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ABSTRACT

To provide converging support that the integration of analog and propositional representational systems is associated with spatial ability, visual, auditory, and bimodal brain event-related potentials were recorded from 50 right-handed Caucasian male recruits at the Naval Training Center, San Diego. Sensory interaction indices were derived for these subjects who had taken the Surface Development Test of spatial ability. Product-moment correlations were computed between sensory interaction indices for eight cerebral sites and spatial ability test scores. Sensory interaction for left and right hemispheric regions was significantly related to spatial ability. As sensory suppression decreased, spatial ability increased. The results substantiated the theory that the visual-imaginal-analog and the auditory-verbal-propositional representational systems are implicated in spatial ability. The extent to which the cortex can inhibit or attenuate the interaction or integration between these dual symbol systems is associated with complicated spatial task performance. (Author)

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SPATIAL PERFORMANCE, COGNITIVE REPRESENTATION, AND CEREBRAL PROCESSES

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To provide converging support that the integration of analog and propositional representational systems is associated with spatial ability, visual, auditory, and bimodal brain event-related potentials were recorded from 50 right-handed Caucasian male recruits at the Naval Training Center, San Diego. Sensory interaction indices were derived for these subjects who had taken the Surface Development Test of spatial ability. Product-moment correlations were computed between sensory interaction indices for eight cerebral sites and spatial ability test scores. Sensory interaction for left and right hemispheric regions was significantly related to spatial ability. As sensory suppression decreased, spatial ability increased. The results substantiated the theory that the visual-imaginal-analog and the auditory-verbal-propositional representational systems are implicated in spatial ability. The extent to which the cortex can inhibit or attenuate the interaction or integration between these dual symbol systems is associated with complicated spatial task performance.

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FOREWORD

This research was performed under in-house independent laboratory research work unit ZR000-01-042.027 (Cognitive Factors in Learning and Retention) under the sponsorship of the Chief of Naval Material (Director of Navy Laboratories). The general goal of this work unit is to investigate cognitive factors, and their associated processes, involved in learning, performance, and retention.

The results of this study are primarily intended for the Department of Defense training and testing research and development community.

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SUMMARY

Background and Problem

An important epistemological dispute has centered on the nature of the mental representations intrinsic to spatial ability. The essential issue has focused on whether it is necessary to propose special types of cognitive processes for spatial information in addition to those associated with verbal information. The amount of match or isomorphism between the internal representations and their external referents has been used to differentiate between analog and propositional processes. Analog representational processes preserve the relational structure of external objects, and propositional representational processes do not.

Analog and verbal symbol systems can either facilitate or inhibit the performance of spatial ability tasks. Facilitation should occur where both representational mechanisms are congruent with the processes demanded by the task; inhibition should occur where either or both of these schemes are not congruent with those processes. Visual and auditory sensory input does impact upon intricate information processing. The sensory interaction or integration between these two stimulus modalities should become increasingly important as higher-order cognitive functioning is required by the task. If sensory inputs, perceptual processes, and representational operations involve the same cerebral mechanisms, then how the brain integrates visual and auditory stimuli resulting in facilitation or inhibition should be related to its performance on complex spatial tasks. This is so since the visual-imaginal-analog system and the auditory-verbal-propositional system are speculated to be implicated in spatial ability.

Objectives

The objectives of this research were to (1) ascertain the amount of association between cerebral sensory interaction and spatial ability, (2) determine the importance of the visual-imaginal-analog system as well as the verbal-auditory-propositional system for spatial task performance, and (3) provide converging support that the interaction or integration of these dual representational systems is associated with spatial ability.

Approach

Visual, auditory, and bimodal event-related potentials (ERPs) were recorded from 50 right-handed Caucasian male recruits from Naval Training Center, San Diego. Sensory interaction indices were derived for these subjects who had taken the Surface Development Test of spatial ability. Product-moment correlations were computed between sensory interaction indices for eight cerebral sites and spatial ability test scores.

Results

Sensory interaction indices for all four left hemisphere sites (frontal, temporal, parietal, and occipital areas) and three right hemisphere sites (frontal, temporal, and parietal areas) were significantly associated with scores on the Surface Development Test. These results suggested that sensory suppression, inhibition, or attentuation at the cortex is significantly related to spatial ability as follows: as sensory suppression lessens, spatial ability increases.

