has been reported on the development of mental scanning.

While assessing the development of different imagery subsystems, Kosslyn, Margolis, Barret, Goldknopf and Daly (1990) studied image scanning in children. Subjects were presented with a "square ring" of boxes covering the entire computer screen (see figure 37). Three boxes in different locations at the periphery of the screen were coloured, and the centre of the screen was empty. Each trial consisted of the presentation of a pattern made of these three cells (with a different location for each trial). Subjects were required to memorise the location of the three target cells. When memorised, they pressed the space bar which resulted in the removal of the pattern. Immediately after, an X or an O appeared within one of the boxes of the square ring. When an X was displayed, subjects had to say whether the X was located in a previously coloured cell. When an O was displayed, subjects had to judge whether the cell located opposite the O on the other side of the ring was previously coloured. This latter condition was supposed to require the activation of an image scanning process while the first one should not. RTs were higher when subjects were supposed to be using a scanning process whatever the age of the subjects (five-, eight- and fourteen-year-olds). The unique difference across age categories was the scanning speed: The older the subjects were, the quicker they responded. These results were in fact also observed in other imagery tasks, especially in mental rotation tasks. These effects have been explained by the modification in efficiency of more central processes (see chapter 3).

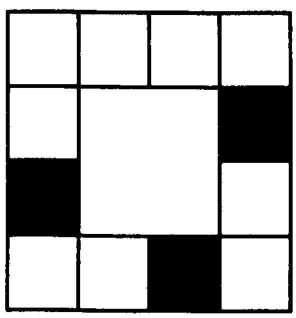

Figure 37 : "Square ring" used in the image scanning task [adapted from Kosslyn *et al.*'s (1990)].

Although interesting, this study is really too simple. Image scanning is assessed in a purely dichotomous way: Scanning or no scanning. Classical studies which assess the scanning abilities of young adults utilize different distances between the targets.

Courbois (1994) has proposed a most interesting task to assess image scanning ability in children. He modified Kosslyn *et al.* 's (1990) task: Three distances were used: No scanning, scanning over a short distance, and scanning over a long distance. Four blocks composed of two contiguous rectangles served as stimuli. Two blocks were centered at the top and the bottom of the screen (referred to as the horizontal blocks), while the two others were centered on the right side and on the left side of the screen (referred to as the vertical blocks). The distance separating the two vertical blocks was approximately twice the distance separating the two horizontal blocks. The centre of the screen was empty and three of the eight rectangles were coloured at random in blue - supposed to represent water - (different rectangles were coloured for each trial). In the *imaginal condition*, subjects (five and eight-year-olds) were required to press the space bar after memorising the location of the coloured rectangles. Once the space bar was depressed, the rectangles emptied and the "water" was replaced by a fish or a fisherman. When a fish was presented, subjects had to decide whether the fish was in a previously filled rectangle. When a fisherman was presented, subjects had to judge whether the rectangle on the opposite side had been filled in. In a *control condition*, the rectangles were not emptied when the fish or the fisherman was displayed.

Courbois (1994) reported that RTs were significantly longer in the control condition than in the imaginal condition in all age categories. Moreover, RTs were longer in younger children - an effect also reported in Kosslyn *et al.*'s (1990) study. In addition, scanning times were significantly affected by the distance. But complementary analysis showed that distance affected RTs more clearly in the imaginal condition, and that the difference between RTs in both conditions is smaller for a short distance than for a long distance. Performance (error rates) was significantly better in eight-year-olds, but was affected by distance in all age categories.

Although distance affected RTs in the imaginal condition, Courbois (1994) suggests that his data do not validate an image scanning hypothesis. Indeed, the increase of RTs between short scanning and long scanning was less important in the imaginal condition than in the case of the perceptual control. Although scanning times were dependent on the scanned distance, the speed at which the attentional window was moved was identical (or even quicker) than the rate at which a visual pattern was scanned. According to Courbois (1994), such results could be explained if we consider that mental scanning is not imaginal but simply perceptual. Subjects would move their eyes to the cells on the opposite side of the fisherman and would respond on the basis of memory traces of the target cells.

In summary, only two studies have been reported so far. However, conflicting results are observed from the studies. The task difficulty would possibly explain the differences between these two studies.

Studies of elderly people

Only one study (Dror & Kosslyn, 1994) assessed mental scanning abilities in the elderly. However, given that many studies have suggested that mental imagery and visual perception share many mechanisms (see Farah, 1988; Finke and Shepard, 1986), it might be reasonable to consider with interest the results reported by Folk and Hoyer (1992) which suggest that the ability to scan a perceptual image is not affected by ageing.

Dror and Kosslyn (1994) presented elderly people (mean age: 63 - which is not very old!) and young adults with a square ring of boxes with three cells filled in black. Subjects were required to memorise the location of these cells. Once memorised, they press the space bar which resulted in a brief display (50 msec) of an arrow followed by the removal of the pattern. The arrow pointed to one cell (that was possibly previously filled in) and the distance between the arrow and the cell could be zero, medium (1.2 cm) or long (2.1 cm). Subjects were required to judge as quickly as possible whether the arrow pointed to a previously filled cell. Results showed that scanning times increased with distance in the same way in both groups. Similarly, the overall level of performance was similar in both groups. It appears that mental scanning ability seems to be preserved with ageing.

Conclusion

Although it is difficult to draw accurate conclusions on the basis of three developmental studies, all of them showed significant effect of distance on scanning times in young children and elderly. However, if the distance effect can be associated with a mental scanning process in the elderly, it might be that another interpretation should be given to the results reported in the child studies: the distance effect could be interpreted in terms of activation of visual perception processes (specifically, eye movements).

EXPERIMENT 4a

Experiment 4a was designed to assess mental scanning ability from childhood to old age. Five and eight-year-olds, young adults and elderly people were tested using the same task. The task is based on a research done by Dror and Kosslyn (1994) and Finke and Pinker (1982) -see above. Three patterns (fish) appeared at the periphery of the computer screen. Subjects were required to memorise the exact location of the fish. Once this was memorised, they pressed the space bar which resulted in the removal of the fish. Immediately after, an arrow was presented for 200 msec. The arrow pointed to a previously presented fish or somewhere else. Subjects were required to judge as quickly as possible whether or not the arrow pointed to a previously presented target.

Two versions of the task were used: A mental scanning task and a perceptual control (the fish were displayed on the screen at the same time as the arrow). Moreover, the effect on subjects' performance of irrelevant information during image scanning was tested. An animated mask filled the screen while the subjects were supposed to be scanning the image.

RTs serve as indicators which test the use of a mental scanning process. A significant increase of RTs with distance in both experimental conditions was expected. Moreover, it was hypothesized that the irrelevant information should not affect the performance of young adults but should affect the ability of young children to scan a mental image.

METHOD

Subjects

Four groups of subjects were tested: 48 5-year-olds (mean age: 5 years 1 month, ranged from 4 years 9 months to 5 years 3 months), 48 8-year-olds (mean age: 8 years 2 months, ranged from 7 years 9 months to 8 years 3 months), 48 young adults (mean age: 24 years, ranged from 19 years old to 32 years olds), and 48 elderly people (mean age: 73 years, ranged from 65 to 80 years of age). Gender was not controlled.

All subjects were volunteers. The children (5 and 8-year-olds) were recruited in several public and private schools in the surroundings of Liège and Brussels, Belgium. The young adults were all students or staff members of the Department of Psychology at the University of Liège. The elderly people came from several sources (private contacts, leisure clubs, or old people's home), all in the Liège area.

No subject suffered or had suffered from a neurological disease.

Material

A 4 X 5 invisible grid covered the entire surface of the computer screen. Three cells in the perimeter were filled in with a fish pattern at random on each trial. When the space bar was pressed, an arrow was displayed for a period (different for the two tests - see below). The arrow was presented in one of the matrix cells but never in the cells composing the screen borders. The arrow was oriented at 0°, 45° or multiple of 45°, and could be presented at three distances from the target (short, medium and long). The arrow could point either to one of the fish or anywhere else. Twenty four trials were administered, half with the arrow pointing to a fish, and half with the arrow pointing somewhere else. Subjects were required to say whether the arrow pointed to a fish. We expected YES responses for half the trials and NO for the other half. The trial ordering was random.

Two tests were used: (1) an imagery test, and (2) a perceptual control. In the imagery test, the fish were immediately removed before a 200 msec presentation of the arrow. In the perceptual control, the fish and the arrow were presented until the subject responded.

Two versions of each test were used, labelled : (1) NOMASK, and (2) ANIMASK. In the NOMASK version, the screen remained empty after the removal of the fish and the arrow in the imagery test, and the presentation of the fish and the arrow in the perceptual control. In the ANIMASK version, circles successively invaded the screen at high speed after the display/removal of the targets and the arrow.

All the situations are represented in figure 38.

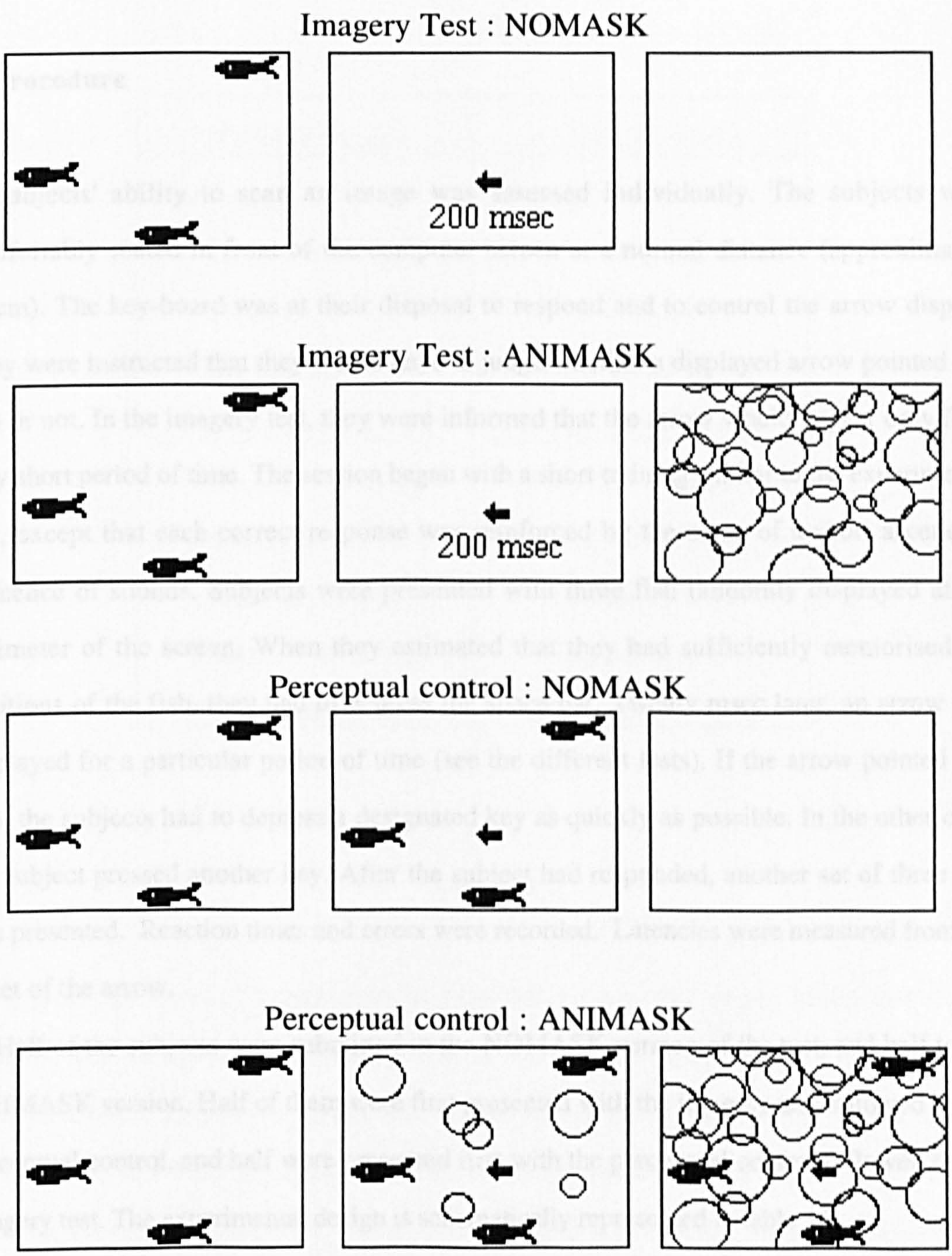

Figure 38 : Schematic representation of the experimental situations : Imagery tests and perceptual control

Procedure

Subjects' ability to scan an image was assessed individually. The subjects were comfortably seated in front of the computer screen at a normal distance (approximately 50 cm). The key-board was at their disposal to respond and to control the arrow display. They were instructed that they would have to judge whether a displayed arrow pointed to a fish or not. In the imagery test, they were informed that the arrow would appear only for a very short period of time. The session began with a short training similar to the experimental test, except that each correct response was reinforced by the onset of a short ascending sequence of sounds. Subjects were presented with three fish randomly displayed at the perimeter of the screen. When they estimated that they had sufficiently memorised the positions of the fish, they had to depress the space bar. Twenty msec later, an arrow was displayed for a particular period of time (see the different tests). If the arrow pointed at a fish, the subjects had to depress a designated key as quickly as possible. In the other case, the subject pressed another key. After the subject had responded, another set of three fish was presented. Reaction times and errors were recorded. Latencies were measured from the onset of the arrow.

Half of the subjects were submitted to the NOMASK version of the test, and half to the ANIMASK version. Half of them were first presented with the imagery test followed by the perceptual control, and half were presented first with the perceptual control followed by the imagery test. The experimental design is schematically represented in table 13.

TABLE 13

NOMASK version	ANIMASK version
Imagery > Perc. Ctrl	*Imagery > Perc. Ctrl*
5-yr-olds: n = 12	5-yr-olds: n = 12
8-yr-olds: n = 12	8-yr-olds: n = 12
Young adults: n = 12	Young adults: n = 12
Elderly people: n = 12	Elderly people: n = 12
Perc. Ctrl > Imagery	*Perc. Ctrl > Imagery*
5-yr-olds: n = 12	5-yr-olds: n = 12
8-yr-olds: n = 12	8-yr-olds: n = 12
Young adults: n = 12	Young adults: n = 12
Elderly people: n = 12	Elderly people: n = 12

RESULTS

Analyses of variance included age (5 year-olds, 8 year-olds, young adults, and elderly people), tests (imagery *versus* perceptual control; in brief : IMA and PER), test versions (with or without an animated mask after the display of the arrow; in brief : NOMASK or ANIMASK), test order (imagery test followed by the perceptual control, or *vice versa*; in brief : IMA-PER and PER-IMA), and the scanning distance (short, medium, and long) as independent variables. The scanning distance and test variables were within subject variables, and the other variables were between subjects variables. Response times (RT) and errors served as dependent variables. As the distance to scan is only clearly defined when the arrow points to the target, only these trials have been analysed for the purpose of this experiment. Response times were submitted to analyses of variance (ANOVA) after the removal of outliers, i.e. RT greater than 10 seconds and those exceeding 2 S.D. from the mean cell.

Response times

Results are reported in figure 39. A global ANOVA revealed a significant effect of Age, F(3,137) = 85.89, Test order, F(1,137) = 7.44, Test version, F(1,137) = 77.52, and Distance, F(2,274) = 30.74, all with $p < 0.05$. Similarly, the interactions Test version x Age, F(3,137) = 20.89, Test version x Test order, F(1,137) = 7.87, Distance x Age, F(6,274) = 2.66, Distance x Test version, F(2,274) = 2.95, Distance x Test order, F(2,274) = 3.39, Distance x Age x Test order, F(6,274) = 3.7, and Distance x Age x Test versions x Test order, F(6,274) = 3.83, were significant with $p < 0.05$.

Imagery test

Subjects in four age categories performed the tests at a significantly different speed, F(3,141) = 78.77, $p < 0.0001$, and the RTs were differently affected by the scanning distance (interaction age x distance, F(6,282) = 2.17, $p < 0.05$) as well as when considered in interaction with the test versions, the scanning distance and the test order (interaction age x distance x test version x test order, F(6,282) = 3.85, $p < 0.001$). A global significant effect of distance was also observed, F(2,282) = 17.62, $p < 0.0001$, and the scanning distance interacted significantly with the test version and the test order, F(2,282) = 3.67, $p < 0.03$.

The other variables or interactions between variables did not significantly affect the reaction times [test version : F(1,141) = 0.74, $p < 0.39$; test order : F(1,141) = 3.48, $p < 0.06$; age x test version : F(3,141) = 0.23, $p < 0.88$; age x test order : F(3,141) = 1.06, $p < 0.37$; test version x test order : F(1,141) = 0.14, $p < 0.71$; age x test version x test order : F(3,141) = 1.7, $p < 0.17$; distance x test version : F(2,282) = 2.83,

$p < 0.06$; distance x age x test version : $F(6,282) = 0.7$, $p < 0.65$; distance x test order : $F(2,282) = 0.77$, $p < 0.47$; and distance x age x test order : $F(6,282) = 1.55$, $p < 0.16$].

The age categories behaved differently in the ANIMASK version of the test. In this case, RTs were globally different between the age categories, $F(3,66) = 32.07$, $p < 0.0001$. No other significant effect was observed [test order : $F(1,66) = 0.58$, $p < 0.45$; age x test order : $F(3,66) = 0$, $p < 1$; distance x age : $F(6,132) = 0.3$, $p < 0.94$; distance x test order : $F(2,132) = 1.69$, $p < 0.18$; and distance x age x test order : $F(6,132) = 1$, $p < 0.43$].

In the NOMASK version, age significantly affected the RTs, $F(3,75) = 48.66$, $p < 0.0001$, and interacted with the order, $F(3,75) = 3.36$, $p < 0.02$, with the distance, $F(6,150) = 2.13$, $p < 0.05$, and with the distance combined with the order, $F(6,150) = 3.75$, $p < 0.002$. No significant effect of the test order was observed when considered independently of the other variables, $F(1,75) = 3.44$, $p < 0.07$, nor when considered in interaction with distance, $F(2,150) = 2.58$, $p < 0.08$.

Consequently, complementary ANOVAs have been computed for each age category considered separately. In the five year-olds, RTs were a function of the scanned distance, $F(2,62) = 4.54$, $p < 0.01$, but the functions were different in the two test versions when considered in interaction with the test order (interaction distance x test version x test order, $F(2,62) = 3.95$, $p < 0.02$). The effects of the scanned distance in the different experimental situations are reported in table 14. As it appeared, when the children were submitted to the imagery test before the perceptual control (IMA-PER), the RT functions were independent of the scanned distance. However, in the other situation (PER-IMA), RTs were influenced by the scanned distance when no animated mask (ANIMASK) was displayed after the arrow presentation. No other significant effect was observed in the five-year-olds [test version : $F(1,31) = 0.05$, $p < 0.83$; test order : $F(1,31) = 1.71$, $p < 0.2$; test version x test order : $F(1,31) = 1.23$, $p < 0.28$; distance x test version : $F(2,62) = 1.01$, $p < 0.37$; and distance x test order : $F(2,62) = 1.23$, $p < 0.3$].

