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VISUOSPATIAL TASKS COMPARED VIA ACTIVATION OF REGIONAL CEREBRAL BLOOD FLOW*

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Abstract—Regional cerebral blood flow was measured in 19 subjects during the performance of three tasks thought to primarily involve right hemisphere processing: judgement of line orientation, mental rotation of three-dimensional cube arrays, and a fragment puzzle task. Asymmetries in hemispheric flow (right side greater) were only observed in the line orientation and rotation conditions and were present in both sexes. The magnitude of the asymmetry was greater in the rotation task which also showed an asymmetry in parietal flow. Thus mental rotation placed the most *asymmetric* demand on cerebral resources. This provides a task that more reliably activates the right hemisphere than those previously reported and suggests a truly "mental manipulative" aspect to right hemisphere advantage in visuospatial performance.

INTRODUCTION

THERE IS some controversy concerning the exact nature of the right hemisphere's advantage in visuospatial processing. A large body of data from research with normal subjects, brain damaged, and "split-brain" patients has indicated a greater role for the right hemisphere in such tasks as figure completion [13, 14, 24], judgements of arc curvature [12] and line orientation [2] and fragment puzzle tasks [13]. Studies using regional cerebral blood flow (rCBF) measurements with normal subjects have not been particularly successful in findings tasks that were truly robust in asymmetrically activating the right hemisphere. RISBERG [19] for example , showed right hemisphere activation during a figure completion task, but only under high motivation conditions (monetary reward). GUR [7] reported right hemisphere activation during line orientation judgement, but only in women.

We conducted a series of experiments in which regional cerebral blood flow (rCBF) was measured in young normal subjects while they performed several different tasks thought to primarily involve right hemisphere processing. This was done as part of a protocol to identify testing conditions best suited for generating reliable asymmetries in hemispheric activation of cortical CBF that could eventually be applied to the study of recovery of function in stroke patients. In addition, because rCBF is known to fairly accurately reflect level of metabolic activity we hoped to obtain a measure of how "involving" of each hemisphere the visuospatial tasks were.

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METHODS

Subjects

Nineteen subjects (mean age 25.1 ± 3.4 yr), 10 male and 9 female, were used in rCBF measures during three task conditions. Another 22 subjects (mean age 25.7 ± 4.2 yr), 12 male and 10 female, were used in rCBF studies of "unactivated" or "resting" states. All subjects were right-handed with no history of familial sinistrality. They were either students or hospital employees and were paid for their participation.

Conditions

The experiments were conducted in a darkened hospital room. Subjects relaxed on a bed in a supine position, with their heads placed on a special rest surrounded by the blood flow detector array. All subjects underwent an initial "dummy" or "sham" rCBF scan, not using any tracer isotope, to them to the procedure. Following this, 19 of the subjects underwent three scans while performing three different tasks. All tasks were visually presented on a rear projection screen located directly above the subjects. Stimuli were white on dark background line drawings that, as projected, subtended a visual angle of approximately 7° vertical and 13° horizontal. The response mode was identical in all tasks, requiring a right index finger movement for "yes" and a left index finger movement for "no" responses.

Puzzles task. In this task, subjects judged whether fragmented figures could form a simultaneously presented whole figure. Both the whole figure and fragments appeared on each slide (see example in Fig. 1(a)). Subjects were to respond with a right index finger movement for "yes, the fragments will form the whole figure" and a left index finger movement for "no". Eighty different puzzle slides were available for presentation. Half were matches and half were mismatches. Each slide remained on the screen until the subject made a decision.

Line orientation task. This task involved a modification of BENTON's test [2] in which a slide showing a line pair was presented for 4.5 sec followed by a 4.5-sec presentation of a fan array of lines with arrows pointing at two of them (see example in Fig. 1(b)). The subject had to decide whether the angle formed by the lines at which the arrows pointed was the same as in the previously presented pair. Eighty pairs of slides were presented over a 12-min period.

