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Are numbers special? The comparison systems of the human brain investigated by fMRI

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Abstract

Many studies have suggested that the intraparietal sulcus (IPS), particularly in the dominant hemisphere, is crucially involved in numerical comparisons. However, this parietal structure has been found to be involved in other tasks that require spatial processing or visuospatial attention as well. fMRI was used to investigate three different magnitude comparisons in an event-related-block design: (a) Which digit is larger in numerical value (e.g., 2 or 5)? (b) Which digit is brighter (e.g., 3 or **3**)? (c) Which digit is physically larger (e.g., 3 or 3)? Results indicate a widespread cortical network including a bilateral activation of the intraparietal sulci for all different comparisons. However, by computing contrasts of brain activation between the respective comparison conditions and applying a cortical distance effect as an additional criterion, number-specific activation was revealed in left IPS and right temporal regions. These results indicate that there are both commonalities and differences in the spatial layout of the brain systems for numerical and physical comparisons and that especially the left IPS, while involved in magnitude comparison in general, plays a special role in number comparison.

Keywords: Intraparietal sulcus; Magnitude; Distance effect

1. Introduction

Are numbers special? Are they represented by a unique brain system? Many accounts of number processing stress the central role of the IPS for number processing (Dehaene, Dehaene-Lambertz, & Cohen, 1998; Dehaene, Piazza, Pinel, & Cohen, 2003). This view is based on patient studies (Dehaene & Cohen, 1997; Lemer, Dehaene, Spelke, & Cohen, 2003) emphasizing the necessity of the IPS of the dominant hemisphere, particularly for number comparison. In addition, electrophysiology studies on monkeys (Nieder & Miller, 2004; Sawamura, Shima, & Tanji, 2002) and neu-

Abbreviations: BOLD, blood oxygen level dependent; CaS, calcarine sulcus; CiS, cingulate sulcus; CoS, collateral sulcus; fMRI, functional magnetic resonance imaging; FEF, frontal eye field; FG, gyrus fusiformis; FOp, frontal operculum; GLM, general linear model; IFG/IFS, inferior frontal gyrus/sulcus; IPL, inferior parietal lobule; IPS, intraparietal sulcus; ITS, inferior temporal sulcus; LS, lateral sulcus; MFG, middle frontal gyrus; MOG, middle occipital gyrus; MTG, middle temporal gyrus; OF, orbitofrontal sulci; OTS, occipito-temporal sulcus; PCS, postcentral sulcus; POS, parieto-occipital sulcus; RS, rolandic (central) sulcus; SFG/SFS, superior frontal gyrus/sulcus; SMA, supplementary motor area; SPL, superior parietal lobule; STS, superior temporal sulcus

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roimaging studies on humans (Pesenti, Thioux, Seron, & De Volder, 2000; Pinel et al., 1999; Pinel, Dehaene, Rivie're, & LeBihan, 2001) revealed bilateral IPS activation during number processing and numerical comparison. Yet, other evidence has suggested that the IPS does not serve as a specialized module for number comparison but is designed to subserve other cognitive processes as well, such as visuospatial analysis (Simon, 1999) or a general magnitude comparison (Walsh, 2003). Moreover, its activity has been reported to be modulated by general task difficulty (Göbel, Johansen-Berg, Behrens, & Rushworth, 2004).

Numbers are claimed to be represented in an abstract fashion on an analogue mental number line (Barth, Kanwisher, & Spelke, 2003; Dehaene et al., 1998; Zorzi, Priftis, & Umilta, 2002). This idea is supported by the *numerical distance effect*, a fundamental behavioral effect that is observed when subjects perform the number comparison task. The distance between two stimuli influences the comparison of the stimuli; the larger the distance between two stimuli, the easier the decision will be and the shorter the reaction time (RT) (Moyer & Landauer, 1967). The number line is generally held to be compressive (Dehaene, 2002, 2003) because comparison times are better predicted when the distance between the two compared numbers are measured on a logarithmic rather than on a linear scale.

However, it is important to note that the reaction time data for the comparison of physical magnitudes across a wide range of domains (e.g., line length, pitch, weight) show exactly the same effects as the comparison of numerical size. Accordingly, the RT profiles for the comparison of both numerical and physical magnitudes are best described by the same logarithmic equation (Welford, 1960). This has led some authors to argue that the mechanism for comparing numerical magnitudes is equivalent to that for the comparison of physical stimuli (Gallistel & Gelman, 1992, 2000; Moyer & Landauer, 1967), a view that is further supported by simulations of number comparison with a recent computational model (Zorzi & Butterworth, 1999).

Therefore, the activation found for number comparison might indicate the operation of a magnitude comparison network rather than a specific numerical network. No study that investigated IPS involvement in number comparison, neurophysiological and neuropsychological alike, examined this possibility. A few recent imaging studies attempted to address the question of whether the way in which the human brain represents numbers is similar to the way in which physical features (Fias, Lammertyn, Reynvoet, Dupont, & Orban, 2003) or other semantic information (Le Clec'H et al., 2000) are represented. Yet, none of these studies manipulated the to-be-compared features (e.g., numerical and physical) and their distances within the same experimental design. Only the latter approach, as taken in the present study, can control for the non-specific activations of other brain areas due to attention, difficulty, semantic content, and the like. For example, Wiese (2003) suggested that language and numerical abilities are dependently linked. Thus, one may suggest that the differences between comparisons are not due to the comparison per se, but are due to the content of the stimuli that are presented. In order to determine commonalities and differences between the numerical and physical comparison systems it is essential to adopt such a design that will manipulate and combine the comparison type and distances. We manipulated three different features, numerical value, luminance, and size, of similar stimulus material and varied the distance in each of these features. Pinel, Piazza, Le Bihan, and Dehaene (2004) addressed the same question with a similar design. They scanned normal subjects with fMRI while they compared size, number, and luminance, which varied orthogonally. They found the expected behavioral interference effect and, in their brain activation data, distributed and overlapping cerebral representations for size, number, and luminance. However, their results could have been influenced by the processing of the irrelevant features that were manipulated as well. Our design was different in that, for each manipulation, we kept the other features constant (e.g., all stimuli for the numerical comparison had the same size and luminance) in order to avoid interference effects and thus be more sensitive to effects specific for the respective comparison. Note that Stroop-like interference between physical size and numerical values (Henik & Tzelgov, 1982; Schwarz & Ischebeck, 2003; Tzelgov, Meyer, & Henik, 1992), and luminance and numerical values (Cohen Kadosh & Henik,submitted for publication) has been documented in previous work. Accordingly, in the current experiment, any overlap between comparison conditions in brain imaging data would then indicate a common magnitude comparison network rather than reflect the implicit and automatic processing of the irrelevant magnitude.

