# Comparing magnitudes across dimensions: a univariate and multivariate approach

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*Abstract* — **Is there a common neural code underlying the representation of different quantity dimensions? In a high resolution fMRI protocol, we compared the activation evoked by the presentation of lines with different lengths, and sets of different numbers. We contrasted the results obtained with standard univariate analyses with a multivariate approach comparing the representational similarities within and between dimensions (i.e. few : short = many : long?). Together, our findings suggest that although the representations of number and size are co-localized in parietal cortex, these two quantity dimensions do not share a common representational code.**

*Keywords* — fMRI, representational similarity analysis, numerosity, length, magnitudes.

## I. Introduction

The representations of size and of number are intimately related in the human brain. For instance, at birth humans expect that an increase (or decrease) in number is accompanied by an equivalent increase (or decrease) in object's size [1]. In adults, comparative judgements on number or on objects' size show reciprocal influences [2]. This suggests the existence of a generalized quantity system underlying the representation of these (and possibly other) dimensions [3].

Recent reports indicate that the parietal cortex hosts overlapping, topographically organized maps of both object size and number [4]. The existence of overlapping maps, however, does not exclude that, at a finer-grained level, the two magnitudes might be represented separately. In this study, we investigated this hypothesis by conducting multivariate analyses of the fMRI signal while subjects compared the numerosity of sets (hereafter referred to as Number) or the length of lines (hereafter Length) [5].

In order to exclude motor preparation effects, we considered the BOLD signal evoked by the stimuli in a time window when no active comparison was being performed. First, we analyzed the dataset with a mass-univariate approach, and compared the relative amplitude of the signal across dimensions and magnitudes. Then, we applied multivariate analyses to investigate whether additional information is represented at the level of the distributed pattern of activity [6].

## II. Materials and Methods

### *A. Subjects*

18 healthy adult volunteers (average age 24.5 y, 8 male) participated in the study (data from 1 participant were discarded for excessive movement in the scanner). All participants were right-handed and had normal or corrected-to-normal vision. They provided signed informed consent and received a monetary compensation for their participation. All procedures were approved by the local ethical committee.

### *B. Stimuli*

Stimuli were generated using Matlab software. Number stimuli consisted in sets of randomly oriented, non-overlapping lines with constant thickness, and varying lengths, according to the low level visual controls described below. Length stimuli consisted in horizontal lines of varying length and thickness, depending on the control condition.

Each dimension varied along 3 levels of magnitudes (small/medium/large). Comparative judgements acquired in 20 adult subjects prior to the present study assured that the discriminability across the stimuli was high and matched across the two dimensions (the numeric ratios between two exemplars of consecutive magnitudes for Number ranged between 0.44 and 0.5 -small number/large number-, while for Length they ranged between 0.56 and 0.6 -short length/long length-). Examples of stimuli are shown in Fig.1.

Two sets of stimuli were generated for each dimension, corresponding to two control conditions. For one set, the total surface area co-varied with magnitude (i.e., more numerous/longer stimuli occupied larger cumulative areas on the screen). For the other set, the total surface area was maintained constant across magnitudes (so that a single elements' area was inversely related to number magnitude, and the lines' thickness was inversely related to their length), and identical across the two dimensions. The total surface area

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used for the second set closely matched the one used for the medium level of magnitudes in the first set of stimuli.

In all the stimuli, the items could occupy random locations within a disc with a diameter corresponding to a visual angle of 30 degrees. Numbers ranged between 10 and 48. The individual items had a constant thickness occupying a visual angle of 0.5 degrees, and a length occupying a visual angle varying between 0.2 and 1 degree, depending on the control condition. In the Length dimension, the lines' lengths ranged between corresponding visual angles of 4.3 and 13.2 degrees. The lines' thickness occupied a constant visual angle of 0.7 degrees in the first control condition, and ranged between 0.4 and 1.2 degrees in the second control condition.

