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Functional magnetic resonance imaging of mental rotation and memory scanning: a multidimensional scaling analysis of brain activation patterns [1]

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Contents

1. Introduction

Mental rotation [6,18,19] and memory scanning [4,12,20] are typical examples of cognitive operations presumably involved in various tasks [7]. The original tasks involved judgements to be indicated by key presses [18,19] or verbal responses [20], whereas recent variants [4,6,12] required directed movements as responses. The cardinal sign of both mental rotation and memory scanning tasks is the increase of the response time with task demands, namely the angle of rotation [6,18,19] or of the number of items in the list scanned [4,12,20]. The rates of processing information in these two kinds of tasks are uncorrelated [12], which suggests that different brain mechanisms may be involved. In contrast, the rates of rotation of a figure or a movement direction are positively correlated [12], which

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suggests that common aspects of brain mechanisms may be involved in widely different cases of mental rotation.

The overall brain mechanisms underlying mental rotation and memory scanning are largely unknown. With respect to mental rotation, a consistent finding of electrophysiological and other studies has been that parietal areas are involved in mental rotation of visual images [1–3,10,11,14–16,21–23,25,26]. With respect to relations between brain activation and task performance, recent studies using functional magnetic resonance imaging (fMRI) [22,23] have indicated an involvement of the parietal areas, bilaterally, with performance outcome and an association of the precentral gyrus of the right hemisphere with the rate of mental rotation in the Shepard and Metzler [19], 3D image paradigm [23].

Neurophysiological studies in the motor cortex of behaving monkeys have provided an insight into the neural processes involved in the mental rotation [5,9] and memory scanning tasks [13] that required directed movements as indicators of response; namely, a slow rotation of a directional population signal in mental rotation [5,9] and an abrupt switch in direction of that signal in memory scanning [13]. Although these studies addressed the question of neural processing within a particular cortical area (i.e. the motor cortex), several brain areas are probably involved in the performance of these tasks. It is also obvious that tasks can resemble (or differ from) each other along different dimensions. For example, some tasks involve mental rotation whereas others involve memory scanning; and some involve mental operations on visual images whereas others involve operations on movement representations. The constellation of brain areas that are differentially involved in, and essentially represent, those dimensions can be revealed best by techniques that allow the determination of engagement of a number of areas by a given task. This information can be obtained accurately in single subjects by fMRI which we employed in this study.

Typically, several areas are activated during performance of a given task, and this set of areas frequently overlaps with the set of another task. This, in turn, implies that task-related information is processed in a distributed fashion by various areas. In the present study, we sought to recover this information from binary functional activation maps using weighted multidimensional scaling.