Discussion and Conclusions

Cerebral sensory interaction is significantly related to spatial ability. How the brain integrates visual and auditory stimuli is associated with performance on a complex spatial task. Sensory inhibition, attenuation, or suppression at left and right frontal, temporal, and parietal areas was positively correlated with spatial ability. Not only the spatially superior and parallel processing right hemisphere but also the linguistically superior and linear processing left hemisphere are associated spatial task performance.

The findings support the theory that the visual-imaginal-analog system and the auditory-verbal-propositional system are involved in spatial ability. The extent to which the cortex can suppress, inhibit, or attenuate the interaction or integration between these dual representational systems is related to spatial task performance. As higher-order cognitive functioning is demanded by the spatial task, sensory interaction between these two stimulus modalities appears to become increasingly important. How the brain integrates visual and auditory stimuli culminating in sensory suppression seems to be associated with performance on complicated spatial tasks. The Surface Development Test is a complex spatial task that taxes the resources of the left and right cerebral hemispheres (i.e., analog as well as propositional representational systems). To associate spatial ability with either hemisphere exclusively or chiefly would be misleading.

CONTENTS

INTRODUCTION

Background and Problem

An important epistemological dispute has centered on the nature of the mental representations intrinsic to spatial ability. The essential issue has focused on whether it is necessary to propose special types of cognitive processes for spatial information in addition to those associated with verbal information. The amount of match or isomorphism between the internal representations and their external referents has been used to differentiate between analog and propositional processes. Analog representational processes preserve the relational structure of external objects, and propositional representational processes do not. An internal transformation is considered analog when the intermediate phases in the process have an isomorphic or one-to-one correspondence with the intermediate phases in the external transformation of the object (Shepard & Cooper, 1982).

Three attributes of propositional representation contribute to its definition (Anderson, 1978): (1) it is abstract and not dependent on the particular characteristics of its instantation, (2) it has truth value in that it is either true or false, and (3) it has rules that govern its formation so that decisions can be made regarding how well it is structured. Using these as criteria, it seems reasonable to propose that implicit propositional systems underlie natural languages, mathematics, computer programs, and semantic networks. An analog representation does not convey these features. However, it does imply an isomorphism, or one-to-one mapping, between a mental representation and its corresponding real referent (e.g., a road map corresponds to the layout of streets and highways, a building corresponds to its architectural plans, a football play on the field corresponds to the coach's diagram of it). Analog representations refer to holistic or global structures, not separate properties of an object that can be listed individually or as a set of propositions.

Criticisms concerning the use of analog representations as explanatory constructs indicated the incoherence of the "picture metaphor" for mental imagery (Shepard & Cooper, 1982). Also, these emphasized the necessity for proposing a single basic symbolic representational system for translating between spatial and verbal processes (Pylyshyn, 1979). Anderson (1978) claimed that propositional processes and representations can mimick phenomena normally employed to support the requirement for analog representations and processes. Mental transformations and rotations have been considered to be primarily analog processes (e.g., Attneave, 1974; Cooper & Shepard, 1973; Kosslyn, 1980; Kosslyn & Pomerantz, 1977; Paivio, 1976). This assertion is controversial since it seems to challenge the notion that human cognition can be simulated by a digital computer (Corballis, 1982). The implication is that the study of mental rotation and other kinds of spatial transformation may necessitate a change in some psychological models (e.g., network theories of cognition) (Anderson & Bower, 1973; Norman, Rumelhart, & LNR Research Group, 1975).

A number of experiments have demonstrated that mental rotation of spatial objects seems to occur in real time. Visualizing or imagining a shape in a different orientation is tantamount to actually seeing it in that position. Apparently, mental rotation is similar to, or interacts with, perceived rotation. The findings of some investigations have confirmed the belief that mental rotation is a global, holistic, uniform, and continuous process that, to some extent, approximates actual physical rotation. That is, rotating a shape cognitively is analogous to rotating it realistically. This seems to imply a similarity in neurophysiological process that take place when one is imagining or perceiving a spatial transformation or rotation (Corballis, 1982; Shepard & Chipman, 1970; Shepard & Cooper, 1982).

Introspective reports from subjects have indicated that they did imagine or visualize when performing mental transformations in the form of a "paper folding" or "surface development" task. These paper-and-pencil tests (Ekstrom, French, Harman, & Derman, 1976; Smith 1964) of mental transformations have been used for a long time for assessing spatial ability. Paper folding or surface development tasks can be considered as mental rotation tasks. That is, each mental fold can be regarded as a rotation. However, each cognitive fold is conceived of as a rigid rotation of only one segment of the object relative to the rest--not the rotation of the complete object. Also, an individual mental rotation or fold can be thought of as only one in a sequence that must be completed before a subject can give a response (Shepard & Cooper, 1982).

