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Short communication

Functional optimization of arithmetic processing in perfect performers

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Abstract

Lesion and imaging studies to date have not clarified which sub-regions of the parietal lobe are specialized for arithmetic processing, and which perform supporting functions. We used functional magnetic resonance imaging to investigate parietal lobe function during arithmetic processing. Functional optimization was examined by analyzing regional differences in brain activation between perfect (100% accuracy) and imperfect performers. Perfect performers had significantly less activation only in the left angular gyrus, a finding that may be associated with skill mastery and long-term practice effects. The present results provide the first direct evidence of localized functional optimization for arithmetic processing in the human brain. © 2000 Elsevier Science B.V. All rights reserved.

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The accurate and rapid processing of arithmetic operations is a human cognitive skill that is called into play almost every day. Imaging studies have identified a network of brain regions, including the parietal cortex, lateral prefrontal cortex, medial prefrontal cortex, and cerebellum, as being involved in arithmetic processing [2,4,11]. Lesion studies, on the other hand, consistently point to the parietal lobe as being involved in dense acalculia [3,8,9,12,13]. However, neither lesion nor imaging studies have addressed the issue of which parietal sub-regions are specialized for arithmetic processing, and which regions perform functions that are related to the task (e.g., working memory and attention).

In the present study, we investigated specialization in parietal lobe function during arithmetic processing using functional magnetic resonance imaging (fMRI.) We analyzed regional differences in brain activation between perfect (100% accuracy) and imperfect performers. Sixteen healthy, right-handed subjects (eight males and eight females; ages 16.84–23.02 years) participated in the study. In alternating 30-s epochs, subjects were presented with an experimental or control condition. In the experimental condition, subjects viewed arithmetic equations in the form

"4 + 2 - 1 = 4" and were asked to respond with a key press if the result shown was correct. In the control condition, subjects viewed a string of seven single digits (e.g., "1325074") and responded only if the string contained "0". Stimuli were presented every 3 s.

Three-operand addition and subtraction was used because it requires subjects to compute the answer, rather than rely primarily on arithmetic fact retrieval. Eight of the sixteen subjects were perfect performers in the arithmetic processing condition; that is, their response accuracy was 100%. The remaining eight subjects had accuracy rates ranging from 78% to 96%, with a mean accuracy of 92% and a standard deviation of 6.2%. For both the perfect and imperfect performers, the gender distribution was four males and four females.

fMRI data were analyzed using techniques implemented in SPM99 [7]. For each subject, brain activation related to arithmetic processing was determined by contrasting experimental and control conditions. We demarcated three regions of interest (ROIs) in the parietal cortex: the superior parietal (SUPAR), supramarginal gyrus (SGM), and angular gyrus (ANG), based on known neuroanatomical surface and cross-sectional landmarks [6].

Consistent with previous imaging studies, whole-brain analysis revealed significant group activation in the parietal cortex, as well as the inferior and middle frontal gyri, right mid-cerebellar hemisphere, right premotor cortex, and left caudate (Fig. 1).

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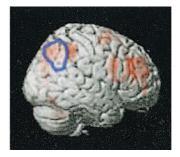


Fig. 1. Brain areas that showed significantly greater activation during arithmetic processing, contrasted to the control condition, included the inferior and middle frontal gyri as well as the angular and supramarginal gyri in the parietal cortices. Angular gyrus is shown outlined in blue.

A three-way ANOVA was performed, using the percentage of voxels activated in each ROI, with a betweensubjects factor of Group (perfect, imperfect performers) and within-subjects factors of ROI (SUPAR, SGM, ANG) and hemisphere (L, R). A significant three-way interaction emerged between Group, ROI and Hemisphere F(2,28) =3.76, p = 0.035. This interaction was further examined by conducting a two-way (Group × ROI) ANOVA for each hemisphere. The right-hemisphere ANOVA yielded no significant interaction (p = 0.743) or main effects. By contrast, the left-hemisphere ANOVA yielded a marginally significant interaction, F(2,28) = 3.21, p = 0.055. This interaction was further explored by examining group differences in each of the three regions using two-tailed *t*-tests. Perfect performers had significantly decreased activation only in the left angular gyrus, F(1,14) = 8.01; p = 0.013(Fig. 2). No other region showed a significant relationship between activation and performance category. The mean activation in the perfect performers (M = 8.38) was less than half that of the imperfect performers (M = 17.12). Further, the variance in activation in this region was significantly less for the perfect (SD = 3.45) than for the imperfect (SD = 8.03) performers (Levene Test, F(1,14) = 4.71, p = 0.047). Tested against the null hypothesis of no activation, perfect performers showed significant activation in this region (t(7) = 6.87; p < 0.001), as did the imperfect performers (t(7) = 6.03; p < 0.001). Within the group of eight imperfect performers, there was a trend toward decreasing activation in the left angular gyrus with increase in accuracy score; however, this correlation was not significant (Spearman, R = -0.42, p = 0.30).