We expected that task-specific[1] areas would show increasing activity with decreasing distance, corresponding to the increasing difficulty (cortical "distance effect"). On the basis of the clinical studies, we expected the cortical specific-distance effects for numbers in the parietal lobe to be unilateral (in the dominant hemisphere) rather than bilateral. Hence, we hypothesized that while a widespread network of areas would be commonly activated by all comparison tasks, a subset of them, particularly along the left IPS, would show a task-specific modulation by number comparison.

[1] We use the term "specific" through this paper to indicate an area whose activation is stronger for a given process relative to other processes. This does not mean necessarily that this area is solely active in response to the given process. This fits the view recently presented by Posner (2003). Posner refers to activations observed under different tasks in the same brain area: *"Although it is not always easy to distinguish between a brain area being specific for a domain or performing a computation that is of particular importance for some domains, either can underlie a form of modularity . . .. Thus these areas and many others that have been described are modules in the sense that they perform specific mental operations . . . sometimes the operations are within a single domain, but sometimes they are more general. In the case of face perception, and for word reading and attention described below several such modules work together in a network to carry out cognitive tasks*." (p. 450)

2. Materials And Methods

2.1. Subjects

Fifteen subjects (eight males, twelve right-handed) with mean age of 27.8 years (S.D.: 4.8 years) were recruited from an academic environment. The study was approved by the local ethics committee. Subjects had no history of neurological or psychiatric disorder and gave written informed consent for participating after the nature of the study had been explained to them.

2.2. Behavioral task

A computer display stimulus consisted of two digits that appeared at a distance of 14 cm from the subject, at the center of a black screen (photometric luminance of 0.2 cd/m^2). The center-to-center distance between the two digits subtended a horizontal visual angle of 16°. There were three different comparisons in separate blocks (Fig. 1): numerical comparison (i.e., which digit is numerically larger?), luminance comparison (i.e., which digit is brighter?), or physical comparison (i.e., which digit is physically larger?). For numerical comparison the digits 1–8 were used, which resulted in three different numerical distances, of 1 (the pairs 1–2, 3–4, 5–6), 2 (the pairs 1–3, 2–4, 5–7) or 4 (the pairs 1–5, 3–7, 4–8). For luminance comparison we formed eight different stimuli that varied only in brightness with constant hue and saturation. Their photometric luminances were 20.9 cd/m^2, 27.7 cd/m^2, 35.8 cd/m^2, 46.5 cd/m^2, 58.4 cd/m^2, 82.5 cd/m^2, 108 cd/m^2, and 175 cd/m^2. The selection of the luminance levels was made in order to create a logarithmic-like function of intensity as reported previously for the representation of numerical quantity (Dehaene, 1989). These luminance levels were used to create three different luminance distances, where every luminance level was scaled to the other levels in a way that corresponded to the numerical pairs. For physical comparison we formed eight different stimuli that varied only in their physical size and subtended a vertical visual angle of 2.9°, 3.1°, 3.4°, 3.7°, 4.1°, 4.5°, 4.9°, and 5.5°. The selection of physical sizes and pairs was made along the same principles as for the luminance stimuli. Thus, each comparison condition used altogether three different distances of 1, 2 and 4 units. In order to avoid any automatic processing of the irrelevant dimensions (i.e., size congruity effect, see Cohen Kadosh & Henik, submitted for publication; Henik & Tzelgov, 1982; Schwarz & Ischebeck, 2003; Tzelgov et al., 1992), the stimuli in each comparison were varied only in the dimension that was relevant to that comparison. For example, the pairs in the numerical comparison varied only in their numerical values but had constant physical size (average size) and luminance level (average luminance) (e.g., the pair 2 4). Similarly, the pairs in the luminance comparison were varied only in the luminance levels but had constant numerical value and physical size (average size) (e.g., 2 2 and 4 4), and the physical pairs were presented according to the same rules (e.g., 2 2 and 4 4). Stimuli were arranged in blocks of trials with each block being composed of six different stimuli. We used ERTS (Experimental Runtime System, Berisoft, Frankfurt, Germany) running on a PC, as stimulus presentation software.