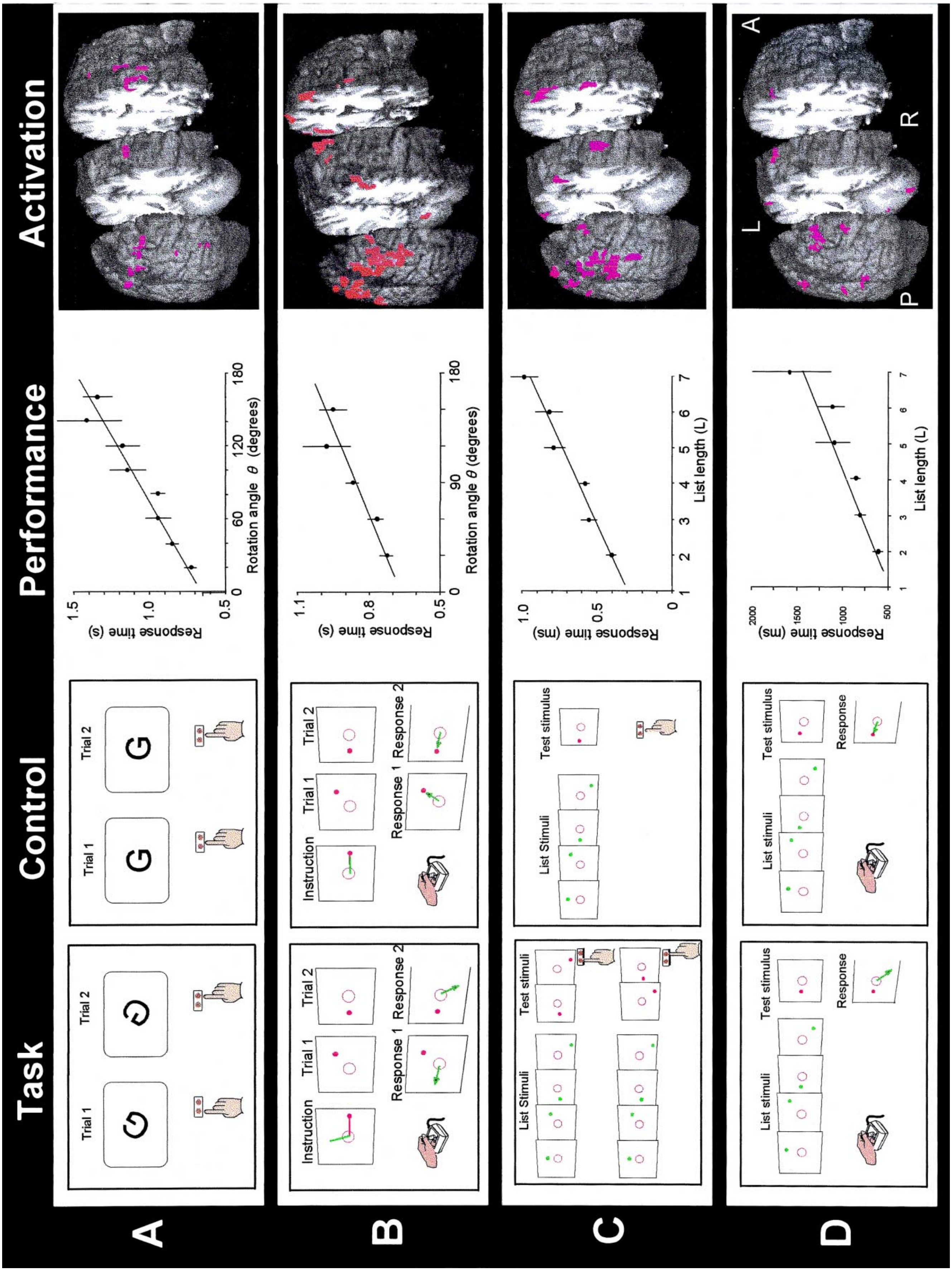
2. Materials and methods

2.1. Tasks

Ten healthy subjects (5 women and 5 men) were paid volunteers and performed the following tasks with the approval of the Institutional Review Board of the University of Minnesota. All subjects were right handed and performed with the right hand. The experimental tasks used, and the corresponding control tasks, are illustrated in Fig. 1. Each subject performed all of the following tasks in a random order.

In the *visual mental rotation task* (task A in Fig. 1), the letter G was shown rotated from −160 to +160° from the upright at 20° intervals, in a random order in different trials. Normal and mirror images of the letter were presented for each angle above. Subjects responded by pressing the left or the right of two buttons to indicate whether the letter was in normal or mirror image orientation, respectively. In the control task (see Fig. 1), the same letter was shown normal and upright, and the subjects responded by just pressing a button without having to make any judgment. In the *movement mental rotation task* (task B in Fig. 1), an instruction angle was shown for 900 ms, and was followed by a stimulus in one of twelve positions on a circle, every 30°; twelve stimuli were shown for each of five instruction angles (30 to 150° counterclockwise, every 30°) in a randomized block design. Subjects responded by moving a joystick-controlled cursor in a direction away from the stimulus at the instructed angle. In the control task, a zero angle was instructed, and subjects responded by moving the joystick in the direction of the stimulus shown. In the context-recognition *visual memory scanning task* (task C in Fig. 1), a sequence (list) of 2 to 7 visual stimuli was shown in a random order on a circle and then two consecutive (test) stimuli were shown again in the same or reverse sequence; subjects responded by pressing the left or the right of two buttons to indicate whether the two test stimuli were presented in the original or reverse sequence, respectively. In the control task, 2 to 7 stimuli were shown but only one as a test stimulus, and the subjects responded by just pressing a button without having to make any judgment. Finally, in the context-recall *movement memory scanning task* (task D in Fig. 1), a sequence of 2 to 7 stimuli was shown in a random order on a circle, and then one (test) stimulus (except the last) was shown again; subjects responded by moving a joystick-controlled cursor in the direction of the stimulus that was presented next to the test stimulus in the sequence. In the control task, the same display was shown and the subjects responded by moving the joystick in the direction of the test stimulus. For both memory scanning tasks, eight circular positions were used, every 45°. Each visual stimulus was shown for 600 ms, and then went off while the next stimulus came on; the delay from the end of the presentation of the last stimulus to the onset of the first test stimulus was 900 ms.