Measures of cerebral electrical activity, electroencephalographic (EEG) and event-related potential (ERP) recordings, represent this neurophysiological process as minute signals obtained from the scalp. The EEG depicts on-going brain activity, while the ERP depicts this activity after specific stimulus events (e.g., light flashes or audible clicks). Typically, for people performing propositional or verbal tasks such as reading prose passages, there is decreased activity over the left hemisphere. For analog or spatial tasks such as recognizing simple random shapes, there is generally a decrease in activity over the right hemisphere. Such decreases may be considered indices of increased information processing within the affected hemisphere. That is, at least two modes of cognitive processing have been shown to be related to the brain's two hemispheres. A propositional, verbal, analytic, sequential, logical manner of information processing has been associated with left-hemisphere activity in most right-handed individuals. Conversely, an analog, spatial, holistic, simultaneous, intuitive manner has been attributed to right hemisphere activity (e.g., Allen, 1983; Bryden, 1982; Helligie, 1980; Hillyard & Kutas, 1983). There is considerable consensus concerning the existence of cerebral lateralities; however, their specific contributions to particular cognitive functions are still very much debatable and continue to be the object of scientific investigation.

It seems reasonable for auditory event-related potentials to trigger, elicit, evoke, or engage the neurophysiological correlates of propositional processing and representation. Likewise, it seems reasonable for visual event-related potentials to trigger, elicit, evoke, or engage the neurophysiological correlates of analog processing and representation. When auditory and visual stimuli are presented together--that is bimodal event-related potentials--then propositional and analog processes and representations should be triggered or elicited. This assumes that perceptual processes and neurophysiological correlates of representational systems are approximately equivalent or at least interact.

Sensory interaction (Butterworth, 1981; Lewis & Froning, 1981; Shipley, 1970, 1977; Shipley & Jones, 1969; Walk & Pick, 1981) has been considered as a joint function of auditory, visual, and bimodal event-related potentials (AERP, VERP, and BERP respectively). As a neurophysiological index, sensory interaction has been conceptualized in terms of the absolute values of BERP and (AERP + VERP). If BERP is larger than (AERP + VERP), it has been thought of as an indicator of neurophysiological excitation or facilitation in cerebral activity. If BERP is smaller than AERP + VERP, it has been thought of as an indicator of neurophysiological inhibition or suppression in cerebral activity. Since the neurophysiological correlates of sensory, perceptual, and representational processes are assumed to be tantamount or at least to intermesh, sensory interaction then reflects the interrelationship, interplay, or interassociation of analog and propositional representational systems. Consequently, with BERP larger than (AERP + VERP), these dual representational processes support, reinforce, or correspond to one another. With BERP smaller than (AERP + VERP), they undermine, weaken, or nonconform to one another.

Imaginal and verbal encoding systems or representational modes have been hypothetically implicated as mediation mechanisms employed in the performance of spatial tasks (Paivio, 1971). The imaginal, visual, or analog encoding or representational mode is primarily a parallel processing system specialized for storage and symbolic manipulation of spatial objects; whereas, the verbal, auditory, or propositional encoding or representational mode is primarily a sequential processing system because of its linguistic nature. These representational mechanisms do not normally function independently of one another or only in one capacity. They are thought to interact continuously in performing complicated spatial tasks.

Imaginal and verbal encoding mechanisms can either facilitate or inhibit the performance of spatial ability tasks. Facilitation should occur where both representational systems are congruent with the processes demanded by the task; inhibition should occur where either or both of these symbolic systems are not congruent with these processes. Visual and auditory sensory input does impact upon intricate information processing. The sensory interaction or integration between these two stimulus modalities should become increasingly important as higher-order cognitive functioning is required by the task. If sensory inputs, perceptual processes, and representational operations involve some of the same cerebral mechanisms, then how the brain integrates visual and auditory stimuli resulting in facilitation or inhibition should be related to its performance on complex spatial tasks. This is so, since the visual-imaginal-analog system and the auditory-verbal-propositional system are speculatively implicated in spatial ability.

Objectives

The objectives of this research were to (1) ascertain the amount of association between cerebral sensory interaction and spatial ability, (2) determine the importance of the visual-imaginal-analog system as well as the verbal-auditory-propositional system for spatial task performance, and (3) provide converging support that the interaction or integration of these dual representational systems is associated with spatial ability.