In the eight year-olds, RTs were significantly different in the two test versions (NOMASK *versus* ANIMASK), $F(1,38) = 4.41$, $p < 0.04$, and they changed as a function of the scanned distance, $F(2,76) = 13.25$, $p < 0.0001$. As the test order did not significantly affect the results, $F(1,38) = 1.62$, $p < 0.21$, and did not interact with other variables [test order x test version : $F(1,38) = 0.82$, $p < 0.37$; test order x distance : $F(2,76) = 0.25$, $p < 0.78$; test order x test version x distance : $F(2,76) = 0.62$, $p < 0.54$], the two subgroups being submitted to the tests in a different order were grouped together. As presented in table 14 and in figure 39, RTs were significantly influenced by the scanned distance in all the experimental situations. This was also confirmed by the absence of a significant effect for the interaction between the distance and test version variables, $F(2,76) = 1.67$, $p < 0.2$.

In the young adults, the scanned distance significantly influenced the RTs, $F(2,72) = 17.04$, $p < 0.0001$, but this influence was different in the two test versions (interaction distance x test version, $F(2,72) = 3.79$, $p < 0.03$) although the test version itself did not significantly affect the RTs, $F(1,36) = 1.22$, $p < 0.28$. However, RTs were dependent on the scanned distance in all the experimental situations (see table 14). Results are displayed on figure 39. As for the eight year old children, all the young adults were combined for these complementary analyses; no order effect was observed [test order : $F(1,36) = 0.85$, $p < 0.36$; test order x test version : $F(1,36) = 1.09$, $p < 0.3$; test order x distance : $F(2,72) = 0.17$, $p < 0.84$; test order x distance x test version : $F(2,72) = 0.49$, $p < 0.61$].

Finally, in the elderly people, RTs were significantly influenced by the scanned distance, $F(2,72) = 6.8$, $p < 0.002$. However, complementary analyses showed that the effect of the scanned distance disappeared in the ANIMASK version of the test (see table 14 and figure 39). As for young adults and eight-year-olds, no single or combined effect of test order was observed [test order : $F(1,36) = 0.02$, $p < 0.88$; test order x test version : $F(1,36) = 1.11$, $p < 0.3$; test order x distance : $F(2,72) = 2.4$, $p < 0.1$; test order x distance x test version :

F(2,72) = 0.22, $p < 0.8$]. In addition, no global difference on RTs was observed between test versions, F(1,36) = 0.01, $p < 0.94$, and test version did not significantly interact with distance, F(2,72) = 1.15, $p < 0.32$.

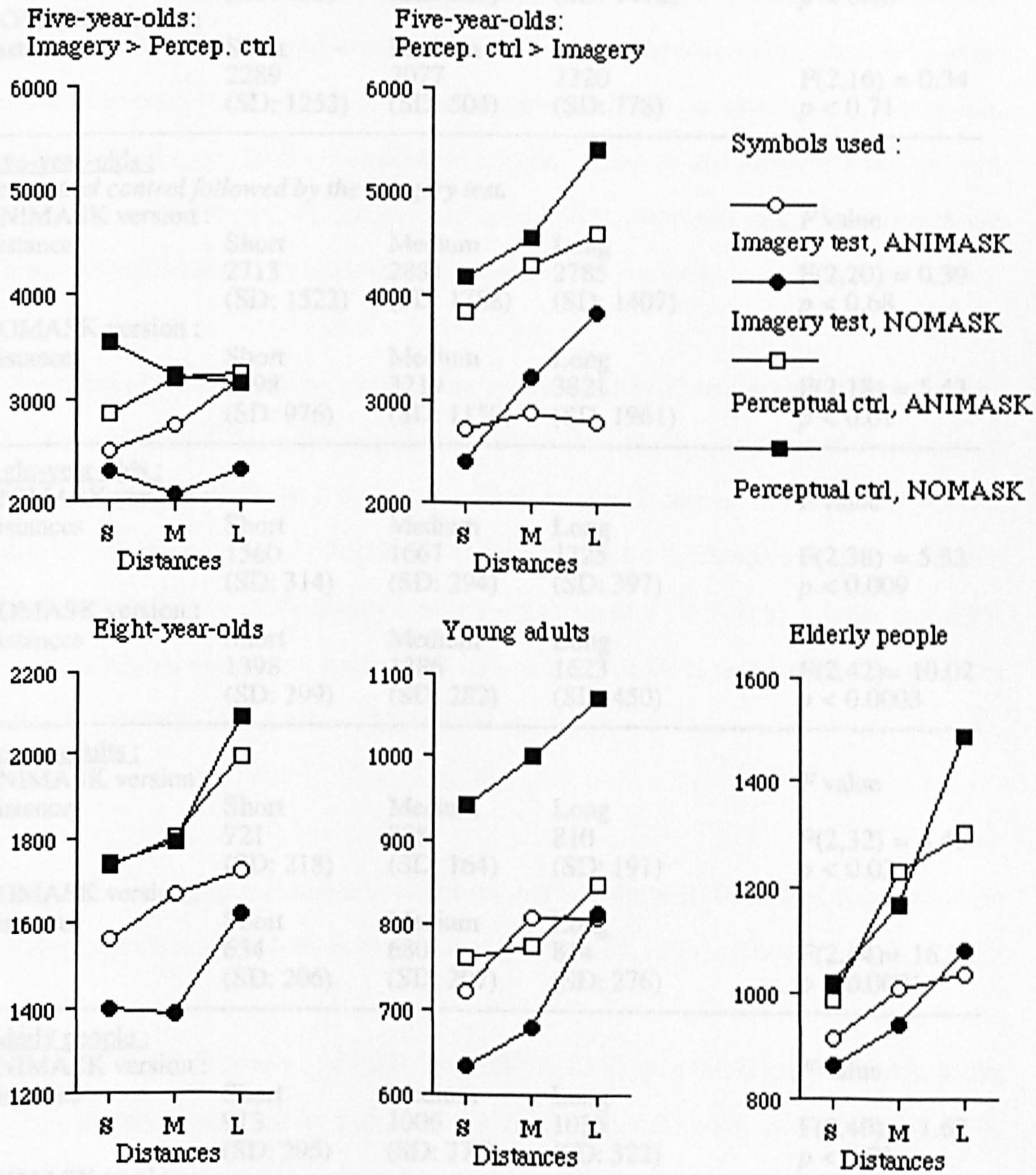

Figure 39 : Reaction times as a function of distance (S = short; M = medium; L = long) in the four age categories in the different experimental conditions (Imagery test and perceptual control, with - ANIMASK - or without - NOMASK - an animated mask) - see symbols used in the right corner of the figure.

TABLE 14

Effect of scanned distance on RTs in msec in the Imagery test

Five-year-olds :

Imagery test followed by the perceptual control.

				F value
ANIMASK version :				
Distances	Short	Medium	Long	
	2497	2735	3198	F(2,8) = 0.81
	(SD: 488)	(SD: 569)	(SD: 1472)	*p* < 0.48
NOMASK version :				
Distances	Short	Medium	Long	
	2289	2077	2320	F(2,16) = 0.34
	(SD: 1253)	(SD: 504)	(SD: 778)	*p* < 0.71

Five-year-olds :

Perceptual control followed by the imagery test.

				F value
ANIMASK version :				
Distances	Short	Medium	Long	
	2713	2881	2785	F(2,20) = 0.39
	(SD: 1522)	(SD: 1788)	(SD: 1407)	*p* < 0.68
NOMASK version :				
Distances	Short	Medium	Long	
	2398	3219	3821	F(2,18) = 5.43
	(SD: 976)	(SD: 1158)	(SD: 1961)	*p* < 0.01

Eight-year-olds :

				F value
ANIMASK version :				
Distances	Short	Medium	Long	
	1560	1667	1725	F(2,38) = 5.33
	(SD: 314)	(SD: 294)	(SD: 397)	*p* < 0.009
NOMASK version :				
Distances	Short	Medium	Long	
	1398	1386	1623	F(2,42)= 10.02
	(SD: 299)	(SD: 282)	(SD: 450)	*p* < 0.0003

Young adults :

				F value
ANIMASK version :				
Distances	Short	Medium	Long	
	721	808	810	F(2,32) = 4.46
	(SD: 218)	(SD: 164)	(SD: 191)	*p* < 0.02
NOMASK version :				
Distances	Short	Medium	Long	
	634	680	814	F(2,44)= 16.15
	(SD: 206)	(SD: 207)	(SD: 276)	*p* < 0.0001

Elderly people :

				F value
ANIMASK version :				
Distances	Short	Medium	Long	
	913	1006	1035	F(2,40) = 1.62
	(SD: 295)	(SD: 377)	(SD: 322)	*p* < 0.21
NOMASK version :				
Distances	Short	Medium	Long	
	863	942	1082	F(2,36) = 7.67
	(SD: 473)	(SD: 506)	(SD: 647)	*p* < 0.002

Perceptual control

Patterns of response in the four age categories were different, $F(3,143) = 76.67$, $p < 0.0001$, but the differences depended on the test order (interaction age x order, $F(3,143) = 3.32$, $p < 0.02$) and when the effect of age was combined with the effects of the scanned distance and the test order (interaction age x distance x test order, $F(6,286) = 3.43$, $p < 0.003$). In addition, a global effect of test order, $F(1,143) = 7.15$, $p < 0.008$, and of distance, $F(2,286) = 23.2$, $p < 0.0001$, was observed. The distance also interacted significantly with test order, $F(2,286) = 3.29$, $p < 0.04$.

No effect of other variables or interaction between variables was observed [test version : $F(1,143) = 0.4$, $p < 0.53$; age x test version : $F(3,143) = 0.38$, $p < 0.76$; test version x test order : $F(1,143) = 0.22$, $p < 0.64$; age x test version x test order : $F(3,143) = 0.27$, $p < 0.85$; distance x age : $F(6,286) = 1.73$, $p < 0.11$; distance x test version : $F(2,286) = 0.93$, $p < 0.39$; distance x age x test version : $F(6,286) = 0.48$, $p < 0.83$; distance x test version x test order : $F(2,286) = 0.5$, $p < 0.61$; and distance x age x test version x test order : $F(6,286) = 1.65$, $p < 0.13$].

The effect of age was observed both in the ANIMASK and NOMASK versions of the test, respectively with $F(3,68) = 44.19$, and $F(3,75) = 35.21$ ($p < 0.0001$).

In the NOMASK version, distance, $F(2,150) = 10.47$, $p < 0.0001$, and the interaction age x distance x test order, $F(6,150) = 3.78$, $p < 0.002$, were also observed to be significant. No other effect was observed in this version of the test [test order : $F(1,75) = 2.6$, $p < 0.11$; age x test order, $F(3,75) = 2.28$, $p < 0.09$; distance x age : $F(6,150) = 0.64$, $p < 0.7$; and distance x test order : $F(2,150) = 2.49$, $p < 0.09$].

In the ANIMASK version, a global effect of test order, $F(1,68) = 5.33$, $p < 0.02$, and distance, $F(2,136) = 15.39$, $p < 0.0001$, was observed. The interaction between age and distance almost reached significance, $F(6,136) = 1.98$, $p < 0.07$. No other significant effect was observed [age x test order : $F(3,68) = 1.13$, $p < 0.34$; distance x test order : $F(2,136) = 0.9$, $p < 0.41$; and distance x age x test order : $F(6,136) = 0.43$, $p < 0.86$].

To understand the psychological meaning of these statistical analyses, several ANOVAs were computed on the age categories separately. In the Five year-olds, RTs were globally influenced by the test order, $F(1,34) = 4.68$, $p < 0.04$, and by the scanned distance, $F(2,68) = 4.38$, $p < 0.02$. In addition, the interaction distance x order was significant, $F(2,68) = 3.88$, $p < 0.03$. Table 15 shows that the scanned distance affected the RTs both when the perceptual control was performed before the imagery test and when no mask was displayed after the presentation of the arrow. Means are shown in figure 39. Test version, $F(1,34) = 0.25$, $p < 0.62$, test version x test order, $F(1,34) = 0.18$, $p < 0.67$, distance x test version, $F(2,68) = 0.48$, $p < 0.62$, and distance x test version x test order, $F(2,68) = 1.49$, $p < 0.23$, did not significantly affect RTs.

In the Eight year-olds, RTs were significantly affected by the scanned distance, $F(2,76) = 20.99$, $p < 0.0001$. The effect of the scanned distance was identical in each experimental situation (see table 15 and figure 39). For these analyses, all eight-year-old subjects were grouped [no test order effect : $F(1,38) = 0.02$, $p < 0.89$; test order x test version : $F(1,38) = 1.48$, $p < 0.23$; test order x distance : $F(2,76) = 1.59$, $p < 0.21$; test order x test version x distance : $F(2,76) = 0.68$, $p < 0.51$]. Moreover, no effect of test version, $F(2,38) = 0.26$, $p < 0.61$, and of the interaction test version x distance, $F(2,76) = 0.61$, $p < 0.54$, was observed.

TABLE 15

Effect of scanned distance on RTs in msec in the Perceptual control

<u>Five-year-olds :</u>

Imagery test followed by the perceptual control.

				F value
ANIMASK version :				
Distances	Short	Medium	Long	
	2849	3196	3254	F(2,14) = 1.53
	(SD: 696)	(SD: 597)	(SD: 717)	*p* < 0.25
NOMASK version :				
Distances	Short	Medium	Long	
	3546	3227	3142	F(2,16) = 0.39
	(SD: 2789)	(SD: 1222)	(SD: 1388)	*p* < 0.68

<u>Five-year-olds :</u>

Perceptual control followed by the imagery test.

				F value
ANIMASK version :				
Distances	Short	Medium	Long	
	3835	4277	4597	F(2,20) = 3.16
	(SD: 1725)	(SD: 1945)	(SD: 2183)	*p* < 0.06
NOMASK version :				
Distances	Short	Medium	Long	
	4179	4559	5403	F(2,18) = 6.04
	(SD: 2236)	(SD: 1897)	(SD: 2851)	*p* < 0.009

<u>Eight-year-olds :</u>

				F value
ANIMASK version :				
Distances	Short	Medium	Long	
	1737	1803	1994	F(2,38) = 6.19
	(SD: 592)	(SD: 499)	(SD: 603)	*p* < 0.005
NOMASK version :				
Distances	Short	Medium	Long	
	1744	1791	2095	F(2,42) = 16.18
	(SD: 292)	(SD: 356)	(SD: 397)	*p* < 0.0001

<u>Young adults :</u>

				F value
ANIMASK version :				
Distances	Short	Medium	Long	
	760	774	849	F(2,32) = 5.72
	(SD: 228)	(SD: 192)	(SD: 259)	*p* < 0.008
NOMASK version :				
Distances	Short	Medium	Long	
	941	1001	1072	F(2,44) = 5.48
	(SD: 280)	(SD: 343)	(SD: 352)	*p* < 0.008

<u>Elderly people :</u>

				F value
ANIMASK version :				
Distances	Short	Medium	Long	
	987	1229	1303	F(2,38) = 10.96
	(SD: 463)	(SD: 723)	(SD: 668)	*p* < 0.0002
NOMASK version :				
Distances	Short	Medium	Long	
	1019	1164	1486	F(2,36) = 7.47
	(SD: 288)	(SD: 499)	(SD: 783)	*p* < 0.002

In the young adults, the test versions, the test order, as well as the scanned distance significantly influenced the RTs, with $F(1,36) = 6.99$, $F(1,36) = 8.72$, and $F(2,72) = 9.44$ respectively, all with $p < 0.05$. However, as the test order did not interact with the other variables [test order x test version : $F(1,36) = 1.53$, $p < 0.22$; test order x distance : $F(2,72) = 0.24$, $p < 0.78$; test order x distance x test version, $F(2,72) = 0.11$, $p < 0.89$], we grouped the young adults all together. RTs were significantly influenced by the scanned distance in all the experimental situations (see table 15 and figure 39) - a fact also suggested by the absence of significant effect of the interaction distance x test version, $F(2,72) = 0.46$, $p < 0.63$.

Finally, in the elderly people, RTs were affected by the scanned distance, $F(2,70) = 15.55$, $p < 0.0001$. This effect was present in each experimental situation (see table 15 and figure 39). No other significant effect was observed [test version : $F(1,35) = 0.37$, $p < 0.55$; test order : $F(1,35) = 0.38$, $p < 0.54$; test version x test order : $F(1,35) = 0$, $p < 1$; distance x test version : $F(2,70) = 1.23$, $p < 0.3$; distance x test order : $F(2,70) = 0.31$, $p < 0.74$; and distance x test version x test order : $F(2,70) = 0.6$, $p < 0.55$].

Errors

Results are reported in figure 40. We carried out a repeated measures ANOVA on errors for the different experimental tests with age (5-year-olds, 8-year-olds, young adults and elderly people), distance (short, medium and large), test version (ANIMASK and NOMASK), and order of condition (Ima > Percep. ctrl and Percep. ctrl > Ima) as independent variables.

Imagery test

ANOVAs showed that subjects from the different age categories performed the test differently, $F(3,175) = 15.35$, $p < 0.0001$. Moreover, errors were different in the two test versions, $F(1,175) = 10.27$, $p < 0.002$, and were affected by the scanned distance, $F(2,350) = 19.86$, $p < 0.0001$. In some age categories, it appeared that test order affected the performances: age x test order, $F(3,175) = 3.14$, $p < 0.03$.

No other significant effect was observed [age x test version : $F(3,175) = 0.86$, $p < 0.46$; test order : $F(1,175) = 0$, $p < 0.99$; test version x test order : $F(1,175) = 1.21$, $p < 0.27$; age x test version x test order : $F(3,175) = 0.23$, $p < 0.88$; distance x age : $F(6,350) = 0.96$, $p < 0.45$; distance x test version : $F(2,350) = 1.12$, $p < 0.33$; distance x age x test version : $F(6,350) = 0.63$, $p < 0.71$; distance x test order : $F(2,350) = 1.12$, $p < 0.33$; distance x age x test order : $F(6,350) = 0.97$, $p < 0.44$; distance x test version x test order : $F(2,350) = 0.95$, $p < 0.39$; and distance x age x test version x test order : $F(6,350) = 0.43$, $p < 0.86$].

Differences across age categories were observed in both test versions: ANIMASK version, $F(3,88) = 8.42$, $p < 0.0001$, and NOMASK version, $F(3,87) = 7.8$, $p < 0.0001$. Similarly, a global significant effect of distance was observed in the ANIMASK, $F(2,176) = 12.46$, $p < 0.0001$, and in the NOMASK version, $F(2,174) = 7.91$, $p < 0.0005$.

The other variables or interaction between variables did not affect performance in the ANIMASK version [test order : $F(1,88) = 0.65$, $p < 0.42$; age x test order : $F(3,88) = 2.22$, $p < 0.09$; distance x age : $F(6,176) = 0.19$, $p < 0.98$; distance x test order: $F(2,176) = 1.8$, $p < 0.17$; distance x age x test order : $F(6,176) = 0.78$, $p < 0.59$], and in the NOMASK version [test order : $F(1,87) = 0.56$, $p < 0.46$; age x test order :

$F(3,87) = 1.18$, $p < 0.32$; distance x age : $F(6,174) = 1.6$, $p < 0.15$; distance x test order : $F(2,174) = 0.03$, $p < 0.97$; distance x age x test order : $F(6,174) = 0.61$, $p < 0.72$].