Each one of the four experimental tasks above was performed during the ‘task period’ which was preceded and followed by a ‘control period’ during which the corresponding control tasks were performed. The sequence of presentation of these four tasks was randomized. Key presses and directed movements were recorded using a nonmagnetic keypad and joystick, respectively. Directed movements were considered correct when they were within ±30° from the required direction. The response time was


Task
Control
Performance
Activation
A
B
C
D
Trial 1
Trial 2
Instruction
Response 1
Response 2
List Stimuli
Test stimuli
List stimuli
Test stimulus
Response
Response time (s)
Response time (ms)
Rotation angle θ (degrees)
List length (L)
L
R
A
P

measured with a precision of 1 ms. Eye movements were recorded during performance in the magnet by electrooculography using Ag/AgCl electrodes and graphite wires. In general, eye movements were infrequent during data acquisition.

2.2. Functional MRI

A 4 Tesla whole body system with head gradients and a homogeneous RF coil [SIS Co. (Sunnyvale, CA) / Siemens (Erlangen, Germany)] was used. A head support system with a deflatable vacuum pillow was used to minimize head movements during the experiment. Multislice coronal anatomic images (T1-weighted) were obtained using a turbo-FLASH sequence with 5 mm slice thickness and in-plane spatial resolution of 1.88 mm $\times$ 1.88 mm. For functional imaging, a $T2^*$-weighted, single-shot Echo-Planar Imaging (EPI) sequence was employed (TE = 25 ms). Imaging planes were coronal, with 5 mm slice thickness and in-plane spatial resolution of 3.75 mm $\times$ 3.75 mm. In total, 35–39 slices were collected, covering the whole brain. The acquisition time for a single slice was 30 ms; for a complete multislice image, the repetition time was 4.7–5.0 s. Images were collected continuously during the experiment. The duration of each of the four experiments was 9.7–10.3 min. In total, 124 multislice images were collected in each experiment (40, 60 and 24 images during the first control, the task, and the second control period, respectively). All images were screened for possible artifacts due to movement of the head. Such movements may induce spatially interleaved positive and negative alterations in image intensity and produce artifacts over large areas, including the borders of the brain image. All images were screened for such artifacts and images were rejected if artifacts were present.

Functional activation maps were generated by comparing the average intensity of each pixel during the task period with that observed during each of the two control periods. A pixel was deemed to be activated if its intensity during the task period was significantly higher than that of each control period ($p < 0.01$, t-test). There were two additional requirements; namely, that (i) at least four contiguous pixels in plane should fulfill the aforementioned statistical criteria, and (ii) for each pixel the coefficient of variation during the control periods should be less than 3%. This latter criterion was added because it has been documented that the coefficient of variation is higher in the vicinity of large vessels as well as outside the brain [8]. Overall, the combination of these criteria aimed at identifying highly consistent activation. The assignment of activated pixels to specific areas was based on anatomical landmarks in 2D images and in 3D reconstructions of brain volumes (VoxelView/Ultra 2.5, Vital Images Inc., Fairfield, IA) as well as on Talairach coordinates [24].

2.3. Multidimensional scaling

Any area that was activated in at least one task and one subject was included in the following analysis. The program ALSCAL of the SPSS statistical package (version 7, SPSS Inc., Chicago IL, 1996) was used to perform multidimensional scaling of the binary functional activation maps. Specifically, the Individual Differences Scaling Model (INDSCAL) was used on a ratio level. The data entered for this analysis consisted of thirty 4×4 (square) 'dissimilarity' matrices, one for each brain area. The number of rows (i) and columns (j) was the same, $i = j = 4$, and corresponded to the 4 tasks used; therefore the matrix was diagonally symmetric. The elements of the matrix, x_{ij}, were the absolute differences between the number of subjects in which the given area was activated in the two corresponding tasks. The total number of subjects was 10, and was the same for all areas and all tasks. Therefore, each matrix represented the dissimilarity in the activation of a given area among the 4 tasks used.