METHOD

Subjects

The subjects were 50 right-handed Caucasian male recruits from the Naval Training Center, San Diego, who were undergoing basic enlisted military instruction. Audition and vision of the subjects were empirically verified as normal.

Spatial Ability Measure

The Surface Development Test (Ekstrom et al., 1976), which is a paper-and-pencil test of mental "paper folding" and "surface development," was employed as a measure of spatial ability. In this test, subjects are required to imagine or visualize how a piece of paper can be folded to form some object. Two drawings are presented for each item. The drawing on the left is of a piece of paper that can be folded on the dotted lines to form the object depicted on the right. The task demands that the subjects imagine the folding and figure out which of the lettered edges on the object are the same as the numbered edges on the piece of paper at the left. Figure 1 depicts a sample item from this test. The subjects' score on this test is the number of correct letters minus a fraction of the number of incorrect letters. They had 6 minutes to complete each of the two parts of this test, which was administered to each subject counterbalanced with brainwave recording.

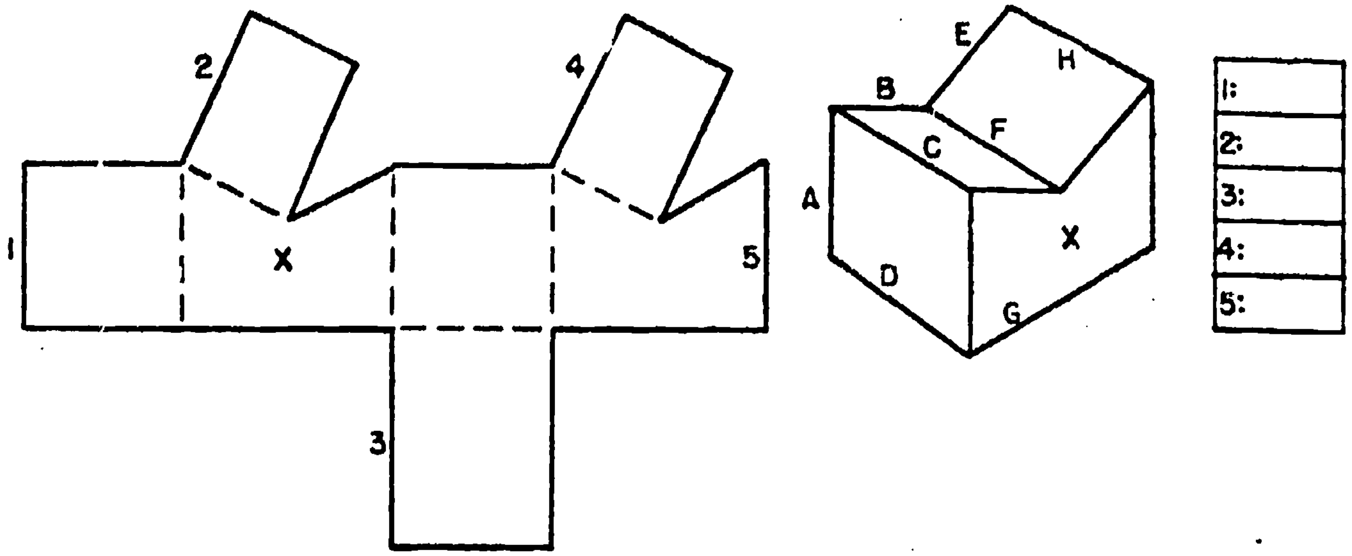

Figure 1. Sample item from the Surface Development Test used to measure spatial ability.

Instrumentation

Data were acquired on a field-portable computer system[1] that included a Data General NOVA 1/10 central processing unit (CPU, 32K memory); a dual-drive floppy disk unit (Advanced Electronics Design, Inc., Model 2500); an optically isolated and multiplexing EEG unit with bandpass set for 0.2-30 Hz; and a videographic display unit, integrated into the CPU, that presented visual stimuli to the subjects and displayed the analyzed ERP data. The signal sampling rate for each channel of the analog EEG waveforms was set at 500 Hz. Permanent storage of all video information was obtained from a video hard copy unit (Tektronix Model 4632).

Stimuli

Visual (V) stimuli were computer-generated black and white checkerboard patterns presented over the video monitor (Panasonic 14-inch Model WV 5400). Binocular visual field stimulation was about 9 degrees visual angle. Each check subtended about 17 minutes visual angle. Average background luminance was about 0.3 ftL and target luminance was about 5 ftL. The patterns were presented aperiodically with interstimulus intervals averaging about 2 seconds (1.0-3.0 seconds).