Similar to accuracy, the variance in the reaction time (RT) scores of the perfect performers was less than half that of the imperfect performers (SD = 188.25 and 409.86 ms, respectively). In addition, the RT of perfect performers was about 300 ms faster than that of imperfect performers (M = 1844 and 1548 ms, respectively), t(14) = 1.85, p < 0.05 (one-tailed).

The whole-brain analysis revealed significant activation in the prefrontal cortex, consistent with what has been reported in several studies of arithmetic processing [1,2,4,5,10,11]. In a post-hoc examination, we used two-

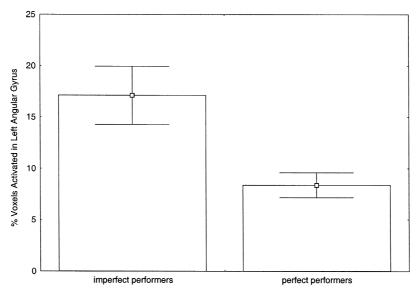


Fig. 2. Perfect performers had significantly less activation than imperfect performers only in the left angular gyrus (left-hand image in Fig. 1, outlined in blue).

tailed *t*-tests to compare activation for the two groups in regions of the prefrontal cortex: the inferior, middle, and superior frontal gyri. No differences in activation between perfect and imperfect performers were found in any of these regions. No gender differences were found in the prefrontal or parietal cortices.

Perfect performers have less activation and less variability in activation only in the left angular gyrus, a finding that may be associated with skill mastery and long-term practice effects. The finding of faster RT for perfect performers supports this interpretation. Although lesion and prior imaging studies have suggested the involvement of the left angular gyrus in mathematical operations [2–4,8,9,11–13], no single region has been implicated in mastery of arithmetic processing to date. The present results provide the first direct evidence of localized functional optimization for arithmetic processing. Note that while both perfect and imperfect performers show significant activation in the left angular gyrus, greater activation is seen in imperfect performers.

More broadly, our findings demonstrate that more refined analysis of brain-behavior relations can yield useful information about functional optimization of specific cognitive processes in the human brain. These data may have future implications for understanding the pathogenesis of learning disorders involving abnormalities of arithmetic processing.

Acknowledgements

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References

- P. Burbaud, O. Camus, D. Guehl, B. Bioulac, J.M. Caille, M. Allard, A functional magnetic resonance imaging study of mental subtraction in human subjects, Neurosci. Lett. 273 (1999) 195–199.
- [2] P. Burbaud, P. Degreze, P. Lafon, J.M. Franconi, B. Bouligand, B. Bioulac, J.M. Caille, M. Allard, Lateralization of prefrontal activation during internal mental calculation: a functional magnetic resonance imaging study, J. Neurophysiol. 74 (1995) 2194–2200.
- [3] S. Dehaene, L. Cohen, Cerebral pathways for calculation: double dissociation between rote verbal and quantitative knowledge of arithmetic, Cortex 33 (1997) 219–250.
- [4] S. Dehaene, E. Spelke, P. Pinel, R. Stanescu, S. Tsivkin, Sources of mathematical thinking: behavioral and brain-imaging evidence, Science 284 (1999) 970–974.
- [5] S. Dehaene, N. Tzourio, V. Frak, L. Raynaud, L. Cohen, J. Mehler, B. Mazoyer, Cerebral activations during number multiplication and comparison: a PET study, Neuropsychologia 34 (1996) 1097–1106.
- [6] H.M. Duvernoy, P. Bourgouin, The human brain: surface, three-dimensional sectional anatomy with MRI, and blood supply, 2nd completely rev. and enl. edn., Springer, Wien, 1999, cm. pp.
- [7] K.J.H.A. Friston, J.-P. Worsley, C.D. Poline, C.D. Frith, R.S.J. Frackowiak, Statistical parametric maps in functional imaging: a general linear approach, Hum. Brain Mapping 2 (1995) 189–210.
- [8] H.J. Kahn, H.A. Whitaker, Acalculia: an historical review of localization, Brain Cogn. 17 (1991) 102–115.
- [9] H.S. Levin, F.C. Goldstein, P.A.A. Speirs. In: K.M.a.V.E. Heilman (Ed.), Clinical Neuropsychology, Oxford Univ. Press, New York, 1993, pp. 91–122.
- [10] P.E. Roland, L. Friberg, Localization of cortical areas activated by thinking, J. Neurophysiol. 53 (1985) 1219–1243.
- [11] L. Rueckert, N. Lange, A. Partiot, I. Appollonio, I. Litvan, D. Le Bihan, J. Grafman, Visualizing cortical activation during mental calculation with functional MRI, Neuroimage 3 (1996) 97–103.
- [12] Y. Takayama, M. Sugishita, I. Akiguchi, J. Kimura, Isolated acalculia due to left parietal lesion, Arch. Neurol. 51 (1994) 286–291.
- [13] E.K. Warrington, The fractionation of arithmetical skills: a single case study, Q. J. Exp. Psychol. [A] 34 (1982) 31–51.