Complementary analyses were carried out on each age category separately. In Five-year-olds, performance was globally affected by the distance, $F(2,88) = 5.02$, $p < 0.009$. However, when the test versions were considered separately, this effect disappeared. No other significant effect was observed in this age category [test version : $F(1,44) = 1.82$, $p < 0.18$; test order : $F(1,44) = 2.06$, $p < 0.16$; test version x test order : $F(1,44) = 0.35$, $p < 0.56$; distance x test version : $F(2,88) = 0.27$, $p < 0.76$; distance x test order : $F(2,88) = 0.04$, $p < 0.96$; distance x test version x test order : $F(2,88) = 0.16$, $p < 0.86$].

In eight-year-olds, performance was globally different in the two test versions, $F(1,43) = 12.29$, $p < 0.001$. However, neither the distance, $F(2,86) = 2.38$, $p < 0.1$, nor the test order, $F(1,43) = 1.98$, $p < 0.17$, significantly affected performance. In addition, they did not interact with other variables [test version x test order : $F(1,43) = 2.24$, $p < 0.14$; distance x test version : $F(2,86) = 0.54$, $p < 0.58$; distance x test order : $F(2,88) = 0.54$, $p < 0.58$; distance x test version x test order : $F(2,86) = 1.5$, $p < 0.23$].

In young adults, errors were influenced by the test version, $F(1,44) = 10.65$, $p < 0.002$, and the distance, $F(2,88) = 4.85$, $p < 0.01$. Complementary analyses showed that the distance effect was only present in the ANIMASK version of the test whatever the test order, $F(2,46) = 5.34$, $p < 0.008$. No other variables or interaction between variables significantly affected performance [test order : $F(1,44) = 1.01$, $p < 0.32$; test version x test order : $F(1,44) = 0.25$, $p < 0.62$; distance x test version : $F(2,88) = 2.43$, $p < 0.09$; distance x test order : $F(2,88) = 0.6$, $p < 0.55$; distance x test version x test order : $F(2,88) = 0.69$, $p < 0.5$].

[redacted]

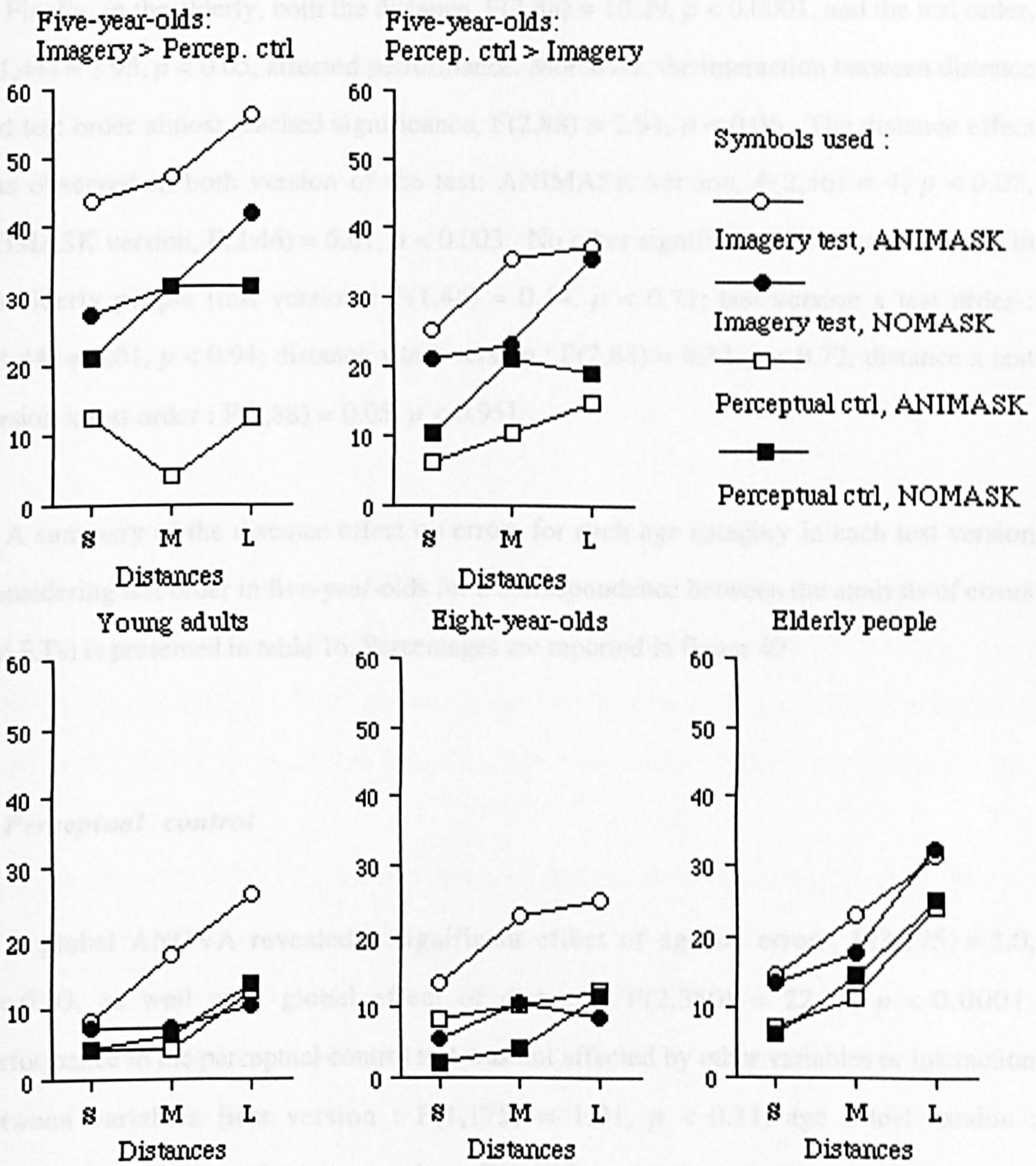

Figure 40 : Errors (in percents) as a function of distance (S = short; M = medium; L = long) in the four age categories in the different experimental conditions (Imagery Test and perceptual control, with - ANIMASK - or without - NOMASK - an animated mask) - see symbols used in the right corner of the figure.

Finally, in the elderly, both the distance, F(2,88) = 10.29, $p < 0.0001$, and the test order, F(1,44) = 3.95, $p < 0.05$, affected performance. Moreover, the interaction between distance and test order almost reached significance, F(2,88) = 2.91, $p < 0.06$. The distance effect was observed in both version of the test: ANIMASK version, F(2,46) = 4, $p < 0.03$, NOMASK version, F(2,46) = 6.61, $p < 0.003$. No other significant effect was observed in the elderly people [test version : F(1,44) = 0.14, $p < 0.71$; test version x test order : F(1,44) = 0.01, $p < 0.94$; distance x test version : F(2,88) = 0.32, $p < 0.72$; distance x test version x test order : F(2,88) = 0.05, $p < 0.95$].

A summary of the distance effect on errors for each age category in each test version (considering test order in five-year-olds for a correspondence between the analysis of errors and RTs) is presented in table 16. Percentages are reported in figure 40.

Perceptual control

A global ANOVA revealed a significant effect of age on errors, F(3,175) = 3.0, $p < 0.03$, as well as a global effect of distance, F(2,350) = 22.72, $p < 0.0001$. Performance in the perceptual control test was not affected by other variables or interaction between variables [test version : F(1,175) = 1.01, $p < 0.31$; age x test version : F(3,175) = 1.82, $p < 0.14$; test order : F(1,175) = 0.5, $p < 0.48$; age x test order : F(3,175) = 0.23, $p < 0.87$; test version x test order : F(1,175) = 0.49, $p < 0.48$; age x test version x test order : F(3,175) = 0.43, $p < 0.73$; distance x age : F(6,350) = 1.7, $p < 0.12$; distance x test version : F(2,350) = 1.31, $p < 0.27$; distance x age x test version : F(6,350) = 0.56, $p < 0.76$; distance x test order : F(2,350) = 1.18, $p < 0.31$; distance x age x test order : F(6,350) = 1.86, $p < 0.09$; distance x test version x test order :

$F(2,350) = 1.73$, $p < 0.18$; distance x age x test version x test order : $F(6,350) = 1.47$, $p < 0.19$].

In the ANIMASK version of the test, the scanned distance significantly influenced error rates, $F(2,176) = 9.8$, $p < 0.0001$. Moreover, a complex interaction between independent variables also appeared to be significant: distance x age x test order, $F(6,176) = 2.68$, $p < 0.02$. This effect will be decomposed in further analyses. No other significant effect was observed in this test version [age : $F(3,88) = 0.76$, $p < 0.52$; test order : $F(1,88) = 0$, $p < 1$; age x test order : $F(3,88) = 0.08$, $p < 0.97$; distance x age : $F(6,176) = 1.2$, $p < 0.31$; distance x test order : $F(2,176) = 0.9$, $p < 0.41$].

In the NOMASK version, significant effects of age, $F(3,87) = 3.79$, $p < 0.01$, and distance, $F(2,174) = 13.87$, $p < 0.0001$, were observed. The other variables or interaction between variables did not affect performance [test order : $F(1,87) = 0.9$, $p < 0.34$; age x test order : $F(3,87) = 0.54$, $p < 0.65$; distance x age : $F(6,174) = 1.06$, $p < 0.39$; distance x test order : $F(2,174) = 1.92$, $p < 0.15$; distance x age x test order : $F(6,174) = 0.81$, $p < 0.56$].

Complementary ANOVAs showed that no independent variables significantly affected younger children's performance [test version : $F(1,44) = 3.03$, $p < 0.09$; test order : $F(1,44) = 0.56$, $p < 0.46$; test version x test order : $F(1,44) = 0.71$, $p < 0.4$; distance : $F(2,88) = 2.24$, $p < 0.11$; distance x test version : $F(2,88) = 1.89$, $p < 0.16$; distance x test order : $F(2,88) = 0.47$, $p < 0.63$; distance x test version x test order : $F(2,88) = 0.54$, $p < 0.58$].

Distance did appear to significantly affect performance in the eight-year-olds, $F(2,86) = 3.96$, $p < 0.02$, in the young adults, $F(2,88) = 6.58$, $p < 0.002$, and in the elderly people, $F(2,88) = 12.39$, $p < 0.0001$.

No other significant effect was observed in the eight-year-olds [test version : $F(1,43) = 0.79$, $p < 0.38$; test order : $F(1,43) = 0.02$, $p < 0.88$; test version x test order : $F(1,43) = 0.18$, $p < 0.67$; distance x test version : $F(2,86) = 0.82$, $p < 0.44$; distance x test order : $F(2,86) = 2.29$, $p < 0.11$; distance x test version x test order : $F(2,86) = 1.71$, $p < 0.19$], in the young adults [test version : $F(1,44) = 0.26$, $p < 0.61$; test order : $F(1,44) = 0.3$, $p < 0.87$; test version x test order : $F(1,44) = 0.26$, $p < 0.61$; distance x test version : $F(2,88) = 0.08$, $p < 0.93$; distance x test order : $F(2,88) = 1.09$, $p < 0.34$; distance x test version x test order : $F(2,88) = 1.91$, $p < 0.15$], and in the elderly people [test version : $F(1,44) = 0.04$, $p < 0.84$; test order : $F(1,44) = 0.11$, $p < 0.74$; test version x test order : $F(1,44) = 0.21$, $p < 0.65$; distance x test version : $F(2,88) = 0.17$, $p < 0.85$; distance x test order : $F(2,88) = 2.72$, $p < 0.07$; distance x test version x test order : $F(2,88) = 2.06$, $p < 0.13$].

A summary for the Distance effect in the two test versions is presented in table 17, and errors (in %) are reported in figure 40.

Discussion

Experiment 4a was designed to assess mental scanning abilities from childhood to old age. A modified version of Finke and Pinker (1982) and Dror and Kosslyn (1994) tasks was used. Subjects were required to judge as quickly as possible whether an arrow (briefly presented) pointed to a target in a previously memorised pattern. The arrow was presented immediately after the removal of the memorised pattern, and the distance between the target and the arrow could be short, medium or long. Subjects did several versions of the task.

The main hypothesis states that if mental scanning is taking place while the subject is solving the task, RTs should be linearly dependent on the scanned distance. Results were somewhat divergent from this basic hypothesis. A second major hypothesis was that RTs should be longer in younger children - a result which is not intrinsically associated with the scanning process.

TABLE 16
Effect of scanned distance on errors in the Imagery Test
Number of correct responses (max: 4) and standart deviations are reported

Five-year-olds :
Imagery test followed by the perceptual control.

ANIMASK version :				*F* value
Distances	Short	Medium	Long	
	2.25	2.08	1.75	F(2,22) = 1.75
	(SD: 1.48)	(SD: 1.37)	(SD: 1.42)	$p < 0.2$
NOMASK version :				
Distances	Short	Medium	Long	
	2.91	2.75	2.33	F(2,22) = 1.24
	(SD: 1.5)	(SD: 1.48)	(SD: 1.61)	$p < 0.31$

Five-year-olds :
Perceptual control followed by the imagery test.

ANIMASK version :				*F* value
Distances	Short	Medium	Long	
	3.0	2.58	2.25	F(2,22) = 1.21
	(SD: 1.12)	(SD: 1.24)	(SD: 1.24)	$p < 0.32$
NOMASK version :				
Distances	Short	Medium	Long	
	3.16	3.08	2.58	F(2,22) = 1.44
	(SD: 0.83)	(SD: 1.24)	(SD: 1.24)	$p < 0.26$

Eight-year-olds :

ANIMASK version :				*F* value
Distances	Short	Medium	Long	
	3.45	3.08	3.0	F(2,46) = 1.65
	(SD: 0.88)	(SD: 0.71)	(SD: 1.1)	$p < 0.2$
NOMASK version :				
Distances	Short	Medium	Long	
	3.78	3.56	3.65	F(2,44) = 0.95
	(SD: 0.67)	(SD: 0.66)	(SD: 0.57)	$p < 0.39$

Young adults :

ANIMASK version :				*F* value
Distances	Short	Medium	Long	
	3.66	3.29	2.95	F(2,46) = 5.34
	(SD: 0.56)	(SD: 0.62)	(SD: 0.99)	$p < 0.008$
NOMASK version :				
Distances	Short	Medium	Long	
	3.71	3.71	3.58	F(2,46) = 0.44
	(SD: 0.55)	(SD: 0.46)	(SD: 0.58)	$p < 0.65$

Elderly people :

ANIMASK version :				*F* value
Distances	Short	Medium	Long	
	3.41	3.08	2.75	F(2,46) = 4.0
	(SD: 0.71)	(SD: 0.82)	(SD: 0.94)	$p < 0.03$
NOMASK version :				
Distances	Short	Medium	Long	
	3.45	3.29	2.7	F(2,46) = 6.61
	(SD: 0.77)	(SD: 1.08)	(SD: 1.12)	$p < 0.003$

TABLE 17
Effect of scanned distance on errors in the Perceptual Control
Number of correct responses (max: 4) and standart deviations are reported

Five-year-olds :
Imagery test followed by the perceptual control.

				F value
ANIMASK version :				
Distances	Short	Medium	Long	
	3.5	3.83	3.5	F(2,22) = 1
	(SD: 1.16)	(SD: 0.38)	(SD: 0.79)	$p < 0.38$
NOMASK version :				
Distances	Short	Medium	Long	
	3.16	2.75	2.75	F(2,22) = 1.28
	(SD: 1.34)	(SD: 1.54)	(SD: 1.6)	$p < 0.3$

Five-year-olds :
Perceptual control followed by the imagery test.

				F value
ANIMASK version :				
Distances	Short	Medium	Long	
	3.75	3.58	3.41	F(2,22) = 2.75
	(SD: 0.86)	(SD: 1.16)	(SD: 1.16)	$p < 0.09$
NOMASK version :				
Distances	Short	Medium	Long	
	3.58	3.16	3.25	F(2,22) = 1.18
	(SD: 0.66)	(SD: 0.83)	(SD: 0.96)	$p < 0.32$

Eight-year-olds :

				F value
ANIMASK version :				
Distances	Short	Medium	Long	
	3.66	3.58	3.5	F(2,46) = 0.74
	(SD: 0.86)	(SD: 0.88)	(SD: 1.02)	$p < 0.48$
NOMASK version :				
Distances	Short	Medium	Long	
	3.91	3.82	3.52	F(2,44) = 3.54
	(SD: 0.28)	(SD: 0.65)	(SD: 0.59)	$p < 0.04$

Young adults :

				F value
ANIMASK version :				
Distances	Short	Medium	Long	
	3.83	3.83	3.5	F(2,46) = 3.17
	(SD: 0.48)	(SD: 0.38)	(SD: 0.58)	$p < 0.05$
NOMASK version :				
Distances	Short	Medium	Long	
	3.83	3.75	3.45	F(2,46) = 3.34
	(SD: 0.38)	(SD: 0.53)	(SD: 0.65)	$p < 0.04$

Elderly people :

				F value
ANIMASK version :				
Distances	Short	Medium	Long	
	3.71	3.54	3.04	F(2,46) = 5.07
	(SD: 0.85)	(SD: 0.65)	(SD: 0.85)	$p < 0.01$
NOMASK version :				
Distances	Short	Medium	Long	
	3.75	3.41	3.00	F(2,46) = 6.91
	(SD: 0.84)	(SD: 1.01)	(SD: 1.25)	$p < 0.002$

Two tasks were used: An imagery task and a perceptual control task. In the imagery task, subjects had to judge whether the arrow pointed to a target after the removal of the to-be-memorised pattern. In contrast, in the perceptual task, the decision was taken while the targets and the arrow were simultaneously presented. In both tasks, it was expected that distance should affect scanning times. However, subjects should respond more quickly in the perceptual control task than in the imagery task. Indeed, in the perceptual control task, a single eye movement is necessary to respond.

Two versions of the tasks were used. An animated mask was displayed immediately after the presentation of the arrow. It was expected that this irrelevant information should not affect subjects' performance if their scanning process is mature. Based on previously published studies, it was hypothesised that this mask could interfere with the scanning process in younger children. However, it should not influence eight-year-olds, young adults, or elderly.

Global analysis revealed that the RTs were influenced by age. The mean RT to respond decreased from five-year-olds, to eight-year-olds, to elderly people and young adults. This probably reflects an increase in speed processing with child development (see Kail, 1986, 1991) and a parallel decrease in the elderly (see Feyereisen, 1994). This issue has already been theoretically addressed in chapter 2 while reviewing the literature on mental rotation abilities.

Surprisingly, overall RTs were longer in the perceptual control than in the imagery task. In fact, although subjects were also required to respond as quickly as possible in the perceptual control, they preferred to be sure of their judgement before responding (which resulted in an increased processing time). Moreover, in this condition, the experimental situation did not force them to respond quickly. Indeed, the pattern remained at their disposal during the information processing. In the imagery task, if they were slow in responding, there was a higher risk of forgetting the location of the targets. The more time they took to judge whether the arrow pointed to a target, the longer they had to keep the pattern in short term memory. It is interesting to notice that young adults responded far more quickly in the ANIMASK version of the perceptual task: The mask invaded the screen and made the judgement more difficult, which forced them, perhaps, to shorten their processing time.