Auditory (A) clicks were presented binaurally over headphones (Sennheiser Model 424X) aperiodically about every 2 seconds (1.0-3.0 second interstimulus intervals). Click intensity was about 65 dB (A) (Bruel and Kjaer Impulse Sound Level Meter, Model 2209, One-Third Octave Filter Set, Model 1616). Headphone leads were shielded to minimize click artifacts.

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[1] Identification of the equipment is for documentation only and does not imply endorsement.

Bimodal (B) presentation included simultaneous presentation of the visual and auditory stimuli. These stimuli were presented aperiodically about every 2 seconds (1.0-3.0 seconds).

During all recording periods, white noise was used for masking. It was presented to the subjects through the headphones and via a speaker in the sound chamber at a level of approximately 50 dB (A). This was done to create more uniform data acquisition conditions across all the subjects. The auditory click stimuli were presented over this background noise.

Procedure

Recording Sites

Eight channels of visual, auditory, and bimodal ERP data were acquired from four pairs of homologous sites: Sites F3 and F4 over the frontal brain region, an association area; sites T3 and T4 over the temporal region, a primary auditory reception area where many visual and auditory nerves interconnect; sites P3 and P4 over the parietal region, a primary association area; and sites O1 and O2 over the occipital region, a primary visual reception area. Ground was at Pz in the mid-parietal area. Sites designated by odd numbers denote left hemisphere locations; and those designated by even numbers, right hemisphere locations.

Electrodes

The subjects were prepared for recording after they had received brief instructions, completed a brief background questionnaire, and signed a privacy act and volunteer consent form. An elastic helmet (Lycra) fitted with plastic holders for the electrodes was placed on the subject's head. Each subject's hair was parted and the scalp cleaned with an alcohol-impregnated cotton swab that was placed through the holders. Electrode cream was placed down the holders and rubbed into the scalp. The electrodes were silver/silver chloride Beckman miniatures (actual surface contact area was 2 mm) with a clear plastic extension tube (38 mm long) attached and filled with electrolytic solution. A small sponge (microcell foam) soaked with electrolyte held the solution in the tube and made contact with the electrode paste on the scalp. The extension tube not only held the electrode in place but also minimized the slow potential drift due to scalp temperature change that would have otherwise been picked up at the recording site. A Beckman mini-electrode fitted with a standard two-sided adhesive wafer served as a reference electrode on the nose.

The helmet and all 10 electrodes could be attached in 6-8 minutes with impedance readings of 2-3K ohms. After all electrodes were in place, the subjects were instructed to observe their real-time EEG activity on the oscilloscope display. They were then instructed to move their jaws, eyebrows, etc. so that they could observe how muscle artifacts could contaminate the ERP data. The subject was then seated in a sound chamber in alignment with the video monitor. A hand-held switch allowed the subject to suspend all stimulus presentation and analysis operations to eliminate artifact. Additional artifact rejection was available by the console operator prior to storing the data.

Event-related Potential (ERP) Data

ERPs were generated on-line, and the analog-to-digital (A/D) sampling speed was one-quarter million samples per second. The visual and auditory ERP data were retrieved from a floppy diskette and the required computations were performed. The data were then displayed on the video monitor and hard copies were obtained. Bimodal ERP data were also computed and displayed in a similar manner.

Eight channels of visual and auditory ERP data are overlaid in Figure 2. Root mean square (RMS) and standard deviation (SD) amplitude values are presented, along with the waveform means values for the half-second post-stimulus epoch (533 msec). SD amplitude values (in microvolts (µV)) are normalized (waveform mean set to zero) RMS values (in µV). For all analyses, only SD amplitude values (in µV) were used. These values have been found to be very effective when employing ERPs to study individual differences among many different kinds of subjects. There are individuals who do not manifest clearly defined ERP components. This index is also advantageous in that it permits the description of ERP amplitude as a single value (Callaway, 1975; Lewis & Froning, 1981). Prestimulus waveforms (133 msec) were also recorded and displayed for each channel. Calibration, polarity, DC offset, time base, and other descriptive information were also displayed. The waveforms in the left column were derived from the left hemisphere (LH). The waveforms from top to bottom were from the front to the back of the head at frontal, temporal, parietal, and occipital sites (F3, T3, P3, O1). Right hemisphere (RH) ERP data from sites F4, T4, P4, and O2 are represented in the right column.