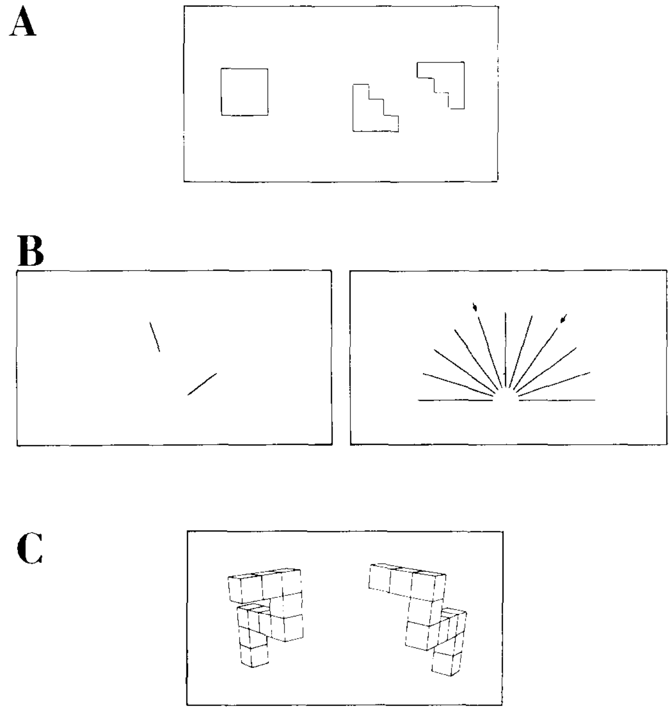

FIG. 1. Examples of test material for (a) fragment puzzle task, (b) line orientation task, and (c) mental rotation.

Rotation task. In this task the stimuli were pairs of figures similar to those used by SHEPARD and METZLER [20]. They consisted of line drawings of cubes arranged so as to represent solid objects with three arms extending in three dimensions (see example in Fig. 1(c)). Half of the pairs consisted of physically identical figures, oriented differently in space. The other half consisted of similar but not identical figures. Eighty different pairs were available for presentation to the subjects. The subjects' task was to mentally rotate either of the two figures, or both, and decide whether the figures were identical or different. The pair of figures remained on the screen until the subject made a decision.

All tasks commenced 1 min prior to xenon inhalation and continued throughout the rCBF scan (11 min). The tasks were presented in a counterbalanced manner across subjects to avoid any order effects.

Because of limitations on the number of procedures we are allowed to perform on volunteers, a separate "resting-state" scan was performed on 22 other young right-handed subjects (described above). The rest state studies were more carefully defined than is typical in many rCBF protocols by monitoring EEG and waiting for at least 20% sustained alpha activity in the spectral analysis before initiating the scan.

CBF was measured in all studies with the ^{133}xenon inhalation technique [15]. Thirty-two detectors, 16 per hemisphere, were arranged in a radial array about the head using the Novo helmet system [17]. Each scan involved inhalation of a xenon/air mixture of 5 mCi/liter concentration for 1 min through a facemask, followed by 10 min of recording xenon clearance rates from cerebral tissue. Curve fitting and flow rate analysis were performed on-line by a computer using a time domain two-compartment, two-artifact model [18]. The dependent measure of flow used was F_1, representing flow in the fastest clearing tissue (i.e., mostly gray matter). Head position was kept consistent through the use of a four projection-light system that aligns the helmet-detector assembly using the auditory meatuses and outer canthuses as landmarks.

RESULTS

Task performance

Table 1 summarizes the performance of subjects across all tasks. The average rate of response was quite similar across tasks, ranging from one every 9 sec in the line orientation task to one every 10.1 sec in the puzzles task. Overall, subjects ranked the puzzles task as "hardest" and line orientation as "easiest". Table 2 breaks down task performance by sex and shows that women did significantly worse than men in the mental rotation task. There was a trend in the same direction for the other two tasks. Such sex differences in visuospatial task performance, especially in mental rotation, have previously been reported [10, 22].

TABLE 1. Mean performance and response rates for the three task condition across all subjects ($n = 19$)

Task	No. completed	Response rate	Percent correct
Puzzles	71.2 (13.0)	10.1 (1.6)	71.2 (6.7)
Orientation[a]	80	9.0	73.6 (9.2)
Rotation	72.2 (12.0)	9.6 (1.5)	88.6 (9.3)

Standard deviation in parentheses.

[a]Orientation task was externally paced with consequently no variability in response rate or items completed (80).

CBF analyses

CBF results during the different conditions were analyzed both in terms of hemispheric mean flow and in terms of regional patterns. Separate analyses were performed comparing the three activation tasks and comparing each task separately with resting-state data. Since the comparison of each task with rest yielded effects completely consistent with the across tasks analysis, we present only the latter.

TABLE 2. Task performance by sex (10 males, 9 females)

Task	Percent completed		Percent correct	
	Females	Males	Females	Males
Puzzles	88.0 (14.6)	91.4 (18.4)	67.4 (9.6)	70.2 (10.5)
Orientation[a]	100	100	71.1 (6.6)	75.9 (11.2)
Rotation	87.7 (14.6)	92.4 (14.9)	[b]83.5 (8.3)	[b]93.1 (8.1)

Standard deviation in parentheses.
[a]Orientation task was externally paced—all subjects completed 80 items.
[b]Significantly different ($t=2.5$; $df=17$; $p<0.05$).