2.3. Procedure

The participants' task was to decide which of two digits in a given display was numerically larger, physically larger, or brighter by pressing a button with the corresponding hand. Each participant took part in three runs that were each composed of nine different blocks (three per comparison type). Each subject completed 162 trials (18 trials for each distance

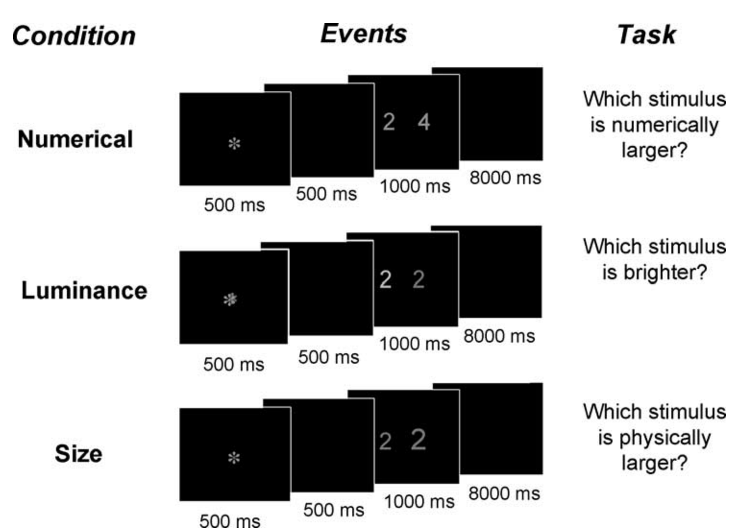

Fig. 1. Paradigm design. Three different tasks containing numerical, size and luminance comparisons. Each pair of stimuli was preceded by a fixation point and a blank (500 ms each) and lasted for 1 s. After 8 s (ITI) a new trial began with the presentation of the fixation point. The subjects had to decide which stimulus was numerically larger, brighter, or physically larger in three different blocks.

in a given comparison) during fMRI data acquisition. The blocks and the stimuli in each block were presented in random order. Participants were asked to respond as quickly as possible but to avoid errors. Correct answers were matched for right and left button presses. The participants indicated their choices by pressing one of two keys corresponding to the side of the display with the selected member of the pair. One key was located on the left side and the other on the right side of the body. The experiment was preceded by a training session (one block for each comparison), which allowed subjects to complete as many trials as necessary to familiarize themselves with the comparison required and the timing of the task. During scanning, the computer display was projected onto a mirror mounted on the head coil. Participants' responses were registered by a fiber-optic response box (Current Designs, Philadelphia, PA, USA).

Each block was preceded by a 6 s instruction on the comparison task to be performed. Each trial began with an asterisk as a central fixation point, presented for 500 ms at the center of a computer screen. Five hundred ms after the fixation point disappeared, a pair of digits appeared for 1 s. The ITI (inter trial interval) was 8 s. The time difference between the last trial in a given block and the first trial of the next block was 34 s. The entire experiment lasted approximately 40 min.

2.4. Design

The variables manipulated were: comparison (numerical, luminance, physical) and distance (1, 2, or 4). Thus, we had a 3×3 factorial design, with all variables within subjects.

2.5. fMRI scanning

Whole brain fMRI data were acquired with a Siemens 1.5 T Magnetom Vision MRI scanner using a gradient echo EPI (echo planar imaging) sequence (16 axial slices; TR (repetition time) = 2000 ms; TE (echo time) = 60 ms; FA (flip angle) = 90°; FOV (field of view) = 210 mm × 210 mm; voxel size: 3.28 mm × 3.28 mm × 5 mm). Functional images were acquired in three runs in a single session. Each run comprised the acquisition of 390 volumes and contained 54 trials (6 trials × 3 distance units × 3 comparisons). Stimulus presentation was synchronized with the fMRI sequence at the beginning of each trial. Each scanning session included the acquisition of a high-resolution, T1-weighted three-dimensional volume (voxel dimensions = 1 mm × 1 mm × 1 mm) for co-registration and anatomical localization of functional data.

2.6. Data preprocessing and GLM statistics

Functional data were preprocessed and analyzed using the BrainVoyager 4.8 software package (www.brainvoyager.com). Statistical analysis was based on the cortex-based general linear model (GLM) of the experiment (Munk et al., 2002). The first two volumes of each run were discarded to allow for T1 equilibration. 3D motion correction and Talairach transformation (Talairach & Tournaux, 1988) were performed for the remaining set of functional data of each subject. The 3D functional data set was re-sampled to a voxel size of 3 mm × 3 mm × 3 mm. Data pre-processing furthermore comprised spatial smoothing with a Gaussian kernel (FWHM = 8 mm), linear trend removal and temporal high pass filtering (high pass: 5 cycles per functional run of 390 volumes). For the GLM, each of the nine conditions of the experimental design was defined as a predictor that assumed the value of 1 for the volume during which a pair of stimuli belonging to that condition (e.g., numbers at distance 1) was presented and the following volume, and 0 for all other volumes. The remaining volumes served as a baseline. The cortex-based GLM of the experiment, with predictors convolved with a hemodynamic response function (Boynton, Engel, Glover, & Heeger, 1996), was computed from the 45 (15 subjects, three runs per subject) z-normalized volume time courses. The cortex-based GLM approach (Goebel & Singer, 1999) was developed for fMRI studies whose hypotheses only pertained to cortical areas. In these cases, data analysis can be confined to cortical voxels, avoiding unnecessarily strict Bonferroni correction. The cortex mask used here was derived from the cortex reconstruction of the MNI (Montreal Neurological Institute) template brain, transformed into Talairach space, and contained 49,058 voxels.

The global level of the signal time-courses in each session was considered to be a confounding effect, and a fixed effects analysis was employed. The obtained p values were corrected for multiple comparisons. The resulting 3D statistical maps for the predictors were projected on the flattened surface reconstruction of the template brain. Each of the maps was associated with a color of the red–green–blue (RGB) system (*red*, physical comparison; *green*, luminance comparison; *blue*, numerical comparison). Effects are only shown if the associated p-value yielded $p' < 0.05$.

