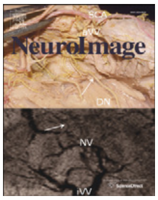
NeuroImage 85 (2014) 391–399

Contents lists available at ScienceDirect

NeuroImage

journal homepage: www.elsevier.com/locate/ynimg



Are the neural correlates of subitizing and estimation dissociable? An fNIRS investigation

Simone Cutini [a,*], Pietro Scatturin [b], Sara Basso Moro [c], Marco Zorzi [a,d]

[a] *Department of General Psychology, University of Padova, Italy*
[b] *Department of Developmental Psychology, University of Padova, Italy*
[c] *Department of Life, Health & Environmental Sciences, University of L'Aquila, Italy*
[d] *IRCCS San Camillo Neurorehabilitation Hospital, Venice-Lido, Italy*

ARTICLE INFO

Article history:
Accepted 13 August 2013
Available online 23 August 2013

Keywords:
fNIRS
Numerical cognition
Numerical magnitude processing
Subitizing
Estimation

ABSTRACT

Human performance in visual enumeration tasks typically shows two distinct patterns as a function of set size. For small sets, usually up to 4 items, numerosity judgments are extremely rapid, precise and confident, a phenomenon known as subitizing. When this limit is exceeded and serial counting is precluded, exact enumeration gives way to estimation: performance becomes error-prone and more variable. Surprisingly, despite the importance of subitizing and estimation in numerical cognition, only few neuroimaging studies have examined whether the neural activity related to these two phenomena can be dissociated. In the present work, we used multi-channel near-infrared spectroscopy (fNIRS) to measure hemodynamic activity of the bilateral parieto-occipital cortex during a visual enumeration task. Participants had to judge the numerosity of dot arrays and indicate it by means of verbal response. We observed a different hemodynamic pattern in the parietal cortex, both in terms of amplitude modulation and temporal profile, for numerosities below and beyond the subitizing range. Crucially, the neural dissociation between subitizing and estimation was strongest at the level of right IPS. The present findings confirm that fNIRS can be successfully used to detect subtle temporal differences in hemodynamic activity and to produce inferences on the neural mechanisms underlying cognitive functions.

Introduction

The ability to perceive and represent visual numerosity is thought to be foundational to numeracy acquisition and it has been linked to mathematical achievement (Halberda et al., 2008; Mazzocco et al., 2011; Piazza et al., 2010). If participants are asked to judge the numerosity of a set of items their enumeration performance typically shows two distinct patterns as a function of set size. For small sets, usually up to 4 items, numerosity judgments are extremely rapid, precise and confident, a phenomenon known as subitizing (Kaufman et al., 1949; Mandler and Shebo, 1982). When this limit is exceeded and serial counting is precluded, exact enumeration gives way to estimation: performance becomes error-prone and response variability increases as a function of set size (e.g., Revkin et al., 2008).

Subitizing is thought to be intimately related to a domain-general system that tracks objects in space and time, the Object Tracking System (OTS) (Trick and Pylyshyn, 1994). The constitutive mechanism of this system is object individuation, that allows to allocate attention over multiple individual items in parallel while separating one item from the others, so that items are perceived as specific entities with a definite identity and location (Mazza and Caramazza, 2011; Melcher and Piazza, 2011; Piazza et al., 2011). In contrast, numerosity estimation is thought to rely on a pre-verbal system for the representation of numerical magnitude, the Approximate Number System (ANS) (Feigenson et al., 2004; Piazza, 2010; Stoianov and Zorzi, 2012). Currently it is widely accepted that subitizing and estimation are selectively connected to the OTS and the ANS, respectively (Burr et al., 2010; Cutini and Bonato, 2012; Hyde, 2011; Piazza, 2010; Piazza et al., 2011; Trick and Pylyshyn, 1994 but see Beran, 2007; Brannon and Terrace, 1998; Cordes et al., 2001). Although it is conceivable that estimation can operate both below and above the subitizing range, only numerosities beyond subitizing range show the classic variability signature obeying Weber's law (Revkin et al., 2008). Indeed, the Weber signature can emerge also for small numerosities if attentional resources are diverted by means of a concurrent task (Burr et al., 2010; Piazza et al., 2011). That is, the dual task condition appears to disrupt the functioning of the OTS and therefore impairs the ability to subitize. Notably, a specific deficit of subitizing (i.e., with spared estimation ability) has been reported in children with Down syndrome (Paterson et al., 2006; Sella et al., in press). Finally, there is evidence that the existence of two distinct systems for numerosity discrimination may be evolutionarily ancient, as it appears to apply even to lower vertebrates like fish (Agrillo et al., 2012).

Neuropsychological and neuroimaging studies show that the parietal cortex is the most important brain region for number processing (see

---

* Corresponding author at: Department of General Psychology, University of Padova, Via Venezia 8, Padova 35131, Italy.
E-mail address: simone.cutini@unipd.it (S. Cutini).