3. Results and discussion

As mentioned above, the cardinal performance feature of the tasks employed is the linear increase of the response time with (i) the angle of rotation, in the mental rotation tasks (A and B in Fig. 1), and (ii) the number of list stimuli, in the memory scanning tasks (C and D in Fig. 1). The slopes of these equations are characteristic of the respective processes. All subjects in the present study showed these relations. Data and fitted regression lines are illustrated for one subject in Fig. 1, in the *Performance* panel.

As expected, several areas were activated during performance of these tasks. Representative 3D images of brain activation from one subject are shown in Fig. 1, in the *Activation* panel. The percentage of subjects for which each of the 30 brain areas studied (columns) was activated in each of the 4 tasks used (rows) is shown graphically in Fig. 2. The pattern of brain activation in a row can be

Fig. 1. Schematic drawings of the tasks used, and representative performance plots and 3D functional activation maps from one subject. (A) visual mental rotation; (B) motor mental rotation; (C) visual memory scanning; (D) motor memory scanning. *Task*: experimental tasks. *Control*: control tasks. The control tasks were designed so that the visual display and the motor responses were very similar with those of the corresponding experimental tasks. Therefore, the functional activation maps reflect the combination of task dimensions and not sensorimotor events. *Performance*: Response time (mean $\pm$ SEM) is plotted against rotation angle (tasks A and B) or list length (tasks C and D). Data are from performance during imaging. *Activation*: Functional activation maps illustrate typical examples from the subject whose performance is illustrated under *Performance*.

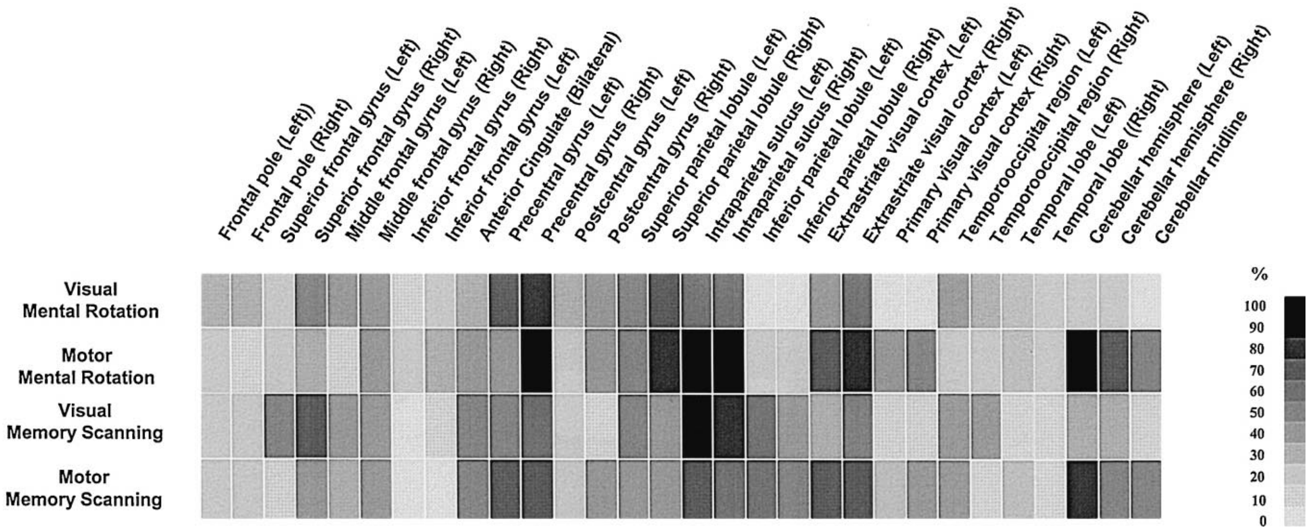


Fig. 2. Schematic diagram showing the percentage of subjects who showed activation of the areas indicated.