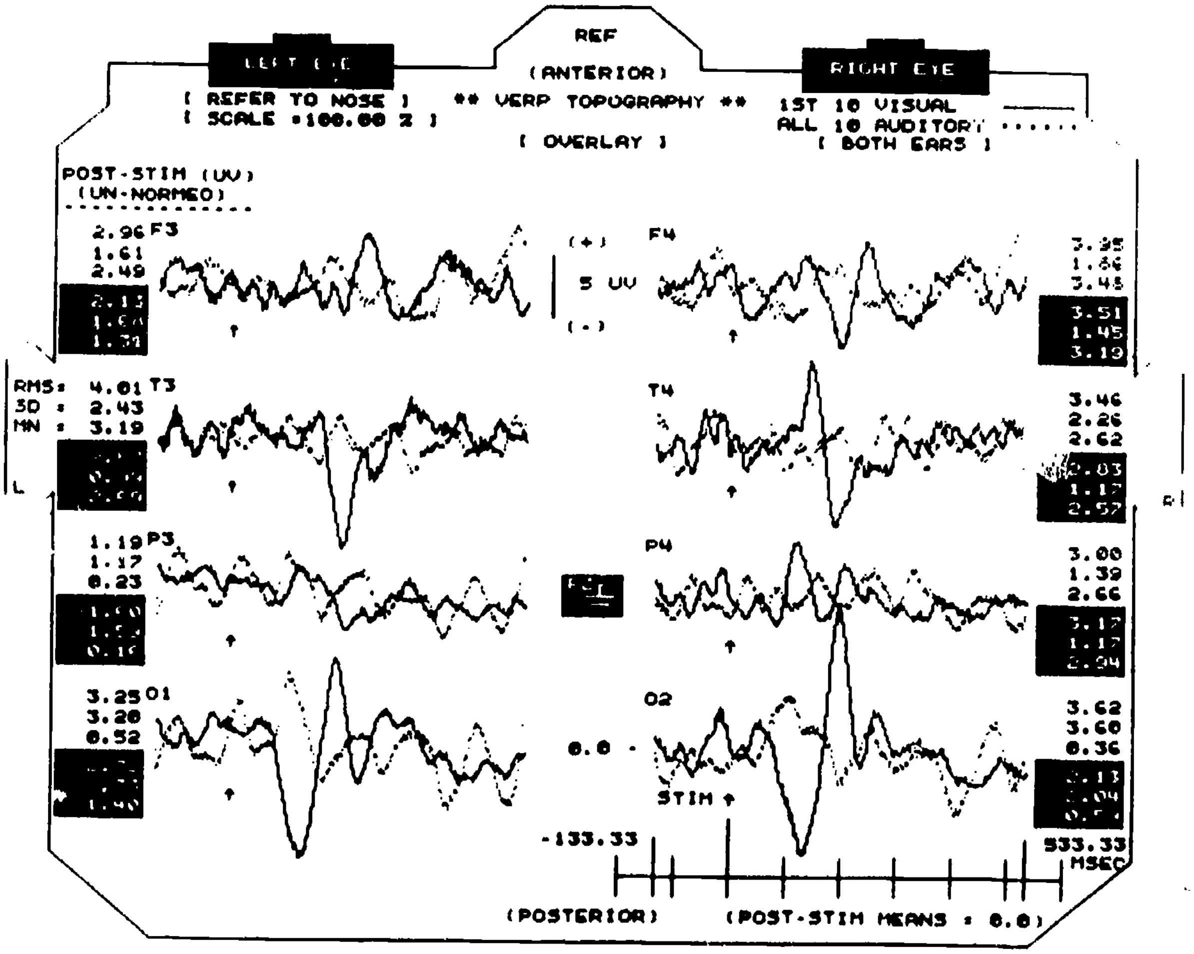

Figure 2. Sample visual and auditory event-related potential data. The left column is from the left hemisphere; and the right column, from the right hemisphere. From top to bottom, the records are from the frontal, temporal, parietal, and occipital areas.