The main hypothesis for this experiment, i.e. the effect of distance on scanning times, was verified. However, complementary analyses on each age category considered independently showed different patterns across age.

RTs were always dependent on distance in young adults and eight-year-olds. Such results are not really surprising since several studies have demonstrated distance-dependence in such tasks in young adults (e.g. Kosslyn, Ball & Reiser, 1978; Finke and Pinker, 1982). Moreover, there is a consensus between developmental psychologists that after eight years of age the imagery subsystems are well developed (see Dean, 1990). However, although the scanning process seems to be well developed in these subjects, it is interesting to observe that the mask seemed to interfere with the analogical process. In young adults, task versions and distance interact significantly, and in eight-year-olds, RTs were globally longer in the ANIMASK version of the tasks. In addition, errors increased significantly in the ANIMASK version in both groups of subjects, particularly for the long distance.

Patterns are somewhat different in younger children and in elderly. Indeed, if distance influenced RTs in the NOMASK version of the imagery task, this effect disappeared in the ANIMASK version. Although the reasons are unclear, the mask interfered with the analogical process (this issue will be reconsidered in the general discussion). However, unlike the other groups of subjects, errors were equal in both versions of the task.

In fact, to be precise, these patterns were observed in five-year-olds when subjects were first presented with the perceptual control followed by the imagery task. Indeed, error rates were higher in this condition (except for the control task with the interfering mask). The difference observed between the two task orders could be due to the difficulty younger children had in understanding the instructions for the task. Being presented with the perceptual control first might have helped them understand the imagery task. It is, however, interesting to notice that error rates were always higher in the ANIMASK version of the imagery task, particularly in the IMA-PER condition where error rates are consistent with guessing. This suggests that when more constraints are imposed on the memory and attentional systems, young children are particularly poor in transformational imagery tasks.

It appears from experiment 4a that scanning abilities (as reflected by distance dependence) are well developed by the age of 8. Moreover, it seems that this new set of data suggests that scanning abilities might not be functioning as well in five-year-olds and in elderly people. Of course, RTs were observed to be dependent on distance in a condition which was in fact almost the same as those used by Kosslyn *et al* (1990) and Dror and Kosslyn (1994), for children and for the elderly respectively -, but when a mask interfered with the scanning processes, this effect was suppressed. Mental scanning abilities seem to be weak in young children and seem to be affected by ageing. The results of experiment 4a will be discussed again in the general discussion in parallel to the data reported in experiment 4b.

EXPERIMENT 4b

In Kosslyn, Ball and Reiser (1978), subjects had to memorise a pattern and to keep it in long term memory. A mental image of the pattern had to be generated from long term memory, and mental scanning is carried out on this memory trace. In contrast, in Finke and Pinker (1982), mental scanning takes place on a pattern representation which is not generated from long term memory. In Pinker and Finke (1982), subjects were required to maintain a visual pattern in short term memory immediately followed by a briefly presented arrow. The arrow took the form of an iconic representation (see for a classical work on iconic memory: Sperling, 1960), i.e. a situation very close to visual perception. Consequently, the cognitive processes engaged in both tasks might be somehow different.

In experiment 4b, the tasks were similar to those used in experiment 4a but a retention interval time was imposed between the removal of the to-be-memorised pattern and the arrow display. As a consequence, subjects had a pattern in short term memory which was to be scanned later.

The main advantage of this new procedure is to engage some memory processes (at least others than those associated with an iconic memory) in a mental scanning task. It is clear that in such a situation, subjects are not confronted with a task similar to that carried out by Kosslyn *et al.* (1978) - they do not have to generate a mental image from associative memory - but are required to maintain a visual (and/or spatial) short term representations in the visual buffer. Mental scanning takes place necessarily on a memory representation.

If subjects use a scanning process, RTs should increase as a function of distance between the arrow and the target. However, in this task, mental scanning abilities interact with the ability to maintain visuo-spatial information in short term memory. We know that image maintenance in young children (e.g. Kosslyn *et al.*, 1990; Wilson *et al.*, 1987) and elderly (e.g. Van der Linden, 1994) is poor (see also chapters 5 and 6). Consequently, the memory component in this task might affect the performance of both children and the elderly.

Subjects

Twenty four five-year-olds (mean age: 5,01, ranged 4;09 to 5;03), 24 eight-year-olds (mean age: 8;02, ranged 7;09 to 8;03), 24 young adults (mean age: 19 years of age, ranged 18;01 to 24;03) and 24 elderly (mean age: 70;02, ranged 66;02 to 77;04) were tested.

Subjects were recruited through the same channels as in experiment 4a.

Material

The material was the same as in experiment 4a except that a retention interval of 2 seconds was introduced between the removal of the fish and the display of the arrow. Moreover, no perceptual control was used in the present experiment.

Procedure

Subjects were distributed among two groups. The first group was submitted to the mental scanning task without an animated mask, and the second group was submitted to the task with an animated mask (12 subjects from each age category were tested in each condition).

The procedure was basically identical to that used in experiment 4a. The difference was that a retention interval of 2 seconds was imposed after the removal of the fish and before the presentation of the arrow for 200 msec. The procedure is presented in figure 41. In summary, subjects were presented with three fish. They were asked to memorise the location of these three fish. Once memorised, they pressed the space bar which removed the fish from the screen. Then, after 2 seconds (retention time), an arrow was presented. It could point to a previously presented fish or not. Subjects were required to indicate as quickly as possible whether the arrow pointed to a previously presented target. In the mental scanning condition (in brief: NOMASK version), the screen remained empty after the offset of the arrow. In the animated mask version (in brief: ANIMASK version), the screen was invaded with circles after the disappearance of the arrow.

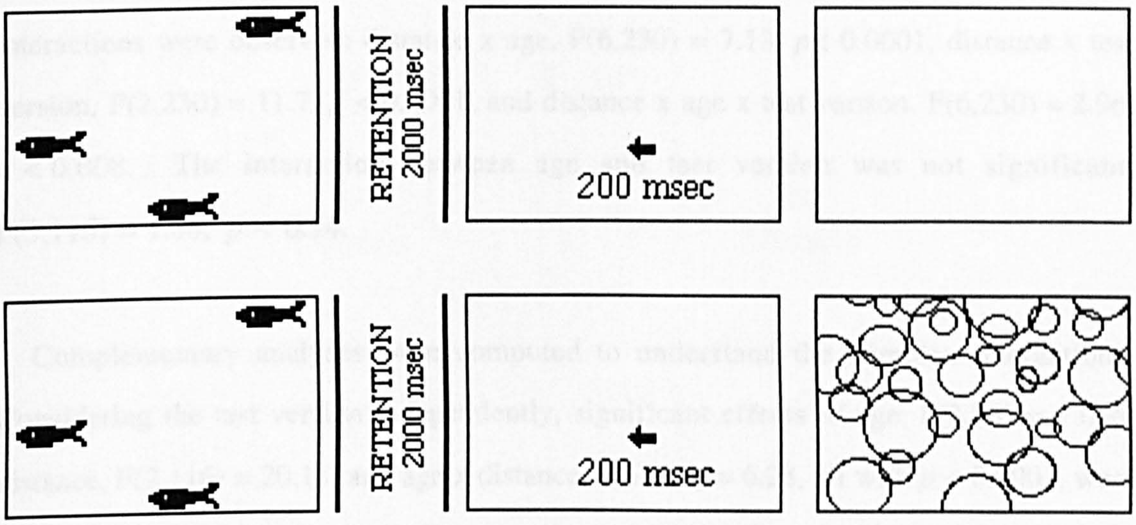

Figure 41 : Schematic representation of the experimental situations

RESULTS

In experiment 4b analyses were applied that were similar to those in experiment 4a. ANOVAs were computed on reaction times for "YES trials" as distance scanned is only controlled in such trials. Age (five-year-olds, eight-year-olds, young adults and elderly), and test version (ANIMASK versus NOMASK) were between-subject independent variables. Distance scanned (short, medium or long) was a within-subject independent variable.

Reaction Times

RT means are reported in figure 42. A global ANOVA carried out on RT means revealed a significant effect of age, $F(3,115) = 25.02$, $p < 0.0001$, test version, $F(1,115) = 12.15$, $p < 0.0007$, and distance, $F(2,230) = 18.92$, $p < 0.0001$. Moreover, several significant interactions were observed: distance x age, $F(6,230) = 7.13$, $p < 0.0001$, distance x test version, $F(2,230) = 11.7$, $p < 0.0001$, and distance x age x test version, $F(6,230) = 2.96$, $p < 0.008$. The interaction between age and test version was not significant, $F(3,115) = 1.86$, $p < 0.14$.

Complementary analyses were computed to understand the complex interactions. Considering the test version independently, significant effects of age, $F(3,58) = 13.66$, distance, $F(2,116) = 20.13$, and age x distance, $F(6,116) = 6.28$, all with $p < 0.0001$, were shown in the ANIMASK version. However, in the NOMASK version, only an effect of age was reported, $F(3,57) = 12.98$, $p < 0.0001$. The effects of distance, $F(2,114) = 0.99$, $p < 0.38$, and the interaction distance x age, $F(6,114) = 1.37$, $p < 0.23$, were not significant.

In five-year-olds, RTs were shown to be significantly different in the two test versions, $F(1,30) = 7.21$, $p < 0.01$, and were globally affected by distance, $F(2,60) = 14.62$, $p < 0.0001$. However, as a significant interaction was reported between test version and distance, $F(2,60) = 7.06$, $p < 0.002$, another ANOVA carried out on the test versions considered separately showed that the distance effect was only really present in the ANIMASK version, $F(2,34) = 14.8$, $p < 0.0001$. This effect was not observed in the NOMASK version, $F(2,26) = 1.27$, $p < 0.29$.

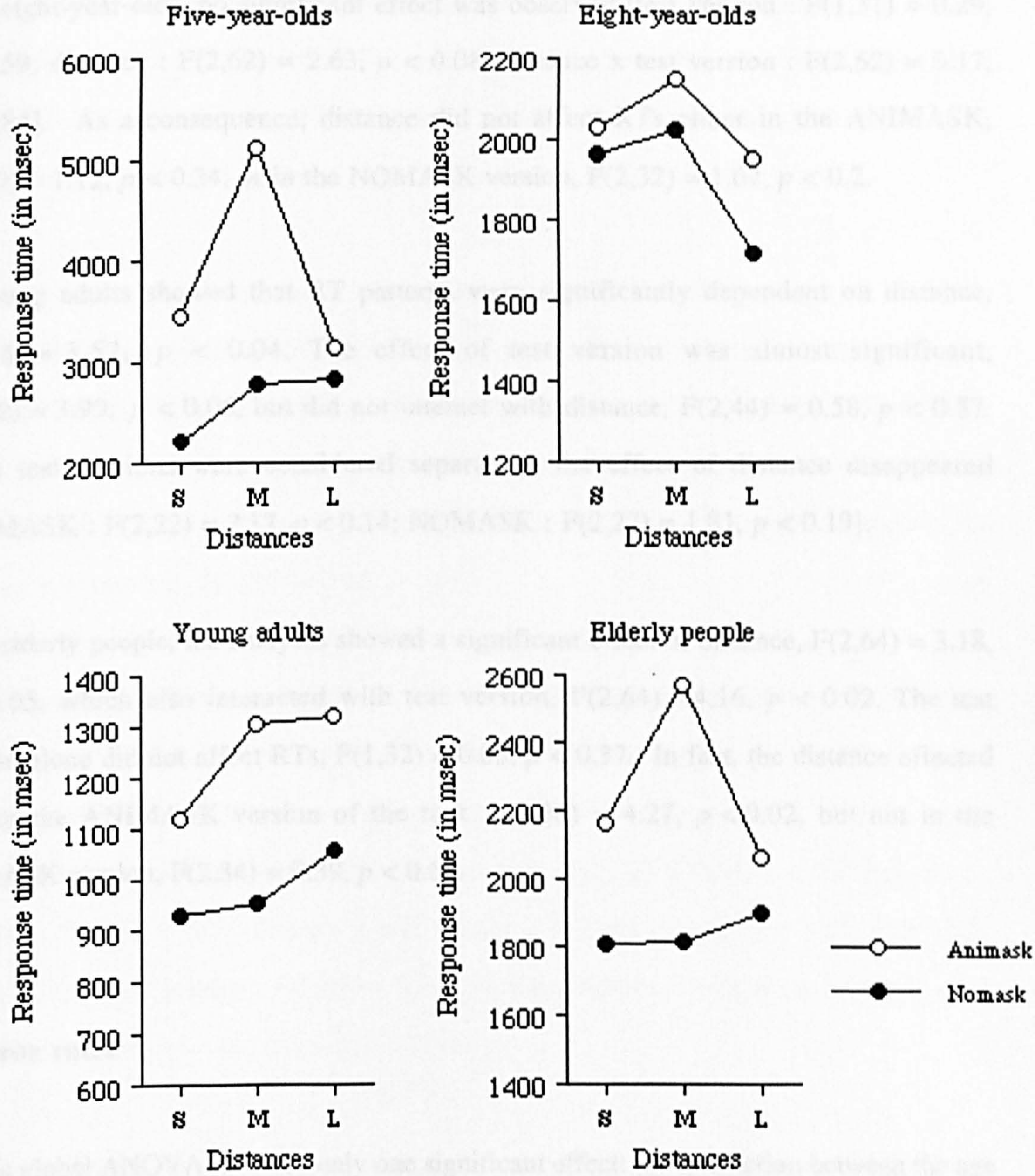

Figure 42 : Reaction times (in msec) as a function of distance (S = short; M = medium; L = long) in the four age categories in the different experimental conditions (Imagery task and perceptual control, with - ANIMASK - or without - NOMASK - an animated mask) - see symbols used on the right side of the figure.

In eight-year-olds, no significant effect was observed [test version : $F(1,31) = 0.29$, $p < 0.59$; distance : $F(2,62) = 2.63$, $p < 0.08$; distance x test version : $F(2,62) = 0.17$, $p < 0.84$]. As a consequence, distance did not affect RTs either in the ANIMASK, $F(2,30) = 1.12$, $p < 0.34$, or in the NOMASK version, $F(2,32) = 1.67$, $p < 0.2$.

Young adults showed that RT patterns were significantly dependent on distance, $F(2,44) = 3.52$, $p < 0.04$. The effect of test version was almost significant, $F(1,22) = 3.99$, $p < 0.06$, but did not interact with distance, $F(2,44) = 0.58$, $p < 0.57$. When test versions were considered separately, the effect of distance disappeared [ANIMASK : $F(2,22) = 2.17$, $p < 0.14$; NOMASK : $F(2,22) = 1.81$, $p < 0.19$].

In elderly people, the analyses showed a significant effect of distance, $F(2,64) = 3.18$, $p < 0.05$, which also interacted with test version, $F(2,64) = 4.16$, $p < 0.02$. The test version alone did not affect RTs, $F(1,32) = 0.83$, $p < 0.37$. In fact, the distance affected RTs in the ANIMASK version of the task, $F(2,30) = 4.27$, $p < 0.02$, but not in the NOMASK version, $F(2,34) = 0.39$, $p < 0.68$.

Error rates

The global ANOVA revealed only one significant effect: the interaction between the age and distance variables, $F(6,252) = 2.36$, $p < 0.03$. The other variables or interaction between variables did not affect error rates [age : $F(3,126) = 2.01$, $p < 0.12$; test version : $F(1,126) = 1.57$, $p < 0.21$; age x test version : $F(3,126) = 1.4$, $p < 0.25$; distance : $F(2,252) = 2.01$, $p < 0.14$; distance x test version : $F(2,252) = 1.73$, $p < 0.18$; distance x age x test version : $F(6,252) = 0.39$, $p < 0.89$].

In fact, only age significantly affected performance in the NOMASK version of the task, $F(3,63) = 2.86$, $p < 0.04$. We did not observe a significant effect of distance, F(2,126) =

0.26, $p < 0.77$, and of the interaction between distance and age, $F(6,126) = 1.27$, $p < 0.28$. In the ANIMASK version of the task, distance had an effect on errors , $F(2,126) = 3.82$, $p < 0.02$, but neither age, $F(3,63) = 0.54$, $p < 0.66$, nor the interaction distance x age, $F(6,126) = 1.51$, $p < 0.18$, affected performance.

Complementary analyses showed that errors were a function of distance only in elderly people, $F(2,70) = 4.58$, $p < 0.01$, but this effect was really only observed while they were submitted to the ANIMASK version of the task, $F(2,34) = 6.01$, $p < 0.006$ [NOMASK : $F(2,36) = 0.42$, $p < 0.66$]. The interaction between distance and test version was not significant, $F(2,70) = 1.93$, $p < 0.15$. In addition, no global difference was observed between test versions, $F(1,35) = 0.15$, $p < 0.7$.

No significant effect could be reported in the other age category. In the five-year-olds, the following results were observed : test version : $F(1,36) = 3.6$, $p < 0.07$; distance : $F(2,72) = 1.44$, $p < 0.24$; distance x test version : $F(2,72) = 1.33$, $p < 0.27$. Similar results were observed in the eight-year-olds : test version : $F(1,32) = 0.53$, $p < 0.47$; distance : $F(2,64) = 2.38$, $p < 0.1$; distance x test version : $F(2,64) = 0.21$, $p < 0.81$, and in the young adults : test version : $F(1,23) = 0.26$, $p < 0.61$; distance : $F(2,46) = 1.45$, $p < 0.24$; distance x test version : $F(2,46) = 0$, $p < 0.99$.

When test versions were considered separately, no effect of distance was observed in the NOMASK version, $F(2,34) = 2$, $p < 0.15$, and in the ANIMASK version, $F(2,38) = 0.24$, $p < 0.78$, in the five-year-olds. Similar results were observed in the eight-year-olds : NOMASK : $F(2,32) = 0.62$, $p < 0.55$; ANIMASK : $F(2,32) = 1.96$, $p < 0.16$, and in the young adults : NOMASK : $F(2,24) = 0.6$, $p < 0.6$; ANIMASK : $F(2,22) = 0.92$, $p < 0.41$.

Error rates are reported in figure 43.