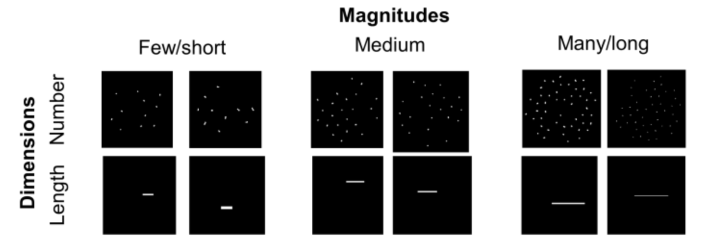


**Fig. 1 Examples of the stimuli.** Subjects performed a comparison task on the numerosity of sets of non-overlapping lines (Number) or the length of single horizontal lines (Length). Each dimension had two different low level visual controls (see text for details).

### C. fMRI task

During the fMRI scans, subjects had to compare sequentially presented pairs of stimuli (Fig.2). A trial began with the presentation of one magnitude (hereafter Mag1), followed by the presentation of the comparison rule (decide if it was larger vs. smaller than the following magnitude (hereafter Mag2)) to be applied. Then, the second magnitude (Mag2) appeared, and the subjects were asked to provide the answer. Mag1 and Mag2 were both Number or Length. The comparison rule could be symbolic (i.e., < or >) or lexical, with the appropriate wording for each dimensions (i.e. longer or shorter length vs. smaller or larger number). For each of the 6 runs, we randomly presented pairs of stimuli with the only constraint that there were a minimum of five trials for each level of magnitude Mag1 in each dimension plus another 2 trials randomly picked from all dimensions and levels of magnitude, for a total of 32 trials per run.

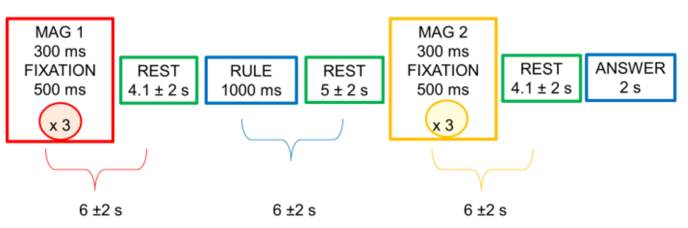


**Fig. 2 Schematic representation of the fMRI task.** MAG1 and MAG2 were presented three times (300 ms each) with a fixation period in between (500 ms). Rest periods between the presentation of MAG1, Rule and MAG2 were jittered of ±2 s.

### D. MRI and fMRI acquisition

Data were collected with a 3 Tesla Siemens Magnetom TrioTim scanner using a 32–channel head coil. Each subject underwent one session: 7 minutes of anatomical acquisition and then 6 functional runs. Anatomical images were acquired using a T1 weighted Mprage sagittal scan (voxels size 1x1x1mm, 160 slices). Functional images were acquired using an echo-planar imaging (EPI) scan (repetition time = 2.3s; echo time = 32ms; field of view = 192mm; voxel size = 1.5x1.5x1.5mm; 280 repetitions; 64 slices, multi–band acceleration factor 2, iPAT 2).

## III. RESULTS

### A. Behavioral data analyses

Despite Length judgment being slightly faster compared to Number (RTs: Number: 781.4 ms vs. Length: 733.9 ms; $t(16) = 3.95$, $p < .01$), accuracy was equally high in both dimensions (Number: 91.2% vs. Length: 92.3%; $t(16) < 1$, n.s.).

### B. fMRI data pre-processing and first level model

Pre-processing of the functional images included: slice time correction, realignment of each scan to the first of each given run, co-registration of anatomical and functional images, motion correction, segmentation, normalization to MNI space and high-pass filtering (128s). The images where then analysed with a general linear model including: 12 regressors of interest (3 magnitudes –small, medium and large- x 2 dimensions -Length and Number- x 2 controls -constant total surface and constant element size), 14 regressors of no-interest (6 for the different Mag2, 6 for the different rules, 2 for left and right answers), 6 motion parameters, 18 regressors accounting for the run effect (6 runs x 1 linear, 1 quadratic, 1 constant effect) and 1 constant. The following univariate and multivariate analyses focus on the 12 beta maps estimated for Mag1 of both Number and Length. These steps, as well as the univariate analyses, were performed with SPM8[1].