Sensory Interaction Indices

In addition to the directly recorded ERP amplitudes, an index was derived to reflect a hypothesized property of brain behavior. To appraise sensory interaction and its association with spatial ability, the relationship between single modality presentations (visual or auditory) and the joint bimodal presentation (simultaneous stimulation of visual checkerboard patterns and auditory clicks) was determined. A sensory interaction index was defined as: BERP - (VERP + AERP) (Federico, Froning, Calder, 1983; Lewis & Froning, 1981; Lewis, Federico, Froning, & Calder, 1981; Shipley, 1970; Shipley & Jones, 1969). If this expression is positive, the bimodal stimulation presentation produces a greater magnitude response than does the sum of separate visual or auditory stimulation. This indicates sensory excitation, facilitation, or potentiation in the brain's nervous system. If the expression is negative, the sensory attenuation, inhibition, or suppression occurs in the nervous system when auditory stimulation is presented at the same time as visual stimulation. This sensory interaction index was derived for left and right hemisphere frontal, temporal, parietal, and occipital areas.

Statistical Analysis

Product-moment correlations were computed between sensory interaction indices for left and right hemisphere sites and Surface Development Test scores. Means and SDs were also computed for these measures.

RESULTS

The means and SDs for left and right hemisphere sensory interactions, together with the correlations between these derived indices and spatial ability test scores ($\overline{X} = 28.34$; SD = 16.76), are presented in Table 1. The negative means for the sensory interaction indices indicated that attenuation, inhibition, or suppression occurred at all cerebral areas. The SDs revealed that this attenuated activity appeared approximately uniform between homologous hemispheric sites. The product-moment correlations disclosed that sensory interaction was positively related to spatial ability. Sensory interaction indices for all four left hemisphere sites (F3, T3, P3, and O1) and for three right hemisphere sites (F4, T4, and P4) were significantly associated with scores on the Surface Development Test. These statistics imply that sensory suppression, inhibition, or attenuation of the cortex is significantly related to spatial ability. The nature of this relationship is that, as sensory interaction indices become less negative, spatial ability scores become more positive. That is, as sensory suppression decreases, spatial ability increases.

Table 1

Descriptive Statistics for Sensory Interactions and Their Correlations with Spatial Ability

Sensory Interaction	$\bar{X}$	SD	r
Left Hemisphere			
Frontal	-0.96	2.01	.43**
Temporal	-1.61	1.46	.31*
Parietal	-1.75	1.54	.36**
Occipital	-2.01	1.71	.37**
Right Hemisphere			
Frontal	-1.21	2.01	.34*
Temporal	-1.57	1.25	.37**
Parietal	-1.81	1.42	.28*
Occipital	-1.55	1.50	.26

*$r(48) \geq .28$; $p < .05$.

**$r(48) \geq .36$; $p < .01$.

DISCUSSION AND CONCLUSIONS

The results indicate that cerebral sensory interaction is positively related to spatial ability; that is, how the brain integrates visual and auditory stimuli is associated with performance on a complex spatial task. Sensory inhibition, attenuation, or suppression at left and right frontal, temporal, and parietal areas was positively correlated with spatial ability. The spatially superior and parallel-processing right hemisphere and also the linguistically superior and linear-processing left hemisphere are associated with spatial task performance. These findings support the theory that the visual-imaginal-analog system and the auditory-verbal-propositional system are involved in spatial ability. It is hypothesized that the extent to which the cortex can suppress, inhibit, or attenuate the interaction or integration between these dual representational systems is related to spatial task performance.

In regard to the nature of the mental representations inherent to spatial ability, the results suggest that both analog and propositional processing are required. It was established that, as sensory suppression decreases, spatial ability increases. This seems to imply that visual and auditory inputs impact upon intricate information processing and that both representational systems undoubtedly influence complex spatial performance. As higher-order cognitive functioning is demanded by the spatial task, sensory interaction between these two stimulus modalities appears to become increasingly important. How the brain integrates visual and auditory stimuli culminating in sensory suppression seems to be associated with performance on complicated spatial tasks. The neurophysiological correlates of sensory, perceptual, and representational processes are assumed to be equivalent or at least to intermesh. Therefore, it is theorized that sensory interaction reflects the interrelationship, interplay, or interassociation of analog and propositional representational systems. Consequently, the results speculatively implicate both of these representational processes in spatial ability.

In agreement with Anderson (1978), who has argued that analog and propositional hypotheses cannot be differentiated on the basis of behavioral evidence, the research described herein suggests that these dual symbol systems are intimated in spatial reasoning. It also involved the left and right cerebral hemisphere in this ability. During this research, paper folding or surface development was considered to be a mental rotation task. Each mental fold was regarded as a rigid rotation of one part of the object relative to the rest. Assuming that mental rotation is a primary component of spatial processing, it would typically and chiefly be expected to be a right hemisphere task. This is especially so in view of this hemisphere's well documented superiority in the execution of spatial skills (e.g., Allen, 1983; Bryden, 1982; Helligie, 1980; Hillyard & Kutas, 1983). Most, but not all, the evidence corroborate this expectancy (e.g., Benton, 1982; Newcombe, 1982; Ratcliff, 1982).