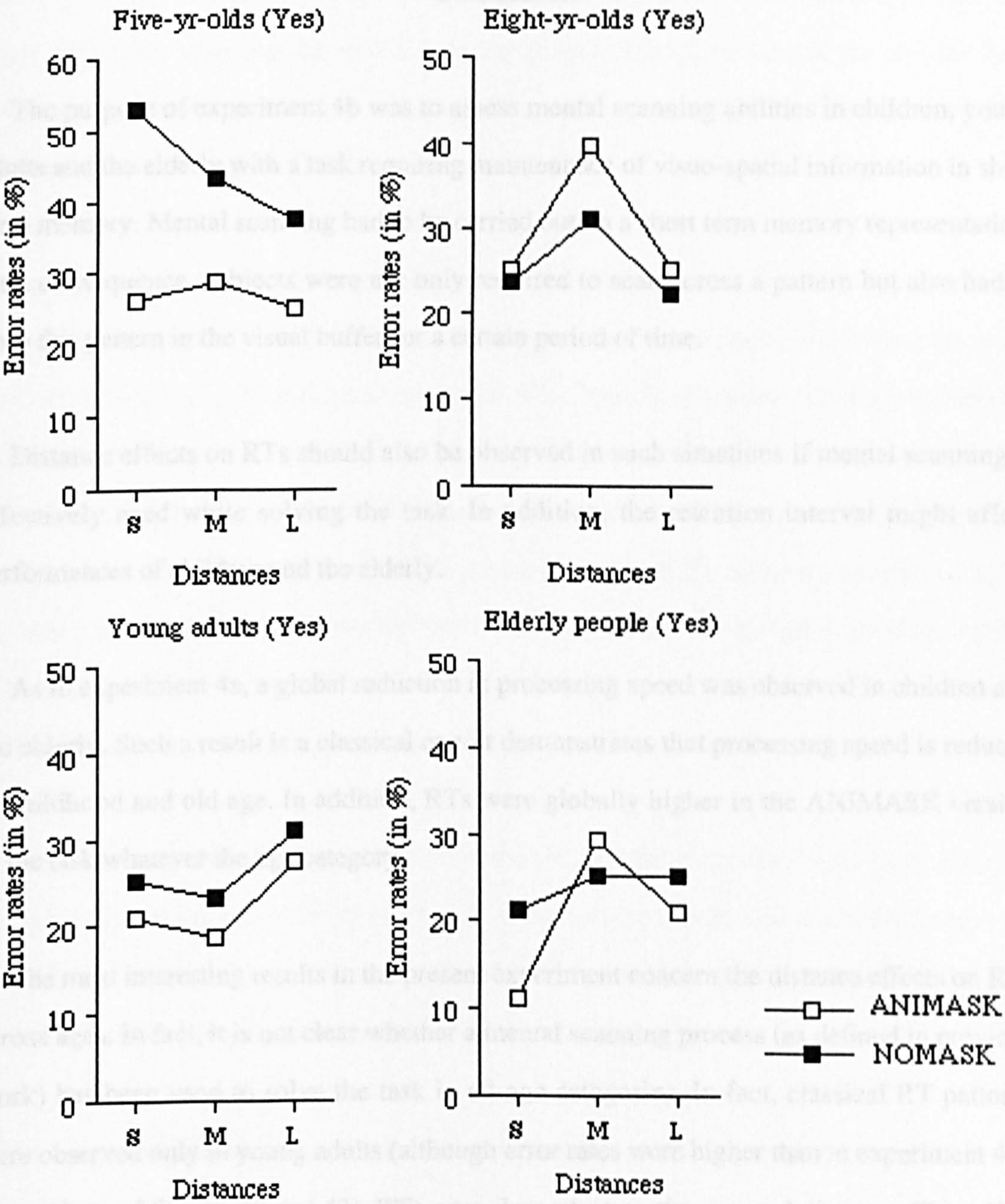

Figure 43 : Errors (in percent) as a function of distance (S = short; M = medium; L = long) in the four age categories in the different experimental conditions (Imagery task and perceptual control, with - ANIMASK - or without - NOMASK - an animated mask) - see symbols used in the right corner of the figure.

Discussion

The purpose of experiment 4b was to assess mental scanning abilities in children, young adults and the elderly with a task requiring maintenance of visuo-spatial information in short term memory. Mental scanning had to be carried out on a short term memory representation. As a consequence, subjects were not only required to scan across a pattern but also had to keep this pattern in the visual buffer for a certain period of time.

Distance effects on RTs should also be observed in such situations if mental scanning is effectively used while solving the task. In addition, the retention interval might affect performances of children and the elderly.

As in experiment 4a, a global reduction in processing speed was observed in children and the elderly. Such a result is a classical one. It demonstrates that processing speed is reduced in childhood and old age. In addition, RTs were globally higher in the ANIMASK version of the task whatever the age category.

The most interesting results in the present experiment concern the distance effects on RTs across ages. In fact, it is not clear whether a mental scanning process (as defined in previous work) has been used to solve the task in all age categories. In fact, classical RT patterns were observed only in young adults (although error rates were higher than in experiment 4a - comparison of figures 40 and 43). RTs were dependent on the scanned distance. This effect was significant when task versions were joined. When considered separately, the distance effect could not be observed. However, as the interaction between task version and distance was not significant, we could reasonably think that increasing the sample of subjects would have led to a significant effect of distance when task versions were considered individually.

In eight-year-olds, distance did not significantly affect RTs. However, surprisingly, there was a tendency to observe an inverted-U RTs function. Such a pattern was in fact also observed in five-year-olds and the elderly for the ANIMASK version of the task. In these subjects, distance significantly affected RTs, but not linearly; medium distance was associated with the highest RT values (see figure 42).

Such results are particularly puzzling and do not confirm the scanning hypothesis. An interpretation might be that for short and long distances, subjects are using the screen borders to respond. It would result in shorter RTs. Indeed, when the distance between the arrow and the target is "medium", the arrow is displayed somewhere in the center of the screen, which makes it more difficult to reference to a frame. Without such help, these trials would be more complicated and would result in higher RTs. Indeed, there is a hint of evidence for better performance for short and long distances in eight-year-olds and the elderly (especially in the ANIMASK version) - although it is not significant. Eight-year-olds and the elderly committed fewer errors in the short and long distance conditions.

For the overall experiment, we should stress the fact that error rates were high in all age categories (especially in younger children). However, we should also take into account the fact that there were only a few trials in a task. Future work should consider this issue and propose a methodology which attempts to reduce errors in subjects.

Consequently, the administration of the current task to children and the elderly failed to confirm the scanning hypothesis. When scanning has to be carried out on a short term representation, the distance effect observed in experiment 4a was suppressed. This suppression cannot be explained by the interference of the mask since no difference was observed between task versions in experiment 4b. The condition in which the scanning is carried out seems to be the sole explanation for such results.

Indeed, it is not surprising to observe different RT patterns in a task which involves image maintenance capacity. Several studies have reported the difficulty young children and elderly people have in keeping visuo-spatial information in short term memory (see above).

CONCLUSION

Experiments 4a and 4b were designed to study the development of mental scanning ability from a life-span perspective. Previously published studies made accurate predictions of children's and elderly people's abilities difficult. Indeed, the results reported from child psychology studies were contradictory (see Kosslyn *et al*;, 1990, Courbois, 1994). In the elderly, only Dror and Kosslyn (1994) reported evidence for good mental scanning ability. However, this experiment did not consider any control condition [which has been particularly critical in rejecting the scanning hypothesis in the study on children done by Courbois (1994)].

When mental scanning was carried out in a condition which does not require the maintenance of visual information in short term memory (experiment 4a), the scanning hypothesis was verified in all subjects. RTs were significantly dependent on the distance between the arrow and the target. In such a condition, the targets were available as icons when the judgment was made. However, when the scanning process was in "conflict" with the presentation of irrelevant information (an animated mask), the distance effect disappeared in younger children and in the elderly.

Kosslyn (1994) has proposed that two different mechanisms might be involved in image scanning: The first process shifts the attention window, and the second transforms the contents of the visual buffer. In the present experiment, the first mechanism was probably used. This first mechanism may be assimilated to imaged saccades. My interpretation of the data reported in experiment 4a is that such imaged saccades might explain the distance effect.

Indeed, no delay was imposed between the removal of the pattern and the presentation of the arrow. Consequently, an iconic trace was probably still present in the visual buffer when the arrow appeared. The scanning process involved in this task is probably similar to those used in scanning external visual patterns.

When the mask was displayed, the scanning process was in conflict with distracting information - information which, in fact, probably masked the iconic trace of the target pattern. As the mask progressively invaded the screen, the information processing speed became lower and the distracting effect of the mask became more powerful. In five-year-olds and in the elderly, information processing speed was lower than in the other subjects. As a result, they should have suffered the most from the animated mask. But in fact, the mask affected performance in all subjects: *Error rates* were globally significantly higher in the ANIMASK version of the imagery task.

So, although it was hypothesized that the scanning process itself would be affected by the introduction of a mask after the arrow display, it seems that its main effect could have been on the iconic trace. Such an interpretation might be consistent with what has been observed in experiment 4b.

Indeed, in experiment 4b, subjects had to keep the pattern in short term memory for two seconds before the presentation of the arrow. Consequently, subjects not only had to scan the pattern but also had to maintain it through active processes in the visual buffer. Image maintenance and mental scanning might have been in conflict during this particular task. As far as image maintenance is concerned, this ability is particularly poor in children and in the elderly (see Kosslyn *et al*;, 1990; Wilson *et al.*, 1986; Bruyer, 1994; see also chapters 5 and 6). In fact, in this condition, the RT patterns did not validate the scanning hypothesis either in the NOMASK version or in the ANIMASK version[1].

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1 The absence of a significant effect of the task version in experiment 4b supports the idea that the mask did not affect the scanning process itself in experiment 4a but rather suppressed the iconic trace of the pattern and the arrow since it was superimposed on it in the visual buffer.

Consequently, most of the data reported in these experiments invalidate the scanning hypothesis especially when subjects have to scan across a pattern maintained in short term memory. It seems that young children and the elderly are poor at maintaining visuo-spatial information in short term memory. In the task, the major characteristic of the pattern is the *localisation* of the target rather than its structure. I would hypothesise that this is again evidence for a poor ability to maintain spatial characteristics in short term memory. It could be evidence for a immaturity of some aspects of the dorsal system (see Kosslyn, 1994) or the spatial component of the VSSP (see Logie, 1995), i.e. the subsystems in charge of the processing of the spatial characteristics of a visual pattern.

Does the distance effect observed in experiment 4a in the NOMASK version of the imagery task reflect the use of a mental scanning process ? Results observed in the perceptual control seem to invalidate this hypothesis. Indeed, based on some results reported by Pinker (1980), it was expected that *scanning speed* should be quicker in the perceptual control than in the imagery task. In the perceptual control, a single saccade is necessary to judge the correspondence between the arrow and the target. In contrast, in the imagery task, a shifting of the attentional window on the visual buffer is necessary. A comparison of the RT functions in the imagery task and perceptual control on figure 27 should convince us that scanning speed is globally equal in both conditions in most age categories - RT functions are more or less parallel (except in the elderly where the scanning speed is even less in the imagery task than in the perceptual control). There is however, a tendency to get a greater scanning speed for the perceptual control in young adults. Consequently, even in the experimental condition where RTs are dependent on distance, we should be cautious in interpreting this chronometrical index as an evidence for mental scanning in children and the elderly.

Moreover, error rates were not significantly affected by the mask in experiment 4b but were greatly affected by it in experiment 4a. We should have observed a similar effect in experiment 4b if the mask had an effect on the scanning process itself.

In summary, with the exception of young adults where some evidence for mental scanning has been observed in these experiments, the data does not support the hypothesis claiming the use of mental scanning in children and in the elderly. Most of the data reported in these two experiments invalidate the scanning hypothesis, particularly when this process is in conflict with other imagery subsystems, namely image maintenance. However, other studies will be necessary to understand which strategies children and the elderly are using when they are submitted to a mental scanning task, and how to explain the interference between image maintenance and scanning abilities.

General conclusion

Several experiments have been presented to evaluate the development of visuo-spatial short term memory in a life-span perspective. Visuo-spatial short term memory has been assessed through transformational imagery tasks. The age categories selected, i.e. five-year-olds, eight-year-olds, young adults and elderly people, seem to be key ages to assess the development of imagery. Indeed, most developmental psychologists accept the idea of poor transformational imagery abilities in preoperational children and have suggested that imagery subsystems might be affected by ageing. However, to my knowledge, no previous study has assessed mental imagery abilities in a life-span perspective using the same set of tasks for all age categories.

The first set of experiments (chapters 3, 4 and 5) concerned the development of mental rotation abilities. A review of the literature suggested that young children (specifically so-called preoperational children) and the elderly are poor at rotating a mental image of a visual pattern. However, as some mental rotation abilities have been reported while using Shepard's paradigm, I wanted to focus my attention on the role of the first steps necessarily taken while performing a mental rotation task, namely the encoding of the rotated stimulus and its maintenance in STM. Indeed, Cooper and Shepard (1973) suggest that these two steps necessarily precede the rotation itself. If these steps were immature or deteriorated with ageing, mental rotation would be carried out on a flimsy basis.

The second set of experiments (chapter 6) considered another imagery subsystem, namely "mental scanning". Very few studies have been published on the development of this subsystem and the data reported so far is ambiguous. In Kosslyn's (1994) theory, mental scanning is conceived as another transformational imagery process. As with mental rotation, it requires the maintenance of a visual pattern in short term memory.

Image maintenance ability has been assessed with reference to Kosslyn's (1994) model although Baddeley's (1986) working memory model - specifically, Logie's (1995) revision of the VSSP - has sometimes been considered while interpreting the data.

Kosslyn's (1994) model was presented extensively in chapter 1. Several subsystems were discussed which are involved in high level vision. Among them, some units are particularly relevant for the purpose of the present thesis. A visual buffer acts as a structure in which mental images are generated. Images are generated from information kept in associative memory reprocessed by two encoding subsystems: The ventral and dorsal subsystems. The ventral subsystem processes the "visual" characteristics of the pattern, i.e. mainly deals with the structure of the image. The dorsal subsystem processes the "spatial" information in parallel. It encodes both the localisation of the objects in space, and the spatial relations between object features. This subsystem is particularly interesting when we consider transformational imagery. Indeed, transformational imagery mainly modifies the spatial characteristics of the pattern.

Baddeley's (1986) working memory is a system with a limited capacity for temporary storage and manipulation during information processing. A central executive is responsible for complex decision and control processes. It is helped by two slave systems: One responsible in the storage of auditory information - the articulatory loop - and one for visuo-spatial information - the VSSP. Logie (1995) has recently investigated the VSSP system. The system comprises a temporary visual store and a temporary spatial store. Long term memory representations are at the origin of image generation. According to Logie (1995), the visual store is subject to decay and is sensitive to new information coming in. The spatial store is used to plan movement, and to rehearse the information kept in the visual store.

Spatial and visual components provide temporary storage of information for the central executive which uses it to solve specific tasks.

In consequence, these two different theoretical models suggest the existence of two related but different subsystems to store visual and spatial information. This distinction is based on behavioural data collected in young adults (e.g. dual-task studies, see for instance, Baddeley & Lieberman, 1980) and on neuropsychological data (e.g. Farah, Hammond, Levine & Calvanio, 1988). It is interesting to find some developmental evidence for a dissociation between both subsystems. This has been considered in the present thesis.

Experiment 1 compared mental rotation abilities in young children, young adults and the elderly using the same set of tasks. Mental rotation tasks were selected from published studies. Basically, they consisted in comparing two stimuli where one was rotated in the picture plane: Pandas (Marmor, 1975), Cones (Marmor, 1975) and Mannequins (Lejeune, 1994). They were constructed on the basis of Shepard's studies in young adults. Experiment 1 confirmed that five-year-olds and the elderly people are poor at mental rotation tasks.

Experiment 2 considered the association which might exist between mental rotation ability and short term memory capacity. Some previously published studies (e.g. Childs & Polich, 1979; Waber, Carlson & Mann, 1982) suggested that the difficulty young children have in solving a mental rotation task might be traced to their difficulty in maintaining visual information in short term memory. In parallel, some studies have demonstrated that the memory span for visual patterns is smaller in young children (Wilson, Scott & Power, 1987) and in the elderly (Feyereisen & Van der Linden, 1992) than in young adults. Is this a source of explanation for poor mental rotation abilities in young children and in the elderly ? A correlational approach between tasks was used in testing this hypothesis. Performance in mental rotation tasks used in experiment 1 was correlated with a classical memory span tasks. Again, poorer mental rotation performance was found in five-year-olds and the elderly than in eight-year-olds and young adults. Similarly, visual short term memory capacity was observed to be smaller in younger children and in the elderly. A correlational analysis between the two sets of tasks suggested that mental rotation abilities and STM span are related across ages.

Does it mean that mental rotation is totally related to visual short term memory ? In fact, the memory task used in experiment 2 - although a classical one - considers visual memory as a single structure. However, we know that Kosslyn (1994) as well as Logie (1995) have suggested that visual short term memory is a dual system: structural and spatial. In fact, the spatial subsystem is fundamental for successful mental rotations. Consequently, the memory task used in experiment 2 was too superficial to independently assess the development of both subsystems.

That is why experiments 3a to 3c had to be carried out. Mental rotation tasks were used to assess the ability to maintain visual and spatial information in STM. The mental rotation tasks were derived from Cooper and Shepard's (1973) study. From Shepard and Metzler's (1971) pioneering work, we know that when subjects have to compare two rotated stimuli, they are rotating a mental image of one of the stimuli before carrying out the comparison. In such studies, RTs served as evidence for the use of such a process: RTs were linearly dependent on stimulus orientation. However, when young adults are provided with information on the structure and the orientation of the to-be-presented stimulus, RTs become independent of the orientation. Subjects have the ability to maintain such information in STM before the presentation of the target. Their visual memory trace makes the activation of a mental rotation process unnecessary.

In two published developmental studies (Childs & Polich, 1978; Waber, Carlson & Mann, 1982), it appeared that young children are poor at maintaining such information in STM: Even when provided with structural and orientation information on the target, RTs remain dependent on stimulus orientation. At that time, visual short term memory was conceived as a single structure; the dissociation between the visual and spatial subsystems had not yet been proposed. The authors claimed that RTs are dependent on stimulus orientation because young children cannot keep visual information in memory and have, consequently, to carry out the mental rotation although they were provided with advanced information on the target. Another interpretation of these data could be that what was lost in young children is the spatial information (the stimulus orientation) rather than the structural information.

In experiment 3a, Childs and Polich's (1978) and Waber *et al.* 's (1982) results were reproduced in five-year-olds when they were provided with information 1000 msec before the display of the target. Flat functions were observed in eight-year-olds, young adults and elderly people. However, when the retention interval was reduced to 500 msec, RTs became independent of stimulus orientation in all subjects. It seems that reducing the retention interval allows all subjects to keep the information in STM and exempt them from the use of mental rotation.

In experiment 3b, an interfering mask was displayed during the retention interval. This irrelevant information made the maintenance of the information provided in STM even more difficult in younger children and in the elderly. In such conditions, stimulus orientation affected RT functions. In other words, orientational information was lost in younger children and in the elderly. Since orientation is processed by the dorsal system or the spatial component of VSSP, I should hypothesise that this system is not mature in five-year-olds and is affected by ageing. Indeed, it appeared in experiment 3c that these subjects are well able to keep structural information in STM. When the provided information was structurally different from the target, all subjects immediately noticed the mismatch between them.

Reconsidering Kosslyn's (1994) model, I suggest that such data tends to provide some developmental evidence for a dissociation between the dorsal and ventral subsystems. It seems that the two subsystems develop at different speeds. The ventral subsystem might be better developed earlier than the dorsal subsystem. Similarly, the data suggest that the same ventral system is not yet affected by ageing when the dorsal subsystem has already begun to deteriorate.