Global (hemispheric mean) analyses

A 2 (gender) × 2 (hemispheres) × 3 (tasks) mixed design analysis of variance (ANOVA) was performed on hemispheric mean flows. This revealed a main effect of gender ($F=6.72$; $df=1, 17$; $p=0.0190$) and hemispheres ($F=25.45$; $df=1, 17$; $p=0.0001$) and a task by hemisphere interaction ($F=3.52$; $df=2, 34$; $p=0.0410$). Figure 2 shows that the main effects are due to the generally higher flow in women and in the right hemisphere. Figure 2 also indicates that the greatest asymmetry occurred during mental rotation and the least in the puzzles task. Post hoc tests indicated that the hemispheric asymmetry ($R>L$) was significant for both the line orientation ($t=3.93$; $df=18$; $p<0.0010$) and rotation ($t=5.05$; $df=18$; $p<0.0001$) conditions.

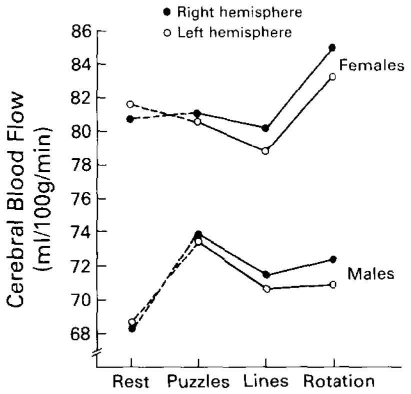

FIG. 2. Hemispheric blood flow during different testing conditions for males and females. Rest state studies (separated by dashed lines) were conducted on a separate group of subjects.

Regional analyses

Based on our experience that the most salient changes in rCBF during cognitive activation occur along the anterior-to-posterior dimension [4, 5] and our desire to separate association areas of the cortex from those involving primary sensory-motor function, we defined four regional groupings of detectors as illustrated in Fig. 3. Construction of these divisions was also influenced by our observation (based on preliminary inspection) that the boundary line between the central region and posterior association region shown in Fig. 3 separate detectors whose increase in flow is greater than the mean hemispheric increase during activation (post-line) and those that decrease relative to the mean hemispheric change during activation (pre-line). This central division thus formed a boundary naturally defined by strong shifts in the pattern of cerebral flow.

A 2 (gender) × 2 (hemispheres) × 4 (regions) × 3 (tasks) mixed design ANOVA was performed on regional flows resulting in a main effect of gender ($F=6.96$; $df=1, 17$; $p=0.0172$), of hemisphere ($F=15.26$; $df=1, 17$; $p=0.001$), and of region ($F=67.9$; $df=3, 51$; $p=0.0000$). Moreover, there was a significant task by region effect ($F=4.36$; $df=1, 102$; $p=0.0006$) and hemisphere by region effect ($F=5.63$; $df=3, 51$; $p=0.0021$). Finally, the ANOVA also demonstrated a task by hemisphere by region interaction ($F=2.65$; $df=6, 102$; $p=0.0198$). Post hoc tests of regional right-left differences showed no significant asymmetries in the "puzzles" task, a significant frontal asymmetry ($R>L$) in the "line orientation" task $t=3.27$; $df=18$; $p=0.0043$) and "rotation" task ($t=6.06$; $df=18$; $p=0.0000$), a central asymmetry ($R>L$) in the "line orientation" task ($t=4.14$; $df=18$; $p=0.0006$), and an asymmetry in the posterior association areas (parietal-temporal) in the "rotation" task ($t=2.64$; $df=18$; $p=0.0167$), all shown in Fig. 3.

DISCUSSION

The large increases in flow observed bilaterally in posterior cerebral regions (Fig. 3) in all three tasks are not surprising considering these areas are classically associated with visual processing. Since all tasks involved visual stimulation, one would expect at least the striate cortex/occipital pole to increase in activity.

Two tasks (line orientation judgement and mental rotation) produced significant asymmetries in mean hemispheric and regional flow patterns while one (fragment puzzles) did not. Despite the fact the puzzle task was quite demanding (in terms of performance, subjective report and overall CBF activation) it did not show a significantly greater activation of the right hemisphere relative to the left. We suspect that many subjects use verbal strategies in organizing the fragments used in the task, resulting in substantial left as well as right activation. Since metabolic measures probably reflect all effort expended, individual strategy variations in certain complex tasks may mask the more focal, seemingly isolated, involvement of regions inferred from some clinical studies [13]. It is also possible that the metabolic data more accurately reflects what is normally used to perform tasks in the absence of brain damage.

The consistent difference between sexes in global overall flow observed under any condition have been reported by several other laboratories and are as yet not accounted for. We did not find, however, significant sex differences in the hemispheric *pattern* of activation, despite the fact females are supposed to be less lateralized than males and have a right hemisphere less specialized for visuospatial processing [9, 11, 23]. There is therefore little evidence provided by rCBF activation that women depend on the right hemisphere less than men with respect to visuospatial processing. If anything, the extent of asymmetric activation seems greater in women. It is possible that this reflects a greater effort on their part in performing these tasks.