2.6.1. Task-related activation across comparisons

Colors were superimposed and areas of overlap (cortical regions showing activation during more than one condition) received the appropriate mixed color (Fig. 3B). The resulting *superposition maps* enabled us to illustrate both the similarities and differences of activation patterns among different comparisons.

2.6.2. Comparison-specific modulation

Areas that showed significantly higher activation for one task (e.g., numerical comparison) than for each of the remaining tasks (in this case: size comparison, luminance comparison) were classified as “comparison-specific” (Fig. 4A). These areas were obtained by a t-test on the clusters that showed differences of the relative contribution (RC) values (see below).

2.6.3. Specific distance effect

An area that was comparison-specific and in addition showed a significant difference between the smallest and largest distances for that comparison (according to the t-test on the RC maps), was classified as showing a distance effect for that particular comparison (Fig. 4B).

2.6.4. Computation of relative contribution values

Activation maps that are based on the direct contrast between two conditions (e.g., a t-test) are biased against areas of overlapping activation. When a considerable amount of overlap can be expected, the RC approach can be chosen instead (Munk et al., 2002). For significantly activated voxels (Fig. 3B), the RC between two selected conditions in explaining the variance of a voxel time course was computed as $RC = (R_{extra}^{(2)} - R_{extra}^{(1)})/(R_{extra}^{(2)} + R_{extra}^{(1)})$, where $R_{extra}^{(i)}$ is the contribution of one or a set of predictors. The contribution of a (set of) predictors to a model is computed as an incremental multiple correlation coefficient, R_{extra}, according to the "extra sum of squares principle" (Draper & Smith, 1998). RC can assume values between 1 (only predictor 2 contributes to the model) and −1 (only predictor 1 contributes). Only clusters with RC values equal or greater than 0.1 were used for further statistical analysis. Because the RC value itself, while valuable for the visualization of the differential recruitment of brain areas by different tasks, does not carry any information about the statistical significance of these differences, we performed a t-test of significant differences between the beta weights associated with the types of comparison (number, size, luminance) and distance levels. Thus, the maps shown in Fig. 4A are based on a sequential application of the RC analysis, which determined the predilection of an area for a certain comparison condition. Later, a t-test confirmed that the activation of that area was actually significantly higher in that condition (e.g., numerical comparison in the case of the blue clusters) than in any other condition.

3. Results

3.1. Behavioral data

For every subject in each condition the mean RT was calculated for correct trials only. These means were subjected to a two-way analysis of variance (ANOVA) with comparison and distances as within subject factors.

All main effects were significant. Participants responded faster to a large distance than to a small distance [$F(2,28) = 121.35$, M.S.E. = 475, $p < 0.001$]. Participants also responded faster to the luminance and size comparison than to the numerical comparison [$F(2,28) = 3.72$, M.S.E. = 1.917, $p < 0.05$]. In addition, the two-way interaction was significant [$F(4,56) = 6.75$, M.S.E. = 437, $p < 0.005$]. To further our understanding regarding the sources of this interaction we conducted simple effects analyses for distance of 1, 2, and 4, separately. The interaction stemmed from a significant difference in the distance of 4 units between the numerical comparison versus the luminance and size comparisons [$F(1,14) = 21.89$, M.S.E. = 824, $p < 0.001$]. In contrast, there were no significant differences between the different tasks for distances of 1, and 2 units ($p > 0.3$). The interaction between comparison type and distance is shown in Fig. 2.

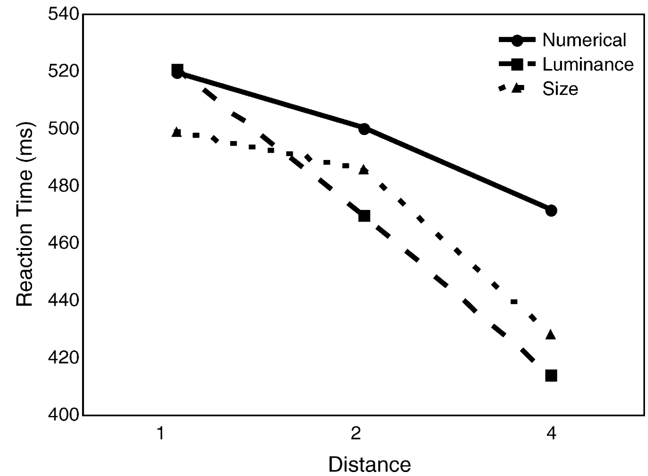

Fig. 2. Behavioral data. Reaction time as a function of type of magnitude comparison and distance.

It might be argued that some of the pairs can be dealt with without actually performing any comparison task, since by the later sessions participants might have discovered that the digits 1, 6, 7 and 8 were always the smaller or the larger ones of the pairs. In order to test for this possibility, we reanalyzed the behavioral data without the first session (i.e., only the second and third sessions), and we included in the analysis only the pairs 1–2, 5–6, 1–3, 5–7, 1–5, 3–7, and 4–8, that theoretically would meet this criterion. If participants solve the task for these pairs without actually comparing the items, no distance effect should be observed in the behavioral data. Contrary to this prediction, the analysis of this subset yielded the same results as that of the entire sample of trials. Moreover, we submitted the data to a three-way ANOVA with the following factors: strategy (all pairs versus those pairs that meet the above criterion for a potentially different strategy), comparison and distance. The factor strategy was not significant nor did it interact with any other factor ($p > 0.2$).