Again, if an interpretation of visual STM as a single structure has to be rejected, the dorsal subsystem should not be conceived as a single subsystem. The data reported in experiments 3a, 3b and 3c should not be interpreted as evidence for an immaturity of the dorsal system *as a whole*. Indeed, Ellis, Katz and Williams (1987) and Shumann-Hengsteler (1992) have shown that the memorisation of object position is immediately effective and evolves little with age. Moreover, position would be automatically encoded (Andrade & Meudell, 1993; Ellis, 1990, 1991). In fact, Kosslyn (1994) has suggested that this system might be decomposed into at least two units: The "Coordinate Spatial Relations Encoding" and the "Categorical Spatial Relations Encoding". Koenig, Reiss and Kosslyn (1990) provided some developmental evidence for poorer functioning of the first subsystem than the second one in young children.

Logie (1995) has suggested that two related systems assist the central executive when visuo-spatial information has to be kept in STM. Among them, a spatial store is not only responsible for maintaining the spatial characteristics of the stimulus but also helps to rehearse the information in the visual store. In terms of Logie's model, I suggest that the difficulty young children and the elderly have in keeping orientation in STM could be due to an immaturity/deterioration of the spatial store at these ages (which consequently could also result in poor mental rehearsal abilities).

In fact, these difficulties in maintaining spatial information in STM were also observed in the two last experiments. In experiments 4a and 4b, mental scanning ability was assessed in a life-span perspective. Mental scanning development has been considered in parallel with mental rotation development since it has to be considered as a transformational imagery system as well. Indeed, Kosslyn (1994) suggested that one of the mechanisms involved in mental scanning consisted of transforming the contents of the visual buffer. It replaces the representation kept in the visual buffer by a new one formed from the content of the image which is contiguous to the previous representation.

In a mental scanning task, subjects are required to memorise a visual pattern before the activation of the mental scanning itself. In such tasks, the critical aspect of the pattern to be memorised is not the structure of the pattern but rather the accurate location of several details. As a consequence, subjects are confronted with the necessity to activate several cognitive subsystems involved in the spatial analysis of the pattern. The dorsal subsystem seems again to be a good candidate for this purpose.

It appeared in experiments 4a and 4b that the mental scanning process is affected by the necessity to maintain the localisation of some details in the visual buffer during task solving. It was particularly the case in five-year-olds and in the elderly, although such observations should also be applied to eight-year-olds in particular conditions. When subjects were required to keep the pattern for 2 seconds in STM, the observed RT patterns were fundamentally different from those observed in classical studies with young adults. Indeed, in these latter studies, scanning times were dependent on the scanned distance, i.e. on the distance between the two relevant details of the pattern. In my experiments, this distance effect was observed only when the constraints on the maintenance of the pattern in memory were minimal, i.e. the pattern had to be maintained during a period which can be assimilated to an iconic memory trace.

When the retention of the pattern was longer or when the iconic trace was interfered with irrelevant information, the scanning process was somehow disrupted. However, although disrupted, performances were better than chance level. These results are somewhat puzzling and I do not have another interpretation to offer. Other studies are necessary to understand how children and elderly solve the task. Single case studies might help us to understand their strategies.

In summary

Several tasks have been used to assess the development of visuo-spatial short term memory. Transformational imagery tasks were used to provide developmental evidence for a dissociation between the spatial and visual components of the so-called visuo-spatial STM.

If the tasks are valid - a topic that I address below -, it seems that young children and elderly might have some difficulties in keeping the spatial characteristics (orientation and location) of a visual pattern in STM. In terms of Kosslyn's (1994) model, we might say that these difficulties could be related to an immaturity of the dorsal system - at least some aspects of it. In terms of Logie's (1995) model, an inefficiency of the temporary spatial store could account for these difficulties.

Consequently, explanations for the difficulties young children and the elderly encountered while carrying out a mental rotation or a mental scanning task (or generally, to a transformational imagery task) should not be sought in the processes engaged in the transformation of images themselves. Indeed, Shepard (1984) has considered that these processes might be innate. Rather, we should consider the development of related processes, especially the development of the structure in which mental images take place.

The validity of the tasks used in the experiments

Mental rotation tasks

Since Marmor's two studies on the development of mental rotation, developmental psychologists have thought that mental chronometry might be the unique way to assess mental rotation in a developmental perspective. However, as seen in chapter 2, the interpretations of chronometrical data in children as well as in the elderly are ambiguous, especially since experimental conditions have been different across published studies (see Dean, 1990). Courbois (1994) has proposed several criticism which might be reconsidered in the context of the present thesis.

We might worry about the ecological validity of such tasks. Indeed, in our everyday life activities, we rarely need to discriminate between normal and mirror-reversed versions of a visual pattern. It could explain why young children find it difficult to use a process which is in fact most of the time useless. However, its artificial character might be useful in assessing some aspects of related process as seen in this thesis.

The use of a paradigm classically applied in young adults might be questionable when applied to children or the elderly. I think that developmental psychologists should stress the differences they observe while testing young and old subjects. These differences - although difficult to interpret - are rich in information. Difficulty in reproducing young adults' results is not always synonymous with a misfunctioning of the cognitive system of children or the elderly. Similarly, similar results could sometimes receive a different interpretation. To illustrate this issue, Lejeune (1994) reported that RTs increasing as a function of stimulus orientation in young children should not necessarily be interpreted in terms of the activation of a mental rotation process. In his study, he showed rather that this linear trend reflects the time to set a psychophysical judgment of the location of some stimulus details. This interpretation was based on an detailed analysis of error rates.

Shepard and Cooper (1982) claimed that the linear trend of RTs is not sufficient to deduce the use of a mental rotation process. We have to be sure that the product of mental rotation is available for other processing, and that the rotation is continuous, i.e. the representation is moved through the different intermediate steps during the rotation. As mentioned by Dean (1990), these two conditions have not yet been explored in developmental studies.

Finally, in these mental rotation tasks, two end-states of stimuli have to be compared. In such a context, is it fundamentally necessary to use mental rotation as defined in the pioneering study (Shepard & Metzler, 1971) ? In fact, Dean (1990) and myself (Lejeune & Decker, 1994) have proposed that in tasks using stimuli rotated in the picture plane, other perceptual processes might be used. This interpretation was in fact initially proposed by Piaget and Inhelder (1966). These perceptual processes would engage the activation of multiple eye movements to compare the rotated stimulus to the same stimulus in its canonical (or learned) orientation. I think that depth rotations might avoid such processes, or at least, necessarily engage other transformational imagery subsystems (see Lejeune & Decker, 1994).

In conclusion, in the light of these previous comments, mental chronometry does not seem to provide clear and absolute evidence for the use of imagery processes in children and probably in the elderly. However, whatever the interpretation of the RT patterns, it does not invalidate the data and the interpretations reported in the present thesis. Indeed, the purpose of this thesis was not to understand how subjects solve a mental rotation task at different ages but rather to investigate the development of related processes, namely the ability to maintain visuo-spatial information in STM, and how these related processes affect information processing during a mental rotation task.

Mental scanning tasks

The mental scanning tasks used in my experimental contribution are probably the most critical ones. Introspectively, we have the impression of being able to scan the image of a well known pattern. Kosslyn *et al.*'s (1978) pioneering study, although open to criticism, was probably the best study to assess mental scanning ability. The new paradigm (see Finke & Pinker, 1982) is fundamentally different from the first one. Image scanning is no longer carried out on an image generated from long term memory but rather on an iconic trace. This iconic trace has its origin in the stimulation of the retina by a pattern displayed on a computer screen. A problem is that this computer screen is a two-dimensional space (Pylyshyn, 1984). Consequently, there might be a risk of confusion between the screen properties and those of the visual buffer. Eye movements might explain RTs patterns: The time required to move the eyes would result in increased RTs (the longer the distance to scan is, the bigger the eye movements are).

It is not obvious that the processes engaged in this new paradigm are similar to those observed with Kosslyn's (1978) method. However, it is unthinkable that we could use Kosslyn's method in developmental studies - especially with children. In fact, in an unpublished study, I (Lejeune, 1993) tried to use Kosslyn's method with young children but only negative results could be reported. Children did not seem to understand the instructions and encountered real difficulties in memorizing the accurate locations of the details on the general pattern.

Other general methodological issues

Subject sampling

A central issue in developmental studies is the age of the subjects. We have seen in chapter 2 that age categories in previously published studies on mental rotation have not always been the same. However, it seems that a distinction between preoperational and operational children is relevant. Consequently, the selection of the ages five and eight in children is relevant. However, the level of operativity has not been measured in children. Consequently, it might be that some of them had a level of operational development different from that supposed to be attained on the basis of their chronological age.

Moreover, in children, age categories were spread over six months. So, a child in the "five-years-old" category could have been four years and nine months old or five years and three months old. Six months in the life of a child is quite a long period of time. However, this is a classical way to define an age category. This could partially explain why the individual differences were important in children. I have analysed the data from means, i.e. I have probably included in the same set of data, performance of children who had different levels of development. I think that we would gain in developmental studies by accurately analysing individual performance.

Similarly, the age of the elderly people generally varied between 65 and 80 years-old. They were all supposed to be healthy. However, the limits between normal and pathological development in elderly are often tiny (see Assal & Machado, 1993). Consequently, subjects tested were probably at a different level of development. With the elderly, we are also confronted with huge individual differences; this is a common issue while investigating ageing (see Ferrandez, 1993). Here again, single case studies would be valuable.

The different levels of development in children and the elderly which have not been controlled in my experiments might explain why I observed some differences across experiments for an identical task in a same age category (see for instance, mental rotation performances in experiments 1 and 2).

Another aspect which could have been interesting in studying the development of imagery is the sex variable. It is now commonly shown that males are usually more efficient than females in spatial processing (at least in young adults). This aspect has not been addressed in the present thesis.

Material used

The application of methodologies used in young adults to children and elderly should not only be considered with reference to theoretical issues but also with reference to the adequacy of the material used to test particular groups of subjects. Specifically, the material basically consisted most of the time in the presentation of visual stimuli on a *computer* screen. If it is more and more common for a child to use computers in the context of his/her games, elderly people are often reluctant to use computers. These machines seem often to be mysterious to them and their comments during task solving make me think that they are scared by the situation. It could also influence their information processing times.

However, as previous studies used similar methodologies, comparisons across experiments are possible. In the near future, new paradigms should be formulated to avoid the interference of a particular material on the performance of subjects.

Perspectives

At present, most of the developmental studies have tried to show differences between children, the elderly and young adults. Young adults have been considered as the reference. Methodologies used with young adults have been applied to different age categories and different patterns of responses have emerged. It has led to the conclusion that children and elderly are poorer at performing imagery tasks than young adults.

However, I think that most developmental studies have considered imagery from a perspective that is too general. Mental rotation, mental scanning, or other transformational imagery sub systems have been considered in a very simplistic way. Their development has been approached as if they consisted of small individual boxes in a cognitive system. Developmental psychology has approached imagery the way it was conceived in the first theoretical models of imagery (see Kosslyn, 1980). Indeed, in these models, the whole system consisted of the juxtaposition of a set of boxes. The ROTATE box referred to the mental rotation process, just as the SCAN box referred to the mental scanning process.

Contemporary cognitive psychology tries to decompose complex processes into several subsystems. Indeed, Kosslyn (1994) modified his early model of imagery functioning in light of research in the neurosciences. He demonstrated that the former "boxes" (especially those concerning the transformational imagery subsystems) have to be considered in connection with several subsystems of high level vision. Imagery architecture is a complex system with multiple interconnected units. In this reformulation of the initial model, he did not refer to developmental studies. I think that it is also the role of developmental psychology to consider the development of these subsystems in the functioning of complex processes such as mental rotation or mental scanning. The relation between transformational imagery sub systems and the ability to maintain visuo-spatial information has been studied in this thesis.

However, a huge amount of work has still to be done to decompose the different subsystems and to understand their genesis. In this thesis, only a small aspect has been considered. Even for this aspect, namely the maintenance of visuo-spatial information in the visual buffer, many studies are required to understand the complexity of this process. The experiments reported have suggested a decomposition between the visual and the spatial components. It appeared that both components could develop differently across ages: The spatial component could be more sensitive to age. However, this spatial component itself is not yet clearly defined. It seems that the "dorsal system" in Kosslyn's (1994) model might be itself decomposed into other units. Kosslyn (1994) himself wrote with humour that although his model seems to be complicated and has been sometimes described as an encyclopedia, it is not yet probably sufficiently complex to account for the different processes humans can carry out.

Other aspects of the whole system will have to be considered in future research. Some have already approached the relationship between imagery and visual perception (for instance in the context of object recognition, see Lejeune, 1992b). The memorisation of location (e.g. Ellis, Katz & William, 1987) has also been considered. Attentional processes also seem to be a good candidate to account for developmental differences. Indeed, the transformational imagery sub systems have been proposed to be strongly related to the central executive in Logie's (1995) model. The understanding of the development of such a system in the context of imagery tasks seems to be necessary.

The decomposition of the "Big Picture" will have to go through the creation of new methodologies as well. You may recall that the history of imagery has been stormy (see chapter 1), and debates were resolved thanks to the use of new approaches, especially neuroscientific ones. Developmental studies should also be innovative in their approach. They should not be limited to the methodologies used in young adults. Moreover, I am firmly convinced that developmental psychology would gain from the analysis of single case performances. We have seen the development of a similar necessity in neuropsychology. Individual differences are too broad and mean values might hide reality. Piagetian studies were in this context far more informative than any other developmental studies.

The time is ripe for an integration of several approaches. Developmental psychology has its role to play in the understanding of cognitive functions. It has a seat in the Parliament of Science besides general cognitive psychology, neuropsychology, comparative psychology, and neurobiology. I am convinced that developmental psychology will shed some light on the complex network of the imagery subsystems.

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APPENDIX 1

Experiment 1:

Mental rotation tasks

Means and standard deviations as a function of task, stimulus orientation and age.

Five-year-olds: Mannequins Task

0°	60°	120°	180°
m: 5.79 s: 0.41	m: 5.45 s: 0.97	m: 5.00 s: 1.1	m: 3.91 s: 1.06

Five-year-olds: Cones Task

0°	60°	120°	180°
m: 5.83 s: 0.38	m: 5.45 s: 0.72	m: 4.71 s: 1.3	m: 3.45 s: 1.67

Five-year-olds: L Task

0°	60°	120°	180°
m: 5.83 s: 0.38	m: 5.45 s: 0.72	m: 4.2 s: 1.88	m: 3.63 s: 1.81

Eight-year-olds: Mannequins Task

0°	60°	120°	180°
m: 4.41 s: 1.44	m: 4.12 s: 1.54	m: 3.95 s: 1.39	m: 3.29 s: 0.95

Eight-year-olds: Cones Task

0°	60°	120°	180°
m: 4.75 s: 1.32	m: 4.25 s: 1.35	m: 3.95 s: 1.48	m: 3.70 s: 1.54

Eight-year-olds: L Task

0°	60°	120°	180°
m: 4.75 s: 1.45	m: 4.12 s: 1.29	m: 3.54 s: 1.66	m: 3.54 s: 1.66

APPENDIX 1 (continued)

Young adults: Mannequins Task

0°	60°	120°	180°
m: 5.75 s: 0.67	m: 5.62 s: 0.64	m: 5.41 s: 1.05	m: 4.41 s: 0.65

Young adults: Cones Task

0°	60°	120°	180°
m: 5.5 s: 0.83	m: 5.75 s: 0.60	m: 5.66 s: 0.63	m: 5.66 s: 0.86

Young adults: L Task

0°	60°	120°	180°
m: 5.62 s: 0.64	m: 5.70 s: 0.62	m: 5.62 s: 0.92	m: 5.25 s: 0.98

Elderly people: Mannequins Task

0°	60°	120°	180°
m: 5.25 s: 1.03	m: 5.00 s: 1.14	m: 4.83 s: 1.09	m: 3.58 s: 1.21

Elderly people: Cones Task

0°	60°	120°	180°
m: 5.54 s: 1.10	m: 5.50 s: 1.10	m: 5.04 s: 0.99	m: 4.66 s: 1.01

Elderly people: L Task

0°	60°	120°	180°
m: 5.13 s: 1.65	m: 5.25 s: 1.36	m: 4.83 s: 1.37	m: 4.66 s: 1.49

APPENDIX 2

Experiment 2:

Mental rotation tasks

Means and standard deviations as a function of task, stimulus orientation and age.

Five-year-olds: Mannequins Task

0°	60°	120°	180°
m: 0.16 s: 0.57	m: 1.33 s: 1.55	m: 2.83 s: 1.69	m: 3.58 s: 2.27

Five-year-olds: Cones Task

0°	60°	120°	180°
m: 1.16 s: 1.11	m: 2.91 s: 1.92	m: 3.08 s: 2.1	m: 0.58 s: 1.51

Five-year-olds: L Task

0°	60°	120°	180°
m: 0.58 s: 1.51	m: 1.66 s: 1.96	m: 2.25 s: 2.3	m: 3.66 s: 2.01

Eight-year-olds: Mannequins Task

0°	60°	120°	180°
m: 0.33 s: 0.88	m: 0.5 s: 1.00	m: 0.66 s: 1.61	m: 1.58 s: 1.56

Eight-year-olds: Cones Task

0°	60°	120°	180°
m: 0.25 s: 0.86	m: 0.41 s: 1.16	m: 0.58 s: 0.79	m: 1.33 s: 1.49

Eight-year-olds: L Task

0°	60°	120°	180°
m: 0.08 s: 0.28	m: 0.25 s: 0.45	m: 0.5 s: 0.67	m: 0.91 s: 1.24

APPENDIX 2 (continued)

Young adults: Mannequins Task

0°	60°	120°	180°
m: 0.25 s: 0.45	m: 0 s: 0	m: 0.16 s: 0.38	m: 0.41 s: 0.9

Young adults: Cones Task

0°	60°	120°	180°
m: 0.08 s: 0.28	m: 0.08 s: 0.28	m: 0 s: 0	m: 0 s: 0

Young adults: L Task

0°	60°	120°	180°
m: 0.16 s: 0.38	m: 0.33 s: 0.77	m: 0.16 s: 0.38	m: 0.33 s: 0.88

Elderly: Mannequins Task

0°	60°	120°	180°
m: 1.00 s: 1.2	m: 0.41 s: 0.99	m: 1.16 s: 1.11	m: 1.66 s: 1.43

Elderly: Cones Task

0°	60°	120°	180°
m: 1.25 s: 1.28	m: 1.83 s: 1.69	m: 1.58 s: 1.62	m: 2.41 s: 2.46

Elderly: L Task

0°	60°	120°	180°
m: 1.08 s: 1.44	m: 1.25 s: 1.28	m: 1.58 s: 1.72	m: 2.5 s: 1.38

APPENDIX 3

Experiment 3a:

Mental rotation tasks

Means and standard deviations as a function of experimental condition, and age.

Five-year-olds: Without advanced information

0°	60°	120°	180°	240°	300°
m: 3300 s: 979	m: 4597 s: 1241	m: 4368 s: 1966	m: 4857 s: 1424	m: 4204 s: 1405	m: 3704 s: 1187
me: 3.5 s: 0.77	me: 3.58 s: 0.49	me: 3.33 s: 0.75	me: 3.25 s: 0.82	me: 3.00 s: 0.89	me: 3.33 s: 0.6

Five-year-olds: Advanced information, retention interval: 1000 msec.