regarded as the 'brain signature' for a particular task. It can be seen that these brain signatures involve the activation of partially overlapping sets of brain areas. For example, some areas (e.g. precentral gyrus, intraparietal cortex, extrastriate cortex) were activated in all four tasks, whereas other areas were predominantly activated under certain conditions (e.g. cerebellum during motor mental rotation and motor memory scanning, and inferior parietal lobule during visual and motor memory scanning). Due to this overlap, brain activation patterns do not allow, by themselves, a unique identification of a task. Obviously, the tasks used share common characteristics while they differ in other ones. However, they are sufficiently complex, so that these similarities and dissimilarities cannot be easily expressed as an exhaustive list of physical, psychological, or brain activation characteristics. Similarly, the activation of particular brain areas can hardly be assigned to a specific attribute of a given task. Now, it is precisely in such a situation that multidimensional scaling can prove valuable, as discussed eloquently by Shepard [17]: Given a group of objects and a matrix of pairwise dissimilarities between them, multidimensional scaling can derive a spatial configuration of these objects such that more similar objects are located nearer to each other. The crucial aspect here is '(dis)similarity', and this can be broadly defined. For example, it could relate to the perceived (dis)similarity of the objects (e.g. between two colors or between two letters), or to actual distances in a specific metric (e.g. distances in miles between two cities). Thus, using multidimensional scaling, one can derive a *perceptual map* of the spectral colors [17] or an *actual map* of the cities in a country [27]. In the present case, we sought to derive a *brain activation map* of the four tasks used, that is to visualize the task similarity in brain space *based on the relative frequency of activation of the brain areas studied during performance of these tasks*.

An important choice in multidimensional scaling concerns the number of dimensions of the configuration space. This is usually decided on grounds of parsimony, explanatory power, or a priori information. In the present study, we specified a two-dimensional solution given that we originally designed the tasks to vary in two dimensions. In general, it is advisable to keep the dimensions to a minimum possible, but in our case the dimensionality of the behavioral task space provided an additional reason for specifying a 2D solution. Another choice concerns the model to be applied. We used the individual differences scaling (INDSCAL) model (also called weighted multidimensional scaling [27]) for two main reasons. First, it treats (i.e. weights) every area individually with respect to the task space, and this is important because it is reasonable to suppose that the tasks used may map differently on different areas. And second, the INDSCAL model derives

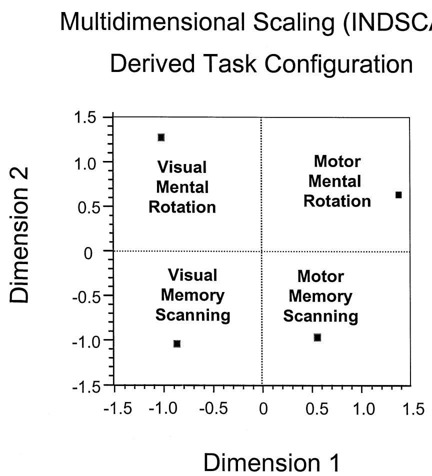


Fig. 3. Task configuration space derived by multidimensional scaling (INDSCAL model). The four tasks used are well separated.

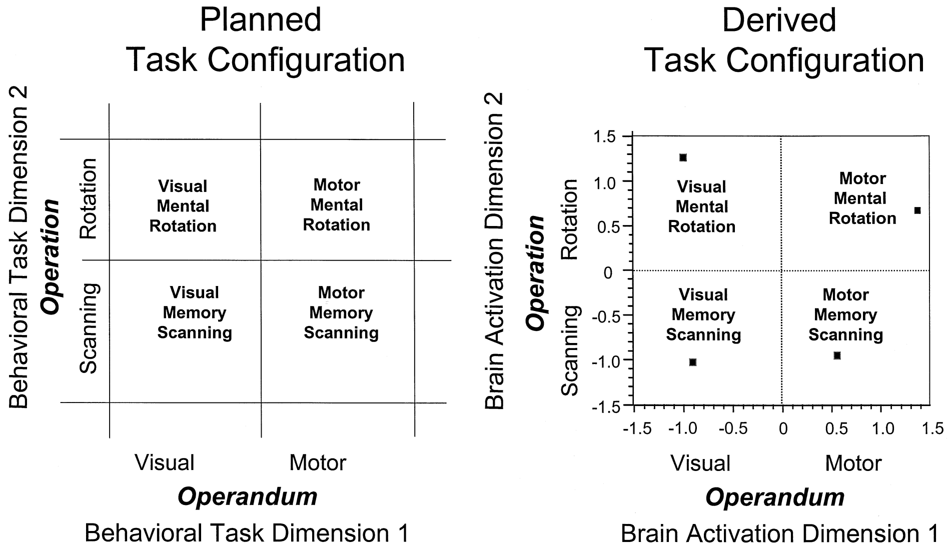


Fig. 4. Interpretation of the results of the multidimensional scaling analysis illustrated in Fig. 3. Left panel: Experimental task design. Right panel: Same plot as that of Fig. 3 but the axes are interpreted to indicate the task dimensions, as on the left panel, in a two-dimensional space derived by multidimensional scaling of the percentage of activation of 30 brain areas.

as a solution a configuration space in which the points are non-rotatable, and, therefore, the dimensions should be readily interpretable. Indeed, this proved to be the case in the present studies.