3.1.1. Error rate analysis

Only the main effects for comparison and distance were significant [$F(2,28) = 5.92$, M.S.E. = 31.3, $p < 0.01$] and [$F(2,28) = 8.99$, M.S.E. = 12, $p < 0.005$], respectively. The error percentages for the numerical, luminance, and size comparison were 3.7, 1.5, and 2.1, respectively. Percentage of errors was larger for distance of 1 and 2 units versus 4 units (3.2, 3.3, and 0.9, respectively). The pattern was similar to the pattern observed in the RT results, and thus excluded any RT-accuracy trade-off.

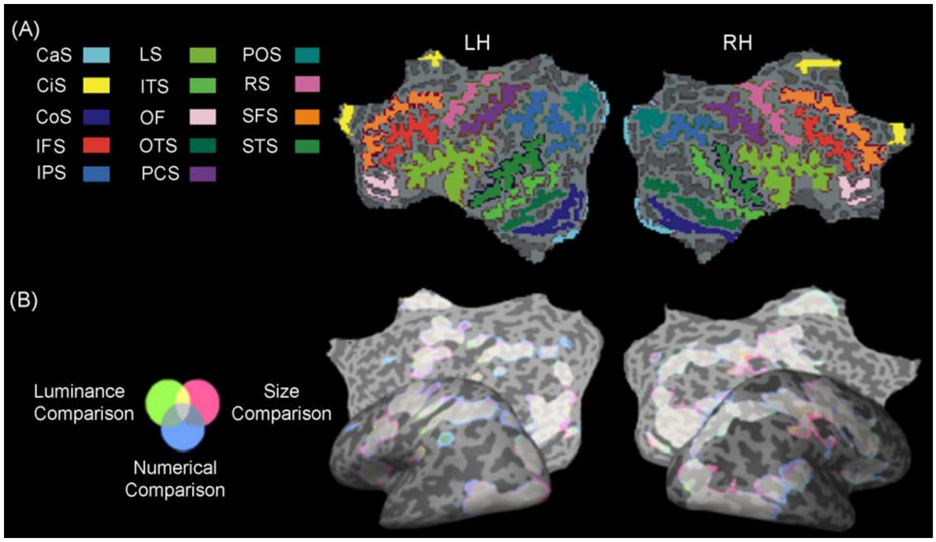

Fig. 3. Cortex-based group analysis of the experiment. (A) Sulcal topography on the cortical flat map of the MNI template brain used for visualization. (B) Task-related activation across comparisons. Superposition maps of the activation during numerical, luminance and physical comparisons. Effects were only shown if the associated p-value yielded $p' < 0.05$ (corrected for multiple comparisons). The 3D statistical maps were then projected on the flattened surface reconstruction of the MNI template brain. Each of the comparisons was associated with a color of the red–green–blue system (red, size; green, luminance; blue, numerical). Colors were superimposed and areas of overlap (cortical regions showing activation during more than one comparison) received the appropriate mixed color.

3.2. fMRI results

The superposition map of the comparison predictors (Fig. 3B) shows activation of a widespread cortical network that was highly similar for all the comparisons. Clusters of activation included the bilateral occipitotemporal and occipitoparietal pathways, IPS, FEF, SMA, IFG, insula and the sensori-motor areas. There was more activation in the right

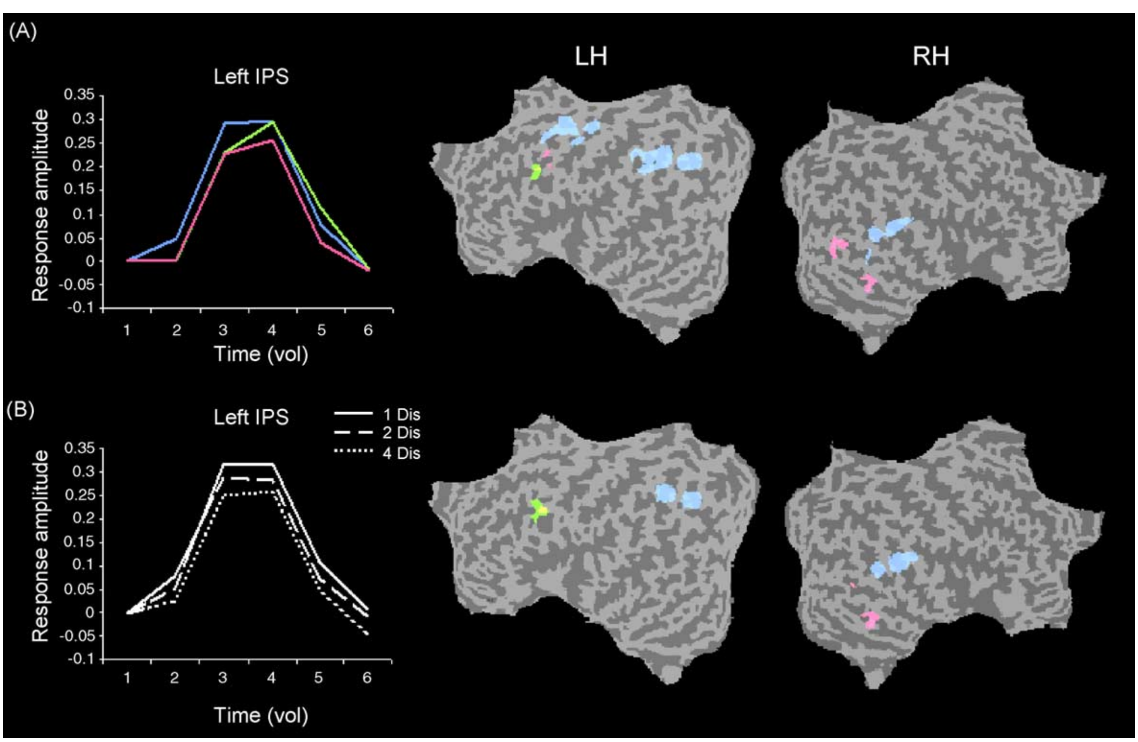

Fig. 4. Comparison-specific and distance-specific modulation. (A) Comparison-specific activation. The areas that demonstrated significantly higher BOLD signal for one comparison vs. the others are shown in their respective colors (as in Fig. 3B). The left plot describes the BOLD time course for each of the comparisons in the left IPS. (B) Specific distance effects are indicated by the appropriate color (as in Fig. 3B). The left plot describes the BOLD time course for the numerical distance in the left IPS (volume 1 is the first volume after the stimulus presentation).