The most robust regional asymmetry observed was a right frontal activation that was highly significant in both the rotation and line orientation tasks. There was a trend in the same direction observed in the puzzles task (Fig. 3). This right frontal activation may be due to general attentional demands associated with most visuospatial tasks [6].

Line orientation judgement produced a significant asymmetry in flow in the central region

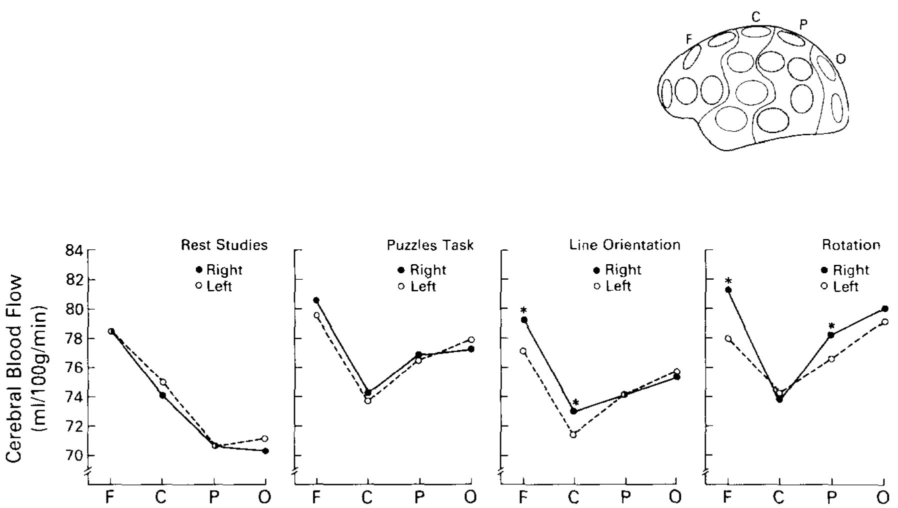

FIG. 3. Brain diagram shows detector placement and groupings used in regional analyses of cerebral blood flow (F: frontal, C: central, P: parietal, O: occipital). Graphs show regional cerebral blood flow for each testing condition. Note the anterior-to-posterior flow gradient associated with resting state studies and the extent of posterior activation during all tasks. Significant lateral asymmetries at the regional level are indicated by asterisks.

(Fig. 3). Inspection showed that this was due mostly to greater right flow recorded by detectors along the sensory-motor strip and superior temporal region. The line orientation task differed from the others in that it was externally paced and involved a minimal (virtually "iconic") memory component. We suspect the central asymmetry ($R > L$) is due to either the small visual memory component [4] or to some aspect of external pacing or to both.

Of the two tasks producing asymmetries, mental rotation showed the greatest absolute asymmetry in mean hemispheric flow. It was also only in the rotation task that an asymmetry in the parietal region was clearly evident, the area classically associated with visuospatial and visuoconstructive processing. A recent EEG study also reported evidence for greater right hemisphere activation during a rotation task than any other condition [16].

The most direct implication of the robust rCBF asymmetries observed in the rotation task is that the task itself is a useful activation or "stress" condition to use in patient studies involving physiological measures of cerebral dysfunction and recovery. Mental rotation provides a task that more reliably activates the right hemisphere than those previously reported.

Speculation beyond these practical implications requires assuming that relative metabolic activity reflects the extent to which cerebral regions are involved in a particular behavioral or mental process. In general, such a relationship appears to exist, based on many studies showing a coupling between demanding mental activity and increases in region metabolism, but many factors may influence it, including task difficulty, experience, habituation, reliance on innate versus learned mechanisms, etc., few of which have been systematically examined. Without relying too heavily on assumptions, we can suggest that mental rotation uses more exclusively right hemisphere "skills" than do the other tasks surveyed. Whether the nature of these "skills" is revealed more by the rotation task than the line orientation task is, of course, a more complex issue. Mental rotation does involve "mental manipulation" in space, a term that has been brought up in the past in reference to right hemisphere superiority, especially in the context of tasks attempted with commissurotomy ("split-brain") patients [8, 21].

Arthur Benton has proposed a model of hemispheric asymmetries in visuoconstructive, visuoperceptive and visuospatial processes where the right hemisphere plays an almost exclusive role at the elementary visuospatial level, involving such things as judging line orientation or arc curvature, and much less of an exclusive role at the visuoconstructive level [1]. Our data cannot address the "exclusivity" issue since this would require subtracting all non-cognitive, sensory-motor components through specially designed control tasks, but it does provide a direct comparison between tasks with very similar stimulus and response components. Judgement of line orientation certainly results in significant hemispheric asymmetry due to greater right hemisphere activation, but mental rotation also depends heavily on right hemisphere processes suggesting that these involve "mental manipulation" as well as more basic judgements of the sort proposed by Benton's model.

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