The results are shown in Fig. 3. The two axes correspond to the two ‘dimensions’ derived by multidimensional scaling; since these were based on the relative frequency of relative activation of brain areas, they can be called ‘brain activation’ dimension 1 and 2. Now, it can be seen that the 4 points corresponding to the 4 tasks fall within the 4 quadrants of the plot, such that the ‘visual’ and ‘motor’ attributes of the tasks fall on either side from the zero point on the abscissa, whereas the ‘mental rotation’ and ‘memory scanning’ attributes fall on either side from the zero point on the ordinate. This arrangement suggests that the brain activation dimensions of the ordinate and the abscissa are readily interpretable as reflecting the mental operation (mental rotation or memory scanning) and its operandum (visual or motor), respectively. This interpretation is exemplified in Fig. 4 in which the plot of Fig. 3 is re-plotted in the right panel together with the experimental task design shown in the left panel. The latter illustrates the fact that there were 2 task dimensions by design, within each of which there were 2 categorical variables. Of the 2 dimensions, one concerned the mental operation (i.e. mental rotation or memory scanning), whereas the other concerned the operandum of the process (i.e. visual image or movement representation). This design can be represented as a 2×2 table the elements of which are the 4 combinations of the categories above, namely visual mental rotation, motor mental rotation, visual memory scanning, and motor memory scanning. Essentially, this task-table and the two task dimensions were successfully recovered from the patterns of activation of the brain areas examined (Fig. 4, right panel): The ordinate corresponds to the process itself (mental rotation or memory scanning), whereas the abscissa corresponds to the operandum of the process (visual image or movement direction). In addition, it is noteworthy that the coordinate values within the latter ‘process dimension’ were very close for the tasks which involved the same process but different operanda. This strengthens our interpretation and underscores the usefulness of this approach in analyzing complicated brain activation patterns from binary functional neuroimaging maps and relating them to aspects of the complex cognitive tasks.

4. Conclusions

Although functional brain imaging provides a powerful tool by which to identify brain areas involved in performance of particular cognitive tasks, the resulting complex functional activation maps are difficult to interpret and even more difficult to relate, as a whole pattern, to the richness of the tasks used. In this paper, we demonstrated the successful application of weighted multidimensional scaling to as complicated brain activation patterns as those resulting from the study of 30 brain areas in 4 highly complex cognitive tasks. Indeed, this analysis yielded a readily interpretable configuration space in which the task dimensions of the mental process (i.e. mental rotation or memory scanning) and its operandum (i.e. visual image or movement direction) were successfully recovered. These results imply that there is sufficient information in the binary pattern of activation of brain areas, as a whole, to resolve the basic dimensionality of highly complex cognitive tasks.

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References

[1] B. Alivisatos, M. Petrides, Functional activation of the human brain during mental rotation, Neuropsychologia 35 (1997) 111–118.

[2] M.S. Cohen, S.M. Kosslyn, H.C. Breiter, G.J. Digirolamo, W.L. Thompson, A.K. Anderson, S.Y. Bookheimer, B.R. Rosen, J.W. Belliveau, Changes in cortical activity during mental rotation — a mapping study using functional MRI, Brain 119 (1996) 89–100.

[3] G. Deutsch, W.T. Bourbon, A.C. Papanicolaou, H.M. Eisenberg, Visuospatial tasks compared via activation of regional cerebral blood flow, Neuropsychologia 26 (1988) 445–452.

[4] A.P. Georgopoulos, J.T. Lurito, Cognitive spatial-motor processes. 6. Visuomotor memory scanning, Exp. Brain Res. 83 (1991) 453–458.

[5] A.P. Georgopoulos, J.T. Lurito, M. Petrides, A.B. Schwartz, J.T. Massey, Mental rotation of the neuronal population vector, Science 243 (1989) 234–236.

[6] A.P. Georgopoulos, J.T. Massey, Cognitive spatial-motor processes. 1. The making of movements at various angles from a stimulus direction, Exp. Brain Res. 65 (1987) 361–370.