Contrary to the norm, Ornstein, Johnstone, Herron, and Swencionis (1980) established that more EEG activity occurred over the left than the right cerebral hemisphere when subjects performed a mental rotation task. De Renzi (1978) reviewed other evidence that implicated the left hemisphere in the execution of complex spatial tasks. He summarized the findings by concluding that the more complicated the spatial task, the more involved is the left hemisphere. This is consonant with data obtained by others (e.g., Federico, 1980a, 1980b; Federico & Montague, 1975) that suggested difficult spatial performance was facilitated by verbal, semantic, or propositional representations or encodings. This kind of mental mediation has been primarily linked with the left hemisphere (e.g., Allen, 1983; Bryden, 1982; Helligie, 1980; Hillyard & Kutas, 1983). As implied by the research described herein, surface development being a complex spatial task taxes the respective resources of the left and right cerebral hemispheres--analog as well as propositional representational systems. To associate spatial ability with either hemisphere exclusively or chiefly would be misleading. Caution must be exercised against absolutely attributing analog symbolizing processes to the right hemisphere and propositional processes to the left hemisphere.

This does not preclude the consideration of the visual, imaginal, or analog symbolizing system as a distinct or separate representational structure that uses a "quasi-pictorial format" (Kosslyn, 1980). Individual differences in analog representational processes and structures, as well as complementary propositional systems, can contribute to individual differences in spatial ability (Lohman & Kyllonen, 1983). One hypothesis proposes that the capacity of the visual short-term memory or buffer, which determines the accuracy and rapidity to generate and refresh images, probably accounts for a considerable portion of the variability in spatial ability (Kosslyn, 1981). Possibly, the subjects who were unable or found it difficult to conjure up a mental image of each object while performing the surface development task were at a certain disadvantage. If these subjects were engaging exclusively or chiefly their verbal, semantic, or propositional representational system when attempting the paper folding task, then they were imposing an incompatible cognitive style of processing that probably prevented successful spatial performance by shunting their visual short-term-memory system. It seems likely that subjects who performed the surface development task well, thus scoring high in spatial ability, had sufficient sensory suppression or inhibition to attenuate the verbal or propositional representational system. This would enable them to employ more completely and properly the visual short-term-memory buffer and its corresponding imaginal or analog representational system to optimize the performance of the spatial task. This is not meant to imply, however, that the propositional representational system was entirely "out of the picture."

Assuming that spatial proficiency involves sensual, perceptual, and representational processes and that the neurophysiological correlates of these cortical operations are tantamount or at least intermesh, this research examined this cognitive ability by associating subjects' performance on a marker test for this intellectual skill with cerebral indices of their sensory interaction. Other researchers have used sensory interaction indices to investigate different mental phenomenon. Shipley (1970), who employed the sensory interaction approach to study retarded children, reported that they were deficient chiefly in their capacity to attend to and monitor multidimensional stimuli. Using similar methodology, Shipley and Jones (1969) found that dyslexics could not process bimodally presented sensory input as well as normal children. They asserted that normals manifested sensory facilitation or excitation more frequently than did dyslexics. Also, the dyslexics demonstrated some modest amounts of attenuation or at least a lack of sensory arousal. Barnet and Lodge (1967), however, reported probable defects of sensory inhibitory mechanisms in mongoloids culminating in more pronounced response habituation in mongoloids than in normals. They speculated that such a loss of suppressing mechanisms in retardates could account for their extreme perseveration in excessively monotonous tasks. Lewis and Froning (1981) found that subjects with high reading ability demonstrated more sensory inhibition than did those with low reading ability. They maintained that such suppression or attenuation is usually associated with normal cortical processes. The major result of this research--as sensory suppression decreases, spatial ability increases--is completely consonant with the results of Barnet and Lodge (1967), Lewis and Froning (1981), and Shipley (1970). It is only partially compatible with results of Shipley and Jones (1969).

It is concluded from this study that (1) cerebral sensory interaction and spatial ability are significantly correlated, (2) the visual-imaginal-analog system as well as the auditory-verbal-propositional system are implicated in spatial task performance, and (3) the interaction or integration between these dual representational systems is associated with spatial ability.

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