### C. Univariate Analyses

For the univariate analyses only, beta maps where smoothed (kernel [4,4,4]). Firstly, random effect analyses were applied to two contrasts: main effect of Number (vs baseline?) and main effect of Length (vs baseline?) (Fig. 3 upper part). All univariate results reported are FWE corrected at p<0.001, and with an extended threshold of 5 voxels. In a whole brain search, a significant main effect of Number was observed in a set of 4 clusters describing a fronto-parieto-occipital network, while for Length, numerous parietal and occipital clusters emerged (Table 1). Restricting the analyses to the parietal lobe, our main region of interest, both Number and Length yielded to the same significant cluster of coordinates 32,-55,55 (highlighted in Fig.3 upper part).

[1] Statistical Parametric Mapping, Wellcome Department of Cognitive Neurology, London, UK.

| Main effect of Number | | Main effect of Length | |
|---|---|---|---|
| **Lobe** | **Coord.** | **Lobe** | **Coord.** |
| occipital | -27, -94, 10 | occipital | 31.5, -73, 26.5 |
| occipital | 19.5, -97, 10 | occipital | -37.5, -70, 2.5 |
| frontal | 51, 11, 32.5 | parietal | -36, -49, 52 |
| parietal | 51, -29, 53.5 | parietal | 31, -55, 55 |

**Table 1 Univariate results: main effects**

Two additional random effect analyses were run searching for regions which activity was linearly modulated by magnitude for each of the two dimensions: linear effect of Number and linear effect of Length (Fig. 3 middle and lower parts). At the whole brain level, one significant cluster in the occipital lobe was positively modulated by Number ([16,-97,6]), and one by Length ([26,-96,12]). Two additional clusters showing a negative linear effect were found for Number only (one in occipital [28,-55,60] and one in parietal [50,-68,2]). We then restricted the analysis to the parietal lobe, and the results confirmed the presence of only one significant cluster showing a negative linear effect of number ([50,-68,2]).

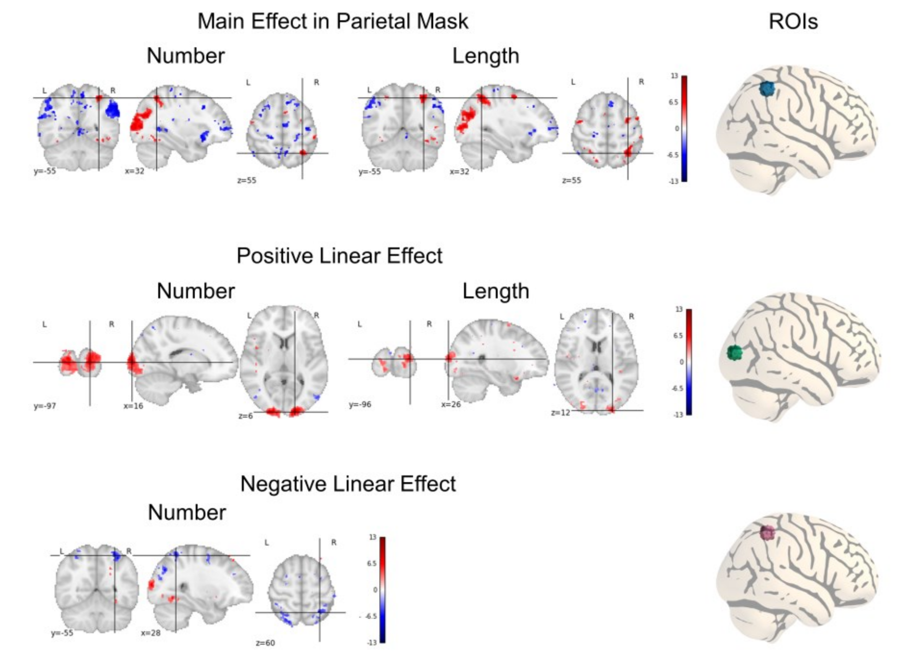


**Fig. 3 Univariate analyses.** Left: results of the group level random effect analyses of the main effect of dimension (Length and Number) as well as the linear effect of magnitude (small/medium/big). Right: region of interest extracted for subsequent multivariate analyses.