[7] A.P. Georgopoulos, G. Pellizzer, The mental and the neural: Psychological and neural studies of mental rotation and memory scanning, Neuropsychologia 33 (1995) 1531–1547.

[8] S.-G. Kim, K. Hendrich, X. Hu, H. Merkle, K. Uğurbil, Potential pitfalls of functional MRI using conventional gradient-recalled echo techniques, NMR in Biomedicine 7 (1994) 69–74.

[9] J.T. Lurito, T. Georgakopoulos, A.P. Georgopoulos, Cognitive spatial-motor processes. 7. The making of movements at an angle from a stimulus direction: Studies of motor cortical activity at the single cell and population levels, Exp. Brain Res. 87 (1991) 562–580.

[10] A.C. Papanicolaou, G. Deutsch, W.T. Bourbon, K.W. Will, D.W. Loring, H.M. Eisenberg, Convergent evoked potential and cerebral blood flow evidence of task-specific hemispheric differences, Electroencephal. Clin. Neurophysiol. 66 (1987) 515–520.

[11] L.M. Parsons, P.T. Fox, J.H. Downs, T. Glass, T.B. Hirsch, C.C. Martin, P.A. Jerabek, J.L. Lancaster, Use of implicit motor imagery for visual shape discrimination as revealed by PET, Nature 375 (1995) 54–58.

[12] G. Pellizzer, A.P. Georgopoulos, Common processing constraints for visuomotor and visual mental rotation, Exp. Brain Res. 93 (1993) 165–172.

[13] G. Pellizzer, P. Sargent, A.P. Georgopoulos, Motor cortical activity in a context-recall task, Science 269 (1995) 702–705.

[14] F. Peronnet, M.J. Farah, Mental rotation: an event-related potential study with a validated mental rotation task, Brain Cogn. 9 (1989) 279–288.

[15] A. Pieret, F. Peronnet, Mental rotation and mirror-image discrimination, Percept. Motor Skills 78 (1994) 515–524.

[16] D.S. Ruchkin, R. Johnson, H. Canoune, W. Ritter, Event-related potentials during arithmetic and mental rotation, Electroencephal. Clin. Neurophysiol. 79 (1991) 473–487.

[17] R.N. Shepard, Multidimensional scaling, tree-fitting, and clustering, Science 210 (1980) 390–398.

[18] R.N. Shepard, L.A. Cooper, Mental Images and their Transformations, MIT Press, Cambridge, MA, 1982.

[19] R.N. Shepard, J. Metzler, Mental rotation of three-dimensional objects, Science 171 (1971) 701–703.

[20] S. Sternberg, Memory-scanning: Mental processes revealed by reaction-time experiments, Am. Scientist 57 (1969) 421–457.

[21] D.T. Stuss, F.F. Sarazin, E.E. Leech, T.W. Picton, Event-related potentials during naming and mental rotation, Electroencephal. Clin. Neurophysiol. 56 (1983) 133–146.

[22] G.A. Tagaris, S.-G. Kim, J.P. Strupp, P. Andersen, K. Uğurbil, A.P. Georgopoulos, Quantitative relations between parietal activation and performance in mental rotation, NeuroReport 7 (1996) 773–776.

[23] G.A. Tagaris, J.P. Strupp, P. Andersen, K. Uğurbil, A.P. Georgopoulos, Mental rotation studied by functional magnetic resonance imaging at high field (4 Tesla): Performance and cortical activation, J. Cogn. Neurosci. 9 (1997) 419–432.

[24] J. Talairach, P. Tournoux, Co-planar Stereotaxic Atlas of the Human Brain, Thieme Medical, New York, 1988.

[25] P.E. Wendt, J. Risberg, Cortical activation during visual spatial processing: relation between hemispheric asymmetry of blood flow and performance, Brain Cogn. 24 (1994) 87–103.

[26] A.A. Wijers, L.J. Otten, S. Feenstra, G. Mulder, L.J. Mulder, Brain potentials during selective attention, memory search, and mental rotation, Psychophysiology 26 (1989) 452–467.

[27] F.W. Young, D.F. Harris, Multidimensional scaling: Procedure ALSCAL, in: SPSS® Base System User's Guide, SPSS Inc., Chicago, IL, 1990, pp. 397–461.