Table 1
Talairach coordinates and statistical details for foci that showed a comparison-specific modulation as presented in Fig. 4A

Contrast	Stereotaxic coordinates			Number of voxels	Hemisphere	Region (BA)	T	P
	x	y	z					
Numerical vs. size	52	−43	8	2221	Right	STS (21/22)	2.28	0.02
	26	−63	41	1247	Right	IPS (7)	2.34	0.01
	34	−54	0	478	Right	MTG (21)	1.96	0.05
	37	1	32	771	Right	IFS (9/40)	2.06	0.03
	−25	−58	42	3162	Left	IPS (7/40)	2.30	0.02
	−25	−17	50	2542	Left	SFS/PCS (6)	2.04	0.04
	−38	−43	38	2096	Left	IPS (40)	2.42	0.01
Numerical vs. luminance	51	−45	8	4912	Right	MTG/STS (21/22)	2.23	0.02
	30	6	11	746	Right	Insula	2.17	0.03
	−25	−55	44	3855	Left	IPS (7/40)	2.60	0.009
	−26	−79	5	3815	Left	MOG (19)	2.22	0.02
	−50	1	21	2726	Left	IFG (44/45)	2.31	0.02
	−28	−21	51	2674	Left	SFS/PCS (6)	2.16	0.03
	−26	−9	50	1057	Left	SFG/MFG (6/8)	2.03	0.04
	−34	−42	45	861	Left	IPL (40)	2.23	0.02
Luminance vs. numerical	−33	−6	34	102	Left	IFG (9/44)	1.96	0.05
Size vs. numerical	40	−72	8	1282	Right	MOG (19)	2.22	0.02
	40	−43	−13	977	Right	FG (37)	2.05	0.04
	−39	−8	30	1699	Left	IFG (44)	2.68	0.007
Size vs. luminance	37	−69	8	2126	Right	MOG (19)	2.28	0.02
	44	−44	−11	1036	Right	FG (37)	2.00	0.04
	−24	−83	3	3470	Left	MOG (18)	2.88	0.003
	−50	0	28	2774	Left	IFG (44)	2.50	0.01
	−36	12	11	922	Left	Fop/insula (45)	2.10	0.03
Luminance vs. size	23	−39	−11	818	Right	Parahippocampal gyrus (36)	2.03	0.04
	26	−64	39	687	Right	SPL (7)	2.08	0.03

temporal lobe than the left, whereas the angular gyrus was more activated on the left than on the right.

3.2.1. Comparison-specific activation

Details regarding comparison-specific activations areas (see Section 2) and the activations maps for the comparison-specific activation are presented in Table 1 and Fig. 4A.

3.2.1.1. Numerical comparison versus size comparison. Relative to the size comparison, the numerical comparison yielded a higher activation of the IPS bilaterally, the right STS, MTG and IFG, and the left SFS/PCS. The size comparison yielded higher activations of the MOG and FG in the right hemisphere and of the IFG in the left hemisphere.

3.2.1.2. Numerical comparison versus luminance comparison. Contrasting numerical versus luminance comparisons revealed higher activations of the right STS and insula and of the left IFG, SFS/PCS, SFG/MFG, MOG, IPL and IPS. Higher activations for luminance comparison were found in the left IFG. This cluster was anterior and medial to the cluster that was found for numerical comparison.

3.2.1.3. Luminance comparison versus size comparison. The right parahippocampal gyrus and the SPL yielded higher activations for luminance comparison. Size comparison versus luminance comparison yielded higher activations of the MOG bilaterally, the right MTG and FG, and the left IFG and FOp/insula.

Table 2
Talairach coordinates and statistical details for areas that showed a specific distance effect as presented in Fig. 4B

Contrast	Stereotaxic coordinates			Number of voxels	Hemisphere	Region (BA)	T	P
	x	y	z					
Numerical distance	55	−40	13	2172	Right	STS (21/22)	2.10	0.03
	36	−56	0	1448	Right	MTG (21)	2.18	0.02
	−24	−55	42	2684	Left	IPS (7/40)	1.99	0.04
Luminance distance	−36	−2	31	1408	Left	IFG (44)	2.13	0.03
Size distance	38	−42	−14	1669	Right	FG (37)	2.24	0.02
	35	−58	4	580	Right	MOG (19)	1.95	0.05
	−43	−5	40	7724	Left	IFG (44)	2.19	0.02

Table 3
Talairach coordinates and statistical details for IPS activation for the distance effects in each comparison

Contrast	Stereotaxic coordinates			Number of voxels	Hemisphere	*T*	*P*
	x	*y*	*z*				
Numerical distance	23[a]	−56	44	771	Right	1.98	0.04
	−24	−55	42	2684	Left	1.99	0.04
Luminance distance	−23	−66	30	1662	Left	1.97	0.04
Size distance	25	−57	41	2765	Right	2.36	0.01
	−25	−53	42	2548	Left	2.46	0.01

[a] Reverse distance effect.

3.2.2. *Specific distance effects*

Distance effects of the areas that met the criteria for a specific distance effect are presented in Table 2 and Fig. 4B.