## *D. Multivariate Analyses*

We then explored the existence of a graded distance effect (i.e., the more similar the magnitudes, the more similar the activation pattern) in five regions of interest (ROIs), two from the literature and three derived from the above univariate analyses (Fig. 3 on the right) in order to directly test whether the functional overlap corresponds to a common representational metric [6]:

- Parietal cluster of the main activation for length and number (PM, coord. 32,-55,55, mean voxels count = 1195) [Note: this is an orthogonal contrast with respect to the differences tested at the multivariate level]
- Occipital cluster with positive linear effect for length and number (PPL, coord. 26,-96,12, mean voxels count = 785)
- Parietal cluster with negative linear effect for number (PNL, coord. 50,-68,2, mean voxels count = 1163)
- Functional equivalent of Ventral Intra Parietal areas (feVIP, coord. 29.1, –49.4, 54.3, mean voxels count = 1210)
- Functional equivalent of Lateral Intra Parietal (feLIP, coord. 22.9, –61.0, 54.2, mean voxels count = 1335)

ROIs were built using SPM toolbox PickAtlas[2].

As a first step, for each dimension (Number and Length) we averaged the beta maps of all the trials in each of the 3 magnitudes (small/medium/large) across the two different stimuli controls (i.e., stimuli controlled for overall area vs. element size), thus obtaining 6 maps (2 dimensions x 3 magnitudes). In a second step, we calculated the Person correlation between these maps in order to construct a neural similarity matrix that describes the similarity of the neural patterns of activation for the different magnitudes and dimensions. Fig. 4a illustrates, as an example, the neural matrix obtained in the occipital peak of the positive linear effect and in the parietal peak of the main effect. These matrices are symmetrical and the diagonal is meaningless (in the figure, it is arbitrary set to 0 for visualization purposes).

A signature of the distance effect would be a higher average correlation between stimuli with close magnitudes distances compared to stimuli with far magnitudes distances. Thus, for both Number and Length, correlation scores from close distances (exemplified in Fig. 4b in red) and far distances (exemplified in Fig. 4b in white) were extracted, and Fisher r-to-z transformed. It should be noted that, inevitably, the close distance is over-represented (compared to the far one), and thus potentially less noisy. Then, for each subject, and separately for Number and Length, the difference between close and far distances was computed. This difference was then tested against zero with a t-test. A significant effect of distance was observed, for both Number ($p<0.001$) and Length ($p<0.05$), in the regions showing a positive linear effect of magnitude (occipital, primary visual areas). Moreover, for Number only, a significant distance effect ($p<0.05$) was observed in the ROI functional equivalent of the VIP (Fig. 5a). A repeated-measures ANOVA with 5 (ROI) x 2 (dimensions) factors revealed only a main effect of region, due to the significantly higher distance effect observed in PPL, but no interaction. This indicates that Number and

[2] http://www.nitrc.org/projects/wfu_pickatlas

Length are encoded according to a magnitude code in the same brain regions.

Finally, in order to investigate whether the very same neural code underlies the representation of both dimensions, we tested whether the distance effect generalized across dimensions by comparing, across dimensions, three different levels (i.e., with a regression): close, medium and far distance (exemplified in Fig. 4b with progressively darker blue). No significant across-dimensions distance effects were found (Fig. 5b).

All multivariate analyses were implemented with custom Python scripts relying on Nilearn[3], Numpy[4], and Scipy[5].