0°	60°	120°	180°	240°	300°
m: 2773 s: 877	m: 3537 s: 1119	m: 3306 s: 1180	m: 4479 s: 1500	m: 3673 s: 1010	m: 3318 s: 1297
me: 3.6 s: 0.41	me: 3.41 s: 0.58	me: 3.16 s: 0.75	me: 2.91 s: 1.39	me: 3.08 s: 1.11	me: 3.58 s: 0.8

Five-year-olds: Advanced information, retention interval: 500 msec.

0°	60°	120°	180°	240°	300°
m: 2565 s: 738	m: 2855 s: 990	m: 2711 s: 1111	m: 2842 s: 845	m: 2405 s: 636	m: 2541 s: 786
me: 3.83 s: 0.41	me: 3.41 s: 1.02	me: 3.66 s: 0.4	me: 3.33 s: 0.87	me: 3.33 s: 0.93	me: 3.75 s: 0.42

Eight-year-olds: Without advanced information

0°	60°	120°	180°	240°	300°
m: 1853 s: 583	m: 2428 s: 1225	m: 2555 s: 1357	m: 2985 s: 1041	m: 2494 s: 1338	m: 2227 s: 1117
me: 4.00 s: 0.00	me: 3.5 s: 0.84	me: 3.75 s: 0.42	me: 3.66 s: 0.61	me: 3.33 s: 0.98	me: 3.58 s: 0.38

Eight-year-olds: Advanced information, retention interval: 1000 msec.

0°	60°	120°	180°	240°	300°
m: 1466 s: 228	m: 1707 s: 429	m: 1653 s: 337	m: 1404 s: 198	m: 1455 s: 282	m: 1456 s: 350
me: 3.91 s: 0.2	me: 3.83 s: 0.26	me: 4.00 s: 0.00	me: 3.83 s: 0.26	me: 3.91 s: 0.2	me: 4.00 s: 0.00

Eight-year-olds: Advanced information, retention interval: 500 msec.

0°	60°	120°	180°	240°	300°
m: 1529 s: 556	m: 1561 s: 411	m: 1472 s: 292	m: 1656 s: 477	m: 1446 s: 389	m: 1394 s: 366
me: 3.66 s: 0.26	me: 3.91 s: 0.2	me: 3.75 s: 0.42	me: 3.66 s: 0.82	me: 3.83 s: 0.26	me: 3.91 s: 0.2

Young adults: Without advanced information

0°	60°	120°	180°	240°	300°
m: 847 s: 224	m: 1087 s: 378	m: 1150 s: 387	m: 1464 s: 430	m: 1203 s: 368	m: 1022 s: 369
me: 3.91 s: 0.2	me: 3.83 s: 0.26	me: 3.91 s: 0.2	me: 3.75 s: 0.42	me: 3.83 s: 0.26	me: 3.75 s: 0.27

Young adults: Advanced information, retention interval: 1000 msec.

0°	60°	120°	180°	240°	300°
m: 660 s: 185	m: 851 s: 250	m: 798 s: 215	m: 758 s: 221	m: 796 s: 225	m: 760 s: 254
me: 3.66 s: 0.41	me: 3.58 s: 0.58	me: 3.66 s: 0.25	me: 3.5 s: 0.63	me: 4.00 s: 0.00	me: 3.83 s: 0.26

Young adults: Advanced information, retention interval: 500 msec.

0°	60°	120°	180°	240°	300°
m: 597 s: 98	m: 626 s: 153	m: 577 s: 130	m: 614 s: 201	m: 583 s: 113	m: 563 s: 104
me: 3.91 s: 0.20	me: 3.58 s: 0.58	me: 3.66 s: 0.61	me: 3.41 s: 0.66	me: 4.00 s: 0.00	me: 3.83 s: 0.41

Elderly people: Without advanced information

0°	60°	120°	180°	240°	300°
m: 1717 s: 774	m: 2710 s: 1680	m: 2981 s: 2306	m: 4276 s: 3864	m: 2907 s: 2205	m: 2209 s: 1160
me: 3.75 s: 0.42	me: 3.58 s: 0.37	me: 3.66 s: 0.61	me: 3.91 s: 1.39	me: 3.75 s: 0.61	me: 3.83 s: 0.41

Elderly people: Advanced information, retention interval: 1000 msec.

0°	60°	120°	180°	240°	300°
m: 2419 s: 1701	m: 3180 s: 2541	m: 3414 s: 3658	m: 3347 s: 3041	m: 2856 s: 2776	m: 3680 s: 5362
me: 3.91 s: 0.2	me: 3.75 s: 0.42	me: 3.41 s: 0.74	me: 3.00 s: 1.04	me: 3.41 s: 0.73	me: 3.58 s: 0.66

Elderly people: Advanced information, retention interval: 500 msec.

0°	60°	120°	180°	240°	300°
m: 2312 s: 1696	m: 3304 s: 2333	m: 2766 s: 2611	m: 2840 s: 2572	m: 2523 s: 2363	m: 2770 s: 2885
me: 3.58 s: 0.38	me: 3.83 s: 0.25	me: 3.83 s: 0.26	me: 3.66 s: 0.61	me: 3.66 s: 0.41	me: 3.5 s: 0.54

APPENDIX 4

Experiment 3b:

Mental rotation tasks

Means and standard deviations as a function of experimental condition, and age.

Five-year-olds: Retention interval, 1000 msec.

0°	60°	120°	180°
m: 2175 s: 423	m: 2838 s: 801	m: 3205 s: 1225	m: 3214 s: 1392
me: 1.00 s: 1.04	me: 1.91 s: 1.24	me: 2.25 s: 1.54	me: 2.83 s: 2.48

Five-year-olds: Retention interval, 500 msec.

0°	60°	120°	180°
m: 2307 s: 591	m: 2632 s: 392	m: 2800 s: 612	m: 3534 s: 1343
me: 0.91 s: 1.56	me: 2.41 s: 1.16	me: 2.41 s: 1.16	me: 3.00 s: 1.8

Eight-year-olds: Retention interval, 1000 msec.

0°	60°	120°	180°
m: 1827 s: 411	m: 1765 s: 211	m: 1838 s: 256	m: 1859 s: 312
me: 0.75 s: 0.62	me: 0.83 s: 0.93	me: 1.33 s: 1.55	me: 1.5 s: 1.78

Eight-year-olds: Retention interval, 500 msec.

0°	60°	120°	180°
m: 1636 s: 230	m: 1748 s: 244	m: 1725 s: 237	m: 1673 s: 286
me: 0.16 s: 0.38	me: 0.66 s: 0.77	me: 0.83 s: 1.26	me: 0.5 s: 0.52

APPENDIX 4 (continued)

Young adults: Retention interval, 1000 msec.

0°	60°	120°	180°
m: 933 s: 174	m: 1102 s: 312	m: 1043 s: 182	m: 1034 s: 290
me: 0.33 s: 0.65	me: 0.42 s: 0.51	me: 0.75 s: 0.86	me: 0.5 s: 0.79

Young adults: Retention interval, 500 msec.

0°	60°	120°	180°
m: 935 s: 256	m: 1076 s: 269	m: 1054 s: 206	m: 993 s: 197
me: 0.33 s: 0.65	me: 0.08 s: 0.28	me: 0.25 s: 0.45	me: 0.41 s: 0.51

APPENDIX 4 (continued)

Elderly people: Retention interval, 1000 msec.

0°	60°	120°	180°
m: 2091 s: 302	m: 2296 s: 506	m: 2610 s: 553	m: 2894 s: 848
me: 0.75 s: 0.86	me: 0.91 s: 0.79	me: 1.25 s: 0.86	me: 2.41 s: 0.99

Elderly people: Retention interval, 500 msec.

0°	60°	120°	180°
m: 2287 s: 460	m: 2463 s: 368	m: 2709 s: 519	m: 2783 s: 433
me: 0.25 s: 0.45	me: 1.42 s: 0.79	me: 1.83 s: 1.19	me: 2.66 s: 0.88

APPENDIX 5

Experiment 3c:

Mental rotation tasks

Reaction times: Means and standard deviations as a function of experimental condition, and age (l > lm: L normal followed by L mirror-reversed; l > l: L normal followed by L normal; c > c: C followed by C; and c > l: C followed by L normal).

Five-year-olds: Retention interval, 500 msec

0°	60°	120°	180°
m(l > lm): 2305 s: 791	m(l > lm): 2672 s: 792	m(l > lm): 2576 s: 1057	m(l > lm): 2618 s: 969
m(l > l): 2451 s: 991	m(l > l): 2605 s: 835	m(l > l): 2594 s: 915	m(l > l): 2634 s: 929
m(c > c): 2405 s: 862	m(c > c): 2516 s: 696	m(c > c): 2519 s: 900	m(c > c): 2526 s: 819
m(c > l): 2314 s: 683	m(c > l): 2408 s: 698	m(c > l): 2388 s: 715	m(c > l): 2383 s: 692

Five-year-olds: Retention interval, 1000 msec

0°	60°	120°	180°
m(l > lm): 2556 s: 853	m(l > lm): 3207 s: 924	m(l > lm): 3424 s: 1253	m(l > lm): 4470 s: 1455
m(l > l): 2533 s: 825	m(l > l): 2857 s: 809	m(l > l): 3094 s: 864	m(l > l): 3836 s: 954
m(c > c): 2505 s: 818	m(c > c): 2723 s: 844	m(c > c): 2884 s: 831	m(c > c): 3092 s: 991
m(c > l): 2308 s: 797	m(c > l): 2409 s: 761	m(c > l): 2384 s: 853	m(c > l): 2416 s: 764

APPENDIX 5 (continued)

Eight-year-olds: Retention interval, 500 msec

0°	60°	120°	180°
m(l > lm): 1365 s: 469	m(l > lm): 1503 s: 419	m(l > lm): 1525 s: 357	m(l > lm): 1680 s: 431
m(l > l): 1362 s: 376	m(l > l): 1482 s: 407	m(l > l): 1476 s: 339	m(l > l): 1588 s: 430
m(c > c): 1372 s: 441	m(c > c): 1445 s: 444	m(c > c): 1449 s: 391	m(c > c): 1515 s: 421
m(c > l): 1247 s: 381	m(c > l): 1279 s: 369	m(c > l): 1263 s: 396	m(c > l): 1310 s: 410

Eight-year-olds: Retention interval, 1000 msec

0°	60°	120°	180°
m(l > lm): 1427 s: 268	m(l > lm): 1653 s: 340	m(l > lm): 1633 s: 269	m(l > lm): 1559 s: 198
m(l > l): 1451 s: 288	m(l > l): 1557 s: 259	m(l > l): 1644 s: 337	m(l > l): 1570 s: 229
m(c > c): 1425 s: 305	m(c > c): 1393 s: 279	m(c > c): 1480 s: 363	m(c > c): 1549 s: 253
m(c > l): 1382 s: 197	m(c > l): 1386 s: 282	m(c > l): 1442 s: 227	m(c > l): 1423 s: 245

Young adults: Retention interval, 500 msec

0°	60°	120°	180°
m(l > lm): 585 s: 110	m(l > lm): 592 s: 128	m(l > lm): 595 s: 130	m(l > lm): 623 s: 150
m(l > l): 568 s: 109	m(l > l): 575 s: 111	m(l > l): 581 s: 116	m(l > l): 586 s: 114
m(c > c): 571 s: 111	m(c > c): 574 s: 112	m(c > c): 584 s: 117	m(c > c): 584 s: 112
m(c > l): 581 s: 110	m(c > l): 585 s: 105	m(c > l): 582 s: 113	m(c > l): 589 s: 109

Young adults Retention interval, 1000 msec

0°	60°	120°	180°
m(l > lm): 655 s: 225	m(l > lm): 775 s: 233	m(l > lm): 768 s: 230	m(l > lm): 770 s: 199
m(l > l): 652 s: 220	m(l > l): 665 s: 217	m(l > l): 676 s: 230	m(l > l): 679 s: 231
m(c > c): 651 s: 198	m(c > c): 649 s: 186	m(c > c): 666 s: 210	m(c > c): 665 s: 193
m(c > l): 663 s: 212	m(c > l): 679 s: 229	m(c > l): 686 s: 234	m(c > l): 685 s: 232

Elderly people: Retention interval, 500 msec

0°	60°	120°	180°
m(l > lm): 2124 s: 1490	m(l > lm): 2724 s: 1907	m(l > lm): 2695 s: 2317	m(l > lm): 2922 s: 2466
m(l > l): 2326 s: 1776	m(l > l): 2455 s: 1783	m(l > l): 2629 s: 2248	m(l > l): 2778 s: 2212
m(c > c): 2222 s: 1598	m(c > c): 2457 s: 1918	m(c > c): 2619 s: 2147	m(c > c): 2612 s: 2101
m(c > l): 2013 s: 1459	m(c > l): 2082 s: 1484	m(c > l): 2314 s: 2110	m(c > l): 2313 s: 2005

Elderly people: Retention interval, 1000 msec

0°	60°	120°	180°
m(l > lm): 2032 s: 1217	m(l > lm): 2445 s: 1307	m(l > lm): 3296 s: 2338	m(l > lm): 3662 s: 2383
m(l > l): 2040 s: 1195	m(l > l): 2303 s: 1268	m(l > l): 2805 s: 1441	m(l > l): 3089 s: 1686
m(c > c): 2045 s: 1229	m(c > c): 2163 s: 1251	m(c > c): 2435 s: 1351	m(c > c): 2536 s: 1329
m(c > l): 1871 s: 1179	m(c > l): 1943 s: 1179	m(c > l): 1926 s: 1213	m(c > l): 1962 s: 1181

Experiment 3c:

Mental rotation tasks

Errors: Means and standard deviations as a function of experimental condition, and age (l > lm: L normal followed by L mirror-reversed; l > l: L normal followed by L normal; c > c: C followed by C; and c > l: C followed by L normal).

Five-year-olds: Retention interval, 500 msec

0°	60°	120°	180°
m(l > lm): 0.25 s: 0.45	m(l > lm): 0.16 s: 0.38	m(l > lm): 0.33 s: 0.65	m(l > lm): 0.41 s: 0.66
m(l > l): 0.33 s: 0.65	m(l > l): 0.25 s: 0.62	m(l > l): 0.16 s: 0.38	m(l > l): 0.5 s: 0.67
m(c > c): 0.25 s: 0.45	m(c > c): 0.25 s: 0.45	m(c > c): 0.33 s: 0.65	m(c > c): 0.5 s: 0.79
m(c > l): 0.16 s: 0.38	m(c > l): 0.25 s: 0.45	m(c > l): 0.16 s: 0.38	m(c > l): 0.33 s: 0.65

Five-year-olds: Retention interval, 1000 msec

0°	60°	120°	180°
m(l > lm): 0.41 s: 0.51	m(l > lm): 0.5 s: 0.67	m(l > lm): 0.75 s: 0.75	m(l > lm): 1.16 s: 0.38
m(l > l): 0.33 s: 0.49	m(l > l): 0.41 s: 0.51	m(l > l): 0.66 s: 0.65	m(l > l): 1.08 s: 0.28
m(c > c): 0.41 s: 0.66	m(c > c): 0.66 s: 0.65	m(c > c): 0.66 s: 0.49	m(c > c): 0.91 s: 0.66
m(c > l): 0.25 s: 0.45	m(c > l): 0.41 s: 0.51	m(c > l): 0.33 s: 0.49	m(c > l): 0.41 s: 0.51

APPENDIX 5 (continued)

Eight-year-olds: Retention interval, 500 msec

0°	60°	120°	180°
m(l > lm): 0.08 s: 0.28	m(l > lm): 0.08 s: 0.28	m(l > lm): 0.08 s: 0.28	m(l > lm): 0.25 s: 0.62
m(l > l): 0.08 s: 0.28	m(l > l): 0.08 s: 0.28	m(l > l): 0.08 s: 0.28	m(l > l): 0 s: 0
m(c > c): 0.16 s: 0.38	m(c > c): 0 s: 0	m(c > c): 0.08 s: 0.28	m(c > c): 0.25 s: 0.62
m(c > l): 0 s: 0	m(c > l): 0.16 s: 0.38	m(c > l): 0 s: 0	m(c > l): 0.08 s: 0.28

Eight-year-olds: Retention interval, 1000 msec

0°	60°	120°	180°
m(l > lm): 0.25 s: 0.45	m(l > lm): 0.16 s: 0.38	m(l > lm): 0.25 s: 0.45	m(l > lm): 0.33 s: 0.65
m(l > l): 0.16 s: 0.38	m(l > l): 0.08 s: 0.28	m(l > l): 0.16 s: 0.38	m(l > l): 0.25 s: 0.62
m(c > c): 0.16 s: 0.57	m(c > c): 0.25 s: 0.45	m(c > c): 0.16 s: 0.57	m(c > c): 0.16 s: 0.38
m(c > l): 0.08 s: 0.28	m(c > l): 0.08 s: 0.28	m(c > l): 0.25 s: 0.62	m(c > l): 0.08 s: 0.28

APPENDIX 5 (continued)

Young adults: Retention interval, 500 msec

0°	60°	120°	180°
m(l > lm): 0.25 s: 0.45	m(l > lm): 0.08 s: 0.28	m(l > lm): 0.16 s: 0.38	m(l > lm): 0.25 s: 0.45
m(l > l): 0.08 s: 0.28	m(l > l): 0.08 s: 0.28	m(l > l): 0.16 s: 0.38	m(l > l): 0.16 s: 0.38
m(c > c): 0.25 s: 0.62	m(c > c): 0.08 s: 0.28	m(c > c): 0.16 s: 0.38	m(c > c): 0.25 s: 0.62
m(c > l): 0.08 s: 0.28	m(c > l): 0.08 s: 0.28	m(c > l): 0.16 s: 0.38	m(c > l): 0.25 s: 0.62

Young adults Retention interval, 1000 msec

0°	60°	120°	180°
m(l > lm): 0.08 s: 0.28	m(l > lm): 0.16 s: 0.38	m(l > lm): 0.16 s: 0.38	m(l > lm): 0.5 s: 0.67
m(l > l): 0.08 s: 0.28	m(l > l): 0 s: 0	m(l > l): 0.16 s: 0.38	m(l > l): 0.33 s: 0.65
m(c > c): 0 s: 0	m(c > c): 0.08 s: 0.28	m(c > c): 0.25 s: 0.45	m(c > c): 0.16 s: 0.38
m(c > l): 0 s: 0	m(c > l): 0.08 s: 0.28	m(c > l): 0.08 s: 0.28	m(c > l): 0.16 s: 0.38

Elderly people: Retention interval, 500 msec

0°	60°	120°	180°
m(l > lm): 0.16 s: 0.38	m(l > lm): 0.16 s: 0.38	m(l > lm): 0.08 s: 0.28	m(l > lm): 0.33 s: 0.49
m(l > l): 0.16 s: 0.38	m(l > l): 0.16 s: 0.38	m(l > l): 0.08 s: 0.28	m(l > l): 0.33 s: 0.49
m(c > c): 0.25 s: 0.45	m(c > c): 0.16 s: 0.38	m(c > c): 0.08 s: 0.28	m(c > c): 0.33 s: 0.49
m(c > l): 0.08 s: 0.28	m(c > l): 0.08 s: 0.28	m(c > l): 0.33 s: 0.65	m(c > l): 0.16 s: 0.38