3.2.2.1. Numerical distance effect. Only the IPS of the left hemisphere and the STS and MTG of the right hemisphere showed significant effects.

3.2.2.2. Luminance distance effect. No area met all of the criteria. However, the BOLD signal for the IFG of the left hemisphere was significantly greater for luminance versus numerical comparison and also showed a distance effect for luminance.

3.2.2.3. Size distance effect. Only the MOG and FG of the right hemisphere and the IFG of the left hemisphere showed a significant effect.

3.2.3. *General distance effect in the IPS*

Part of the IPS was activated for all three types of distances (i.e., numerical, size and luminance, Table 3). A part of the left anterior IPS region showed a distance-specific effect (for numbers, see previous section). The numerical distance effect was observed bilaterally, but the right IPS did not show a number-specific modulation (e.g., no significant difference between numerical and luminance comparison). For size comparison, a distance effect was found in the IPS bilaterally. These bilateral regions of the IPS largely overlapped with the ones that also showed an effect for numerical distance. However, as mentioned before, the overall activation of the left IPS was higher for the numerical comparison condition. Finally, more posterior and ventral parts of the left IPS showed a luminance distance effect. The same lateralization pattern was also obtained when only the right-handed participants were included. Clusters of all three-distance effects overlapped in the left IPS, posterior to the area where we found a distance-specific effect for numbers (see Fig. 5).

3.2.4. *Random effects analysis*

Due to our main interest in the degree of specificity of the IPS for number comparison, we conducted a random effects analysis ($p < 0.001$, uncorrected) on the twelve right-handed subjects in the same steps as mentioned above for the IPS. All reported task and distance effects in the IPS were also

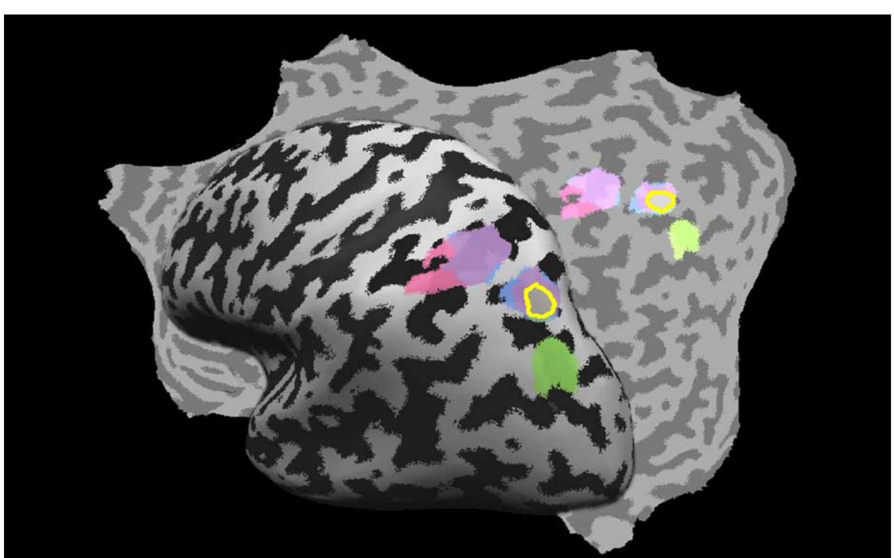

Fig. 5. Clusters of distance effects projected on flat and inflated maps of the left hemisphere (red, size; green, luminance; blue, numerical) and their overlap (in gray, circled in yellow) in the left posterior IPS. For details about the statistical procedure see Section 2.

significant in the random effects analysis. In sum, we found a double dissociation between areas showing a strong modulation and distance effect for numerical comparison in the left IPS and right temporal lobe and areas showing the same effect for physical comparisons in the left IFG.

4. Discussion

We addressed the question whether numerical comparison is specifically subserved by a distinct neural circuit or region, supposed to be centered on the left IPS. We analyzed brain activation in response to three different comparison tasks (numerical, size, and luminance) and found a largely overlapping network of frontal, parietal, and occipitotemporal areas of both hemispheres, thus confirming the view that many of the neural resources used for number comparison are shared by other comparison tasks as well (Fig. 3B). In a second step we looked for comparison-specific modulations of this network, as reflected in the amplitude of the BOLD signal, by computing direct contrasts between the tasks (Fig. 4A). However, even such a "task-specific" activation might be brought about by differences between the conditions (e.g., stimulus properties, general level of difficulty) that do not directly reflect the cognitive operation at issue. We, therefore, performed a third step of analysis in order to reveal the areas that show specific distance effects (i.e., areas that showed both a task-specific modulation and a distance effect for the given comparison) (Fig. 4B).