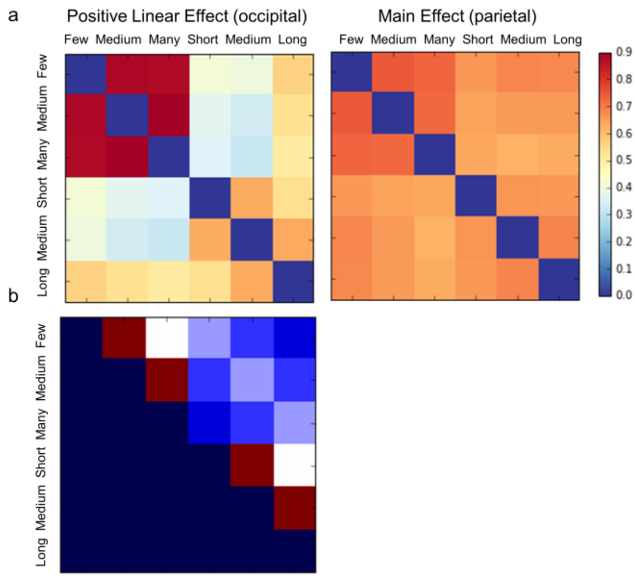


**Fig. 4 Representational similarity analysis.** a: examples of the similarity matrices computed in each of the selected ROIs. b: theoretical model of the distance effect(s).

## IV. Conclusion

We aimed at investigating the hypothesis that different quantitative dimensions (number and length) might share a common neural code, using a combination of univariate and multivariate analyses. We have been able to show that, although both number and length are represented according to a similar quantity code (expressed as the distance effect across magnitudes) in occipital and parietal cortex, they do not appear to share a common representational/neural code: small, medium and large numbers elicit patterns of activation that are uncorrelated with the ones elicited by short, medium and long lengths.

Future work will investigate the neural representation of the different rules (symbolic vs verbal). Moreover, similar analyses of Mag2 will reveal whether a common representational code for number and length is subject to the active comparison process. Finally, our similarity analysis can be extended to whole brain data thanks to a searchlight approach, overcoming the limitations of our ROIs approach. To this end, the development of appropriate non-parametric algorithms will be necessary in order to evaluate the significance of the results (i.e., permutation test).

[3] http://nilearn.github.io/
[4] http://www.numpy.org/
[5] http://www.scipy.org/scipylib

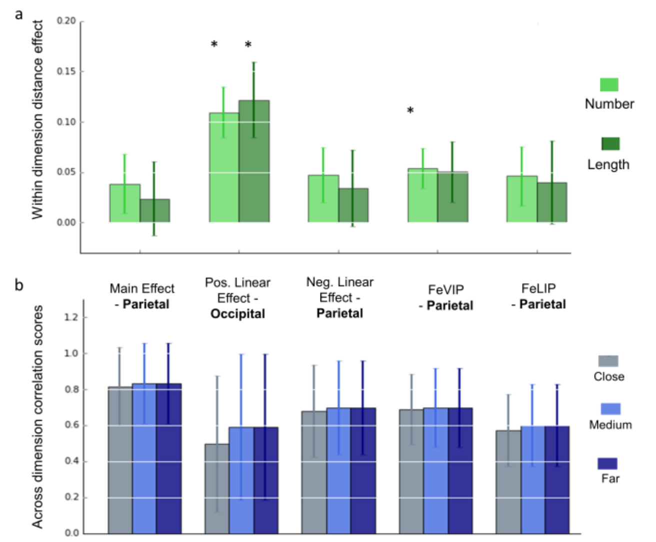


**Fig. 5 Multivariate results.** a: distance effect within dimension in each of the ROIs (i.e., subtraction of Fisher-transformed scores at Close Distance – Far Distance). b: distance effect across dimensions (i.e., Fisher-transformed correlation scores at the three distances: Close, Medium and Far). Both graphs are showing the average scores across subjects (n=17), with error bar representing the standard error of the mean.

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