Elderly people: Retention interval, 1000 msec

0°	60°	120°	180°
m(l > lm): 0.58 s: 0.51	m(l > lm): 0.41 s: 0.51	m(l > lm): 0.91 s: 0.66	m(l > lm): 1.08 s: 0.66
m(l > l): 0.41 s: 0.51	m(l > l): 0.41 s: 0.51	m(l > l): 0.75 s: 0.62	m(l > l): 0.91 s: 0.28
m(c > c): 0.33 s: 0.49	m(c > c): 0.33 s: 0.49	m(c > c): 0.66 s: 0.49	m(c > c): 0.58 s: 0.51
m(c > l): 0.16 s: 0.38	m(c > l): 0.25 s: 0.45	m(c > l): 0.25 s: 0.45	m(c > l): 0.5 s: 0.52

APPENDIX 6

Experiment 4a

Means and standard deviations

Five-year-olds: Perceptual Control - ANIMASK version - Order Imagery > Perception

Short -Yes	Medium - Yes	Long - Yes	Short -No	Medium - No	Long - No
m: 3.5 s: 1.16	m: 3.83 s: 0.38	m: 3.5 s: 0.79	m: 2.91 s: 1.44	m: 3.0 s: 1.21	m: 3.2 s: 1.19

Five-year-olds: Imagery task - ANIMASK version - Order Imagery > Perception

Short -Yes	Medium - Yes	Long - Yes	Short -No	Medium - No	Long - No
m: 2.25 s: 1.48	m: 2.08 s: 1.37	m: 1.75 s: 1.42	m: 2.0 s: 1.53	m: 2.16 s: 1.26	m: 1.91 s: 1.56

Five-year-olds: Perceptual Control - ANIMASK version - Order Perception > Imagery

Short -Yes	Medium - Yes	Long - Yes	Short -No	Medium - No	Long - No
m: 3.75 s: 0.86	m: 3.58 s: 1.16	m: 3.41 s: 1.16	m: 3.25 s: 0.75	m: 3.75 s: 0.45	m: 3.5 s: 0.67

Five-year-olds: Imagery task - ANIMASK version - Order Perception > Imagery

Short -Yes	Medium - Yes	Long - Yes	Short -No	Medium - No	Long - No
m: 3.0 s: 1.12	m: 2.58 s: 1.24	m: 2.5 s: 1.24	m: 1.75 s: 1.05	m: 1.75 s: 0.96	m: 2.0 s: 1.04

APPENDIX 6 (continued)

Five-year-olds: Perceptual Control - SCAN version - Order Imagery > Perception

Short -Yes	Medium - Yes	Long - Yes	Short -No	Medium - No	Long - No
m: 3.16 s: 1.34	m: 2.75 s: 1.54	m: 2.75 s: 1.6	m: 3.16 s: 1.4	m: 2.83 s: 1.52	m: 2.83 s: 1.58

Five-year-olds: Imagery task - SCAN version - Order Imagery > Perception

Short -Yes	Medium - Yes	Long - Yes	Short -No	Medium - No	Long - No
m: 2.91 s: 1.5	m: 2.75 s: 1.48	m: 2.33 s: 1.61	m: 2.25 s: 1.06	m: 2.16 s: 1.4	m: 2.58 s: 1.51

Five-year-olds: Perceptual Control - SCAN version - Order Perception > Imagery

Short -Yes	Medium - Yes	Long - Yes	Short -No	Medium - No	Long - No
m: 3.58 s: 0.66	m: 3.16 s: 0.83	m: 3.25 s: 0.96	m: 2.58 s: 1.08	m: 2.91 s: 0.9	m: 3.16 s: 0.83

Five-year-olds: Imagery task - SCAN version - Order Perception > Imagery

Short -Yes	Medium - Yes	Long - Yes	Short -No	Medium - No	Long - No
m: 3.16 s: 0.83	m: 3.08 s: 1.24	m: 2.58 s: 1.24	m: 2.33 s: 1.15	m: 2.25 s: 1.13	m: 2.33 s: 0.98

APPENDIX 6 (continued)

Eight-year-olds: Perceptual Control - ANIMASK version - Order Imagery > Perception

Short -Yes	Medium - Yes	Long - Yes	Short -No	Medium - No	Long - No
m: 3.66 s: 1.15	m: 3.5 s: 1.16	m: 3.41 s: 1.37	m: 3.5 s: 0.67	m: 3.75 s: 0.45	m: 3.83 s: 0.38

Eight-year-olds: Imagery task - ANIMASK version - Order Imagery > Perception

Short -Yes	Medium - Yes	Long - Yes	Short -No	Medium - No	Long - No
m: 3.58 s: 0.66	m: 3.16 s: 0.71	m: 2.75 s: 1.28	m: 2.0 s: 0.73	m: 2.25 s: 1.13	m: 2.25 s: 1.48

Eight-year-olds: Perceptual Control - ANIMASK version - Order Perception > Imagery

Short -Yes	Medium - Yes	Long - Yes	Short -No	Medium - No	Long - No
m: 3.66 s: 0.49	m: 3.66 s: 0.49	m: 3.58 s: 0.51	m: 3.75 s: 0.45	m: 3.83 s: 0.38	m: 3.75 s: 0.45

Eight-year-olds: Imagery task - ANIMASK version - Order Perception > Imagery

Short -Yes	Medium - Yes	Long - Yes	Short -No	Medium - No	Long - No
m: 3.33 s: 1.07	m: 3.0 s: 0.73	m: 3.25 s: 0.86	m: 2.5 s: 0.9	m: 3.0 s: 0.95	m: 2.0 s: 0.85

APPENDIX 6 (continued)

Eight-year-olds: Perceptual Control - SCAN version - Order Imagery > Perception

Short -Yes	Medium - Yes	Long - Yes	Short -No	Medium - No	Long - No
m: 4.0 s: 0.0	m: 4.0 s: 0.0	m: 3.33 s: 0.65	m: 3.75 s: 0.45	m: 3.91 s: 0.28	m: 3.75 s: 0.45

Eight-year-olds: Imagery task - SCAN version - Order Imagery > Perception

Short -Yes	Medium - Yes	Long - Yes	Short -No	Medium - No	Long - No
m: 4.0 s: 0.0	m: 3.66 s: 0.65	m: 3.91 s: 0.28	m: 3.16 s: 0.83	m: 3.75 s: 0.45	m: 3.41 s: 0.51

Eight-year-olds: Perceptual Control - SCAN version - Order Perception > Imagery

Short -Yes	Medium - Yes	Long - Yes	Short -No	Medium - No	Long - No
m: 3.81 s: 0.4	m: 3.63 s: 0.92	m: 3.72 s: 0.46	m: 3.54 s: 0.93	m: 3.63 s: 0.5	m: 3.81 s: 0.4

Eight-year-olds: Imagery task - SCAN version - Order Perception > Imagery

Short -Yes	Medium - Yes	Long - Yes	Short -No	Medium - No	Long - No
m: 3.54 s: 0.93	m: 3.45 s: 0.68	m: 3.36 s: 0.67	m: 3.27 s: 1.19	m: 3.0 s: 1.26	m: 2.63 s: 1.28

APPENDIX 6 (continued)

Young adults: Perceptual Control - ANIMASK version - Order Imagery > Perception

Short -Yes	Medium - Yes	Long - Yes	Short -No	Medium - No	Long - No
m: 4.00 s: 0.0	m: 3.66 s: 0.49	m: 3.58 s: 0.51	m: 3.91 s: 0.28	m: 3.91 s: 0.28	m: 3.66 s: 0.65

Young adults: Imagery task - ANIMASK version - Order Imagery > Perception

Short -Yes	Medium - Yes	Long - Yes	Short -No	Medium - No	Long - No
m: 3.75 s: 0.45	m: 3.08 s: 0.66	m: 2.83 s: 1.02	m: 2.75 s: 0.96	m: 3.0 s: 1.12	m: 2.83 s: 0.83

Young adults: Perceptual Control - ANIMASK version - Order Perception > Imagery

Short -Yes	Medium - Yes	Long - Yes	Short -No	Medium - No	Long - No
m: 3.66 s: 0.65	m: 4.0 s: 0.0	m: 3.41 s: 0.66	m: 3.75 s: 0.45	m: 3.58 s: 0.51	m: 3.83 s: 0.38

Young adults: Imagery task - ANIMASK version - Order Perception > Imagery

Short -Yes	Medium - Yes	Long - Yes	Short -No	Medium - No	Long - No
m: 3.58 s: 0.66	m: 3.5 s: 0.52	m: 3.08 s: 0.99	m: 3.08 s: 0.79	m: 3.8 s: 0.99	m: 2.75 s: 0.96

APPENDIX 6 (continued)

Young adults: Perceptual Control - SCAN version -
Order Imagery > Perception

Short -Yes	Medium - Yes	Long - Yes	Short -No	Medium - No	Long - No
m: 3.75 s: 0.45	m: 3.75 s: 0.45	m: 3.5 s: 0.67	m: 3.83 s: 0.38	m: 3.75 s: 0.45	m: 3.83 s: 0.38

Young adults Imagery task - SCAN version -
Order Imagery > Perception

Short -Yes	Medium - Yes	Long - Yes	Short -No	Medium - No	Long - No
m: 3.66 s: 0.65	m: 3.66 s: 0.49	m: 3.58 s: 0.66	m: 3.58 s: 0.66	m: 3.75 s: 0.45	m: 3.91 s: 0.28

Young adults: Perceptual Control - SCAN version -
Order Perception > Imagery

Short -Yes	Medium - Yes	Long - Yes	Short -No	Medium - No	Long - No
m: 3.91 s: 0.28	m: 3.75 s: 0.62	m: 3.41 s: 0.66	m: 3.83 s: 0.38	m: 4.0 s: 0.0	m: 3.91 s: 0.28

Young adults: Imagery task - SCAN version -
Order Perception > Imagery

Short -Yes	Medium - Yes	Long - Yes	Short -No	Medium - No	Long - No
m: 3.75 s: 0.45	m: 3.75 s: 0.45	m: 3.58 s: 0.51	m: 3.83 s: 0.38	m: 3.75 s: 0.45	m: 3.58 s: 0.66

APPENDIX 6 (continued)

Elderly: Perceptual Control - ANIMASK version -
Order Imagery > Perception

Short -Yes	Medium - Yes	Long - Yes	Short -No	Medium - No	Long - No
m: 3.41 s: 1.16	m: 3.75 s: 0.62	m: 3.16 s: 0.83	m: 3.5 s: 0.79	m: 2.91 s: 1.16	m: 3.58 s: 0.79

Elderly: Imagery task - ANIMASK version -
Order Imagery > Perception

Short -Yes	Medium - Yes	Long - Yes	Short -No	Medium - No	Long - No
m: 3.58 s: 0.66	m: 3.5 s: 0.52	m: 2.75 s: 0.96	m: 2.25 s: 0.96	m: 2.66 s: 1.07	m: 2.5 s: 0.79

Elderly: Perceptual Control - ANIMASK version -
Order Perception > Imagery

Short -Yes	Medium - Yes	Long - Yes	Short -No	Medium - No	Long - No
m: 4.0 s: 0.0	m: 3.33 s: 0.65	m: 2.91 s: 0.9	m: 3.33 s: 1.15	m: 3.33 s: 0.88	m: 3.66 s: 0.65

Elderly: Imagery task - ANIMASK version -
Order Perception > Imagery

Short -Yes	Medium - Yes	Long - Yes	Short -No	Medium - No	Long - No
m: 3.25 s: 0.75	m: 2.66 s: 0.88	m: 2.75 s: 0.96	m: 2.75 s: 1.21	m: 2.66 s: 0.88	m: 1.91 s: 0.79

APPENDIX 6 (continued)

Elderly Perceptual Control - SCAN version -
Order Imagery > Perception

Short -Yes	Medium - Yes	Long - Yes	Short -No	Medium - No	Long - No
m: 3.66 s: 1.15	m: 3.5 s: 1.16	m: 2.75 s: 1.42	m: 3.91 s: 0.28	m: 3.83 s: 0.38	m: 3.58 s: 0.79

Elderly: Imagery task - SCAN version -
Order Imagery > Perception

Short -Yes	Medium - Yes	Long - Yes	Short -No	Medium - No	Long - No
m: 3.58 s: 0.51	m: 3.66 s: 0.65	m: 2.75 s: 1.13	m: 3.0 s: 0.85	m: 2.75 s: 1.42	m: 3.08 s: 1.16

Elderly: Perceptual Control - SCAN version -
Order Perception > Imagery

Short -Yes	Medium - Yes	Long - Yes	Short -No	Medium - No	Long - No
m: 3.83 s: 0.38	m: 3.83 s: 0.88	m: 3.25 s: 1.05	m: 2.75 s: 1.13	m: 3.08 s: 0.79	m: 2.75 s: 1.05

Elderly: Imagery task - SCAN version -
Order Perception > Imagery

Short -Yes	Medium - Yes	Long - Yes	Short -No	Medium - No	Long - No
m: 3.33 s: 0.98	m: 2.91 s: 1.31	m: 2.66 s: 1.15	m: 3.25 s: 0.96	m: 3.0 s: 0.95	m: 3.25 s: 0.75

APPENDIX 7

Five-year-olds: Perceptual Control - ANIMASK version.

Short -Yes	Medium - Yes	Long - Yes	Short -No	Medium - No	Long - No
m: 3.62 s: 1.01	m: 3.71 s: 0.85	m: 3.45 s: 0.97	m: 3.08 s: 1.13	m: 3.37 s: 0.96	m: 3.33 s: 0.96

Five-year-olds: Imagery task - ANIMASK version

Short -Yes	Medium - Yes	Long - Yes	Short -No	Medium - No	Long - No
m: 2.62 s: 1.34	m: 2.33 s: 1.31	m: 2.12 s: 1.36	m: 1.87 s: 1.29	m: 1.95 s: 1.12	m: 1.95 s: 1.3

Five-year-olds: Perceptual Control - SCAN version

Short -Yes	Medium - Yes	Long - Yes	Short -No	Medium - No	Long - No
m: 3.37 s: 1.05	m: 2.95 s: 1.23	m: 3.0 s: 1.31	m: 2.87 s: 1.26	m: 2.87 s: 1.22	m: 3.0 s: 1.25

Five-year-olds: Imagery task - SCAN version

Short -Yes	Medium - Yes	Long - Yes	Short -No	Medium - No	Long - No
m: 3.04 s: 1.19	m: 2.91 s: 1.34	m: 2.45 s: 1.41	m: 2.29 s: 1.08	m: 2.21 s: 1.25	m: 2.45 s: 1.25

APPENDIX 7 (continued)

Eight-year-olds: Perceptual Control - ANIMASK version

Short -Yes	Medium - Yes	Long - Yes	Short -No	Medium - No	Long - No
m: 3.66 s: 0.86	m: 3.58 s: 0.88	m: 3.5 s: 1.02	m: 3.62 s: 0.57	m: 3.79 s: 0.41	m: 3.79 s: 0.41

Eight-year-olds: Imagery task - ANIMASK version

Short -Yes	Medium - Yes	Long - Yes	Short -No	Medium - No	Long - No
m: 3.45 s: 0.88	m: 3.08 s: 0.71	m: 3.0 s: 1.1	m: 2.25 s: 0.84	m: 2.62 s: 1.09	m: 2.12 s: 1.19

Eight-year-olds: Perceptual Control - SCAN version

Short -Yes	Medium - Yes	Long - Yes	Short -No	Medium - No	Long - No
m: 3.91 s: 0.28	m: 3.82 s: 0.65	m: 3.52 s: 0.59	m: 3.65 s: 0.71	m: 3.78 s: 0.42	m: 3.78 s: 0.42

Eight-year-olds: Imagery task - SCAN version -
Order Perception > Imagery

Short -Yes	Medium - Yes	Long - Yes	Short -No	Medium - No	Long - No
m: 3.78 s: 0.67	m: 3.56 s: 0.66	m: 3.65 s: 0.57	m: 3.21 s: 0.99	m: 3.39 s: 0.98	m: 3.04 s: 1.02

APPENDIX 7 (continued)

Young adults: Perceptual Control - ANIMASK version.

Short -Yes	Medium - Yes	Long - Yes	Short -No	Medium - No	Long - No
m: 3.83 s: 0.48	m: 3.83 s: 0.38	m: 3.5 s: 0.58	m: 3.83 s: 0.38	m: 3.75 s: 0.44	m: 3.75 s: 0.53

Young adults: Imagery task - ANIMASK version

Short -Yes	Medium - Yes	Long - Yes	Short -No	Medium - No	Long - No
m: 3.66 s: 0.56	m: 3.29 s: 0.62	m: 2.95 s: 0.99	m: 2.91 s: 0.88	m: 3.04 s: 1.04	m: 2.79 s: 0.88

Young adults: Perceptual Control - SCAN version

Short -Yes	Medium - Yes	Long - Yes	Short -No	Medium - No	Long - No
m: 3.83 s: 0.38	m: 3.75 s: 0.53	m: 3.45 s: 0.65	m: 3.83 s: 0.38	m: 3.87 s: 0.33	m: 3.87 s: 0.33

Young adults: Imagery task - SCAN version

Short -Yes	Medium - Yes	Long - Yes	Short -No	Medium - No	Long - No
m: 3.71 s: 0.55	m: 3.71 s: 0.46	m: 3.58 s: 0.58	m: 3.71 s: 0.55	m: 3.75 s: 0.44	m: 3.75 s: 0.53

APPENDIX 7 (continued)

Elderly: Perceptual Control - ANIMASK version

Short -Yes	Medium - Yes	Long - Yes	Short -No	Medium - No	Long - No
m: 3.71 s: 0.85	m: 3.54 s: 0.65	m: 3.04 s: 0.85	m: 3.41 s: 0.97	m: 3.12 s: 1.03	m: 3.62 s: 0.71

Elderly: Imagery task - ANIMASK version

Short -Yes	Medium - Yes	Long - Yes	Short -No	Medium - No	Long - No
m: 3.41 s: 0.71	m: 3.08 s: 0.82	m: 2.75 s: 0.94	m: 2.5 s: 1.1	m: 2.66 s: 0.96	m: 2.21 s: 0.83

Elderly: Perceptual Control - SCAN version

Short -Yes	Medium - Yes	Long - Yes	Short -No	Medium - No	Long - No
m: 3.75 s: 0.84	m: 3.41 s: 1.01	m: 3.00 s: 1.25	m: 3.33 s: 1.01	m: 3.45 s: 0.72	m: 3.16 s: 1.01

Elderly: Imagery task - SCAN version

Short -Yes	Medium - Yes	Long - Yes	Short -No	Medium - No	Long - No
m: 3.45 s: 0.77	m: 3.29 s: 1.08	m: 2.7 s: 1.12	m: 3.12 s: 0.89	m: 2.87 s: 1.19	m: 3.16 s: 0.96