The main finding was that the left IPS showed both a task-specific modulation of the BOLD signal for numerical comparison and a numerical distance effect. While this result conforms to other imaging studies of number comparison (Pesenti et al., 2000; Pinel et al., 1999; Pinel et al., 2001; Pinel et al., 2004), these studies reported bilateral activation of the IPS. In contrast, patient studies have revealed that unilateral damage to the IPS of the dominant hemisphere (Dehaene & Cohen, 1997; Lemer et al., 2003) might cause an inability to compare numerical quantity. Our study reconciles this apparent contradiction in that we also find a bilateral activation for all comparison tasks, but in the subsequent analysis steps, narrow down the activation specifically related to numerical comparison to the left IPS. The convergence of task-specificity and distance effect suggests that this area is indeed closely related to number comparison and that its activation in the present experiment was not due to other cognitive factors such as visuospatial ability (Simon, 1999) or task difficulty (Göbel et al., 2004) that have been associated with the right IPS. The similarity of the stimuli presented in our three tasks makes it very unlikely that visuospatial processing alone or differences in saccade rates would produce task-specific activation differences (let alone, the cortical distance effects). It might be less obvious why we are so confident that the activation differences were not caused by differences in task-difficulty. Although the numerical task differed from the other tasks in the degree of difficulty, as measured by a difference in RT of 19–25 ms, the activation of the left IPS cannot in our view be explained by this small difference in difficulty because other tasks that yielded even larger differences in difficulty did not activate this region (e.g., luminance distance with an RT difference of 98 ms). In order to exclude this possibility formally, we compared activation levels between the different tasks for the distance levels that showed no significant RT differences across tasks and no interaction between task and distance (i.e., we excluded the distance of 4 units). Again, the same part of the IPS showed a significantly higher activation for numerical comparison. Another novel result of the present study is the overlap of different distance effects in the posterior part of the left IPS (Fig. 5). The left posterior IPS was also found by Fias et al. (2003) to be activated by comparisons of lines, angles and two-digit numbers. In line with the explanation provided by Fias et al. (2003) and Walsh (2003) this area might be related to the processing of general magnitude. Pinel et al. (2004) did not find an overlap among numerical, size and luminance distances in either the left or right IPS. However, the absence of this effect in their study might be ascribed to the size congruity paradigm they used. By independently manipulating the three dimensions, Pinel et al., although carefully controlling for RT difference across tasks and subjects, might have masked some distance effects by the irrelevant dimensions that were concurrently manipulated. Interference between physical properties and numerical value in numerical and physical comparison tasks has been described at the behavioral level (Henik & Tzelgov, 1982) and is likely to be reflected in brain activation levels as well. The design of the present study explicitly aimed to control for these interference effects by keeping the irrelevant magnitudes equal for the two stimuli. Note that in the numerical task we did obtain greater activation in a region involved in number comparisons in other studies (i.e., left anterior IPS). This suggests that if there were automatic or non-conscious activations they do not correspond, at least in magnitude, to those associated with conscious number comparisons. Hence, while this study pinpoints the areas that are modulated by a given comparison, the results of Pinel et al. (2004) might include areas that are involved in the automatic access to magnitude representations. Future studies, combining these two experimental designs, might be able to differentiate between the neural substrates of automatic and intentional magnitude processing.

Two additional regions, in the right MTG and along the right STS, also showed the numerical distance effect on cortical activation. The right MTG was also found to be modulated by the numerical distance effect in the study by Pinel et al. (2001). These authors explained the right MTG activation as playing a role in the mediation between symbols and meanings of numbers. A numerical distance in the right STS, however, has not been described before. Kiehl et al. (1999) reported that a region along the right STS with similar Talairach coordinates (56, −38, 16) to the one that was observed in our study (54, −40, 12) was activated during processing of words that contained abstract information relative to words that contained concrete information. Given the abstract nature of numerical information, and the close relationship between language and numbers (Wiese, 2003), this makes it plausible that the right STS would also be active during number processing. Another study (Price et al., 1994) found right STS and MTG activation during the short but not long presentation of semantic stimuli (150 ms versus 981 ms). This suggests that increased activation in these areas is related to additional attention to the semantic information. A comparison between the different tasks under the condition where no RT differences were observed (i.e., without the distance of 4 units), yielded the same results. An integrative, albeit speculative explanation for the numerical distance effects in areas that have been implicated in the semantic representation of numbers, which would include the IPS but also the MTG and STS, would be that the demand on the semantic representation of numbers increases with decreasing numerical distance. According to this idea, numbers are connected to one another in a similar way to representation of other words (e.g., dog–cat, table–chair). Thus, close numbers (e.g., 6–7) are more difficult to compare because they are linked by stronger connections than numbers that are further apart (e.g., 2–6). This semantic representation might be an effect of gradual language acquisition quite similar to what has been observed in other semantic subsystems. If the temporal lobe components of the wider cortical network of information about numbers can compensate for losses of IPS function, parietal patients with an inability to compare numbers should be rare and the majority of patients with damage to the left IPS, and even patients with bilateral damage to the IPS, should still be able to compare numbers and show a numerical distance effect, which is in fact what we and others have reported (Bloch-David, Henik, & Rafal, 2003; van Harskamp, Rudge, & Cipolotti, 2002).

The activation of the right FG and the MOG as specific comparison areas for size might be explained in light of recent findings on the retinotopy of extrastriate visual areas (Levy, Hasson, Avidan, Hendler, & Malach, 2001; Malach, Levy, & Hasson, 2002), according to which the FG in particular is activated due to resolution needs. In the size comparison task the discrimination between the two objects needs a sufficient resolution (especially when the distance is just 1 unit) and would, therefore, rely on analysis of fine details that is supported by these brain structures. Finally, the left IFG was the only region that showed a significant contrast between physical and numerical comparisons, and distance effects for size and luminance. Thompson-Schill, D'Esposito, Aguirre, and Farah (1997) reported this region to be activated during a semantic selection task and to scale with selection demand. According to these authors, this would either implicate the left IFG in selection in general or, more specifically, in semantic selection. The fact that in our study this area was primarily activated during non-semantic tasks (luminance and size comparison) would support the first alternative.

In conclusion, none of the areas observed in our study was activated *exclusively* for a given comparison in the number, luminance or size domain. Our findings thus resemble the reports of continuous and overlapping representations of objects in the ventral stream (Ishai, Ungerleider, Marthin, Schouten, & Haxby, 1999). However, the observation of task-specific modulations in various frontal, temporal, and parietal brain areas, especially in the left IPS for numerical comparison, indicates that, regardless of the prominent commonalities, there are also important differences in the functional neuroanatomy of the systems for physical and numerical comparisons.

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