1053-8119/$ – see front matter © 2013 Elsevier Inc. All rights reserved.
http://dx.doi.org/10.1016/j.neuroimage.2013.08.027

Arsalidou and Taylor, 2011; Dehaene et al., 2003, for reviews), and macaque single-cell recordings have revealed that intraparietal areas contain neurons tuned to specific numerosities (for a review see Nieder, 2005). Indeed, the results of brain imaging studies converge in highlighting the intraparietal sulcus (IPS) as the core region for the semantic processing of numerical magnitude (Ansari et al., 2006; Cohen Kadosh et al., 2005; Cutini et al., 2012a; Eger et al., 2003; Piazza et al., 2004, 2007; Pinel et al., 2001; Zorzi et al., 2011). IPS appears to be critically involved in numerosity estimation: for instance, fMRI adaption revealed bilateral IPS as the only region sensitive to a change in numerosity during passive viewing of dot arrays (Piazza et al., 2004). IPS activity has also been systematically observed during numerosity comparison (e.g., Ansari et al., 2007; Castelli et al., 2006).

Several studies have attempted to functionally dissociate subitizing or estimation from serial counting (Piazza et al., 2002, 2003, 2006): these investigations depict a large cortical network for estimation and counting, including the extrastriate middle occipital and bilateral intraparietal areas. A positron emission tomography (PET) investigation (Piazza et al., 2002) revealed a link between counting and increased activity in the parieto-occipital cortex, whereas no brain region showed larger activity for numerosities within the subitizing range. In an fMRI investigation of the neural correlates of estimation and counting (Piazza et al., 2006), estimation elicited the activity of a right lateralized fronto-parietal neural circuitry, while counting involved bilateral premotor and left-lateralized prefrontal–parietal areas. In particular, activity of IPS was strongly characterized by a hemispheric asymmetry: while estimation heavily relied on right IPS, counting was more related to the left IPS. Another fMRI study aimed at investigating the role of attention in subitizing and counting (Piazza et al., 2003) found a sudden increase in posterior parietal cortex activity only from numerosity four upwards, suggesting the presence of a dichotomy between number processing within and beyond the subitizing range. Although it is worth noting that these results are broadly consistent with a recent voxel-based morphometry study of brain-damaged patients, focused on visual enumeration (Demeyere et al., 2012), none of these neuroimaging studies was able to detect a specific pattern of activity for subitizing.

Moreover, only few studies have directly compared subitizing and estimation. In an fMRI investigation, Ansari et al. (2007) found that the temporo-parietal junction (rTPJ), an area thought to be involved in stimulus-driven attention (Corbetta and Shulman, 2002), was activated during numerosity comparison, but only for numerosities up to 3 or 4. Selective activity of rTPJ in response to small numbers was also found in the fMRI study of Vetter et al. (2011), which also showed a modulation related to attentional load, in agreement with the hypothesis that subitizing requires attentional resources (Burr et al., 2010; Piazza et al., 2011; Vetter et al., 2008). Nevertheless, no neuroimaging study to date has reported a neural dissociation between subitizing and estimation at the level of IPS activity.

Here we recorded the hemodynamic activity of the human parietal cortex during visual enumeration of dot arrays within and beyond the subitizing range using functional near-infrared spectroscopy (fNIRS). Similarly to functional magnetic resonance imaging (fMRI), fNIRS monitors hemodynamic changes in the cerebral cortex (see Cutini et al., 2012b; Ferrari and Quaresima, 2012, for reviews); however, unlike the blood-oxygen-level-dependent (BOLD) signal of fMRI, which is gathered from the paramagnetic properties of deoxyhemoglobin (HbR), fNIRS is based on the intrinsic optical absorption of blood. As a result, fNIRS can simultaneously record the variations of HbR, oxygenated hemoglobin (HbO), and total hemoglobin (HbT) concentrations with a much higher temporal resolution, thereby potentially providing a richer picture of cortical hemodynamics when compared with fMRI (see, e.g., Brigadoi et al., 2012; Cutini et al., 2012a; Szűcs et al., 2012). Furthermore, fNIRS imposes negligible physical constraints on participants, and its tolerance to movement artifacts with respect to fMRI might be regarded as a further added value. Interestingly, fNIRS has already been proficiently used to detect activity in the parietal cortex during the execution of numerical tasks (Cutini et al., 2012a; Dresler et al., 2009; Richter et al., 2009); in addition, a recent fNIRS study on preverbal infants (Hyde et al., 2010) highlighted a right hemisphere dominance in the parietal cortex for number processing.

In the present study, we sought to investigate with fNIRS the modulation of hemodynamic activity in the parieto-occipital regions during subitizing and estimation. We used a numerosity judgment task, in which participants had to judge the numerosity of dot arrays and indicate it by means of verbal response (i.e., numerosity naming). As a control condition, we employed an Arabic number naming task, which implied the same number range and required the same type of response. We expected to find a strong engagement of the parieto-occipital cortex during numerosity naming, with a dominant role of the right hemisphere (Piazza et al., 2002). More specifically, we aimed at detecting the presence of a modulation of IPS activity related to the numerosity of the dot array. Crucially, with fNIRS such modulation might be characterized both in terms of amplitude and latency, as shown in a recent optical study with the numerical distance effect (Cutini et al., 2012a). Moreover, we asked whether the modulation of IPS activity would reveal a signature of the transition between subitizing and estimation, which would provide compelling neural evidence for a functional dissociation between these two phenomena. More specifically, the presence of a marked non-linearity in IPS activity relative to the increase of numerosity would provide a neural signature of the transition between subitizing and estimation, as usually observed in the behavioral data.

Materials and methods

Participants

Eleven students at the University of Padova (nine right-handed, six females; mean age 24, range 20–26) participated in the experiment after providing their informed consent. All participants had normal or corrected-to-normal vision, and normal color vision. No participant reported a prior history of neurological or psychiatric disorders, and none was under medication at the time of testing. The study was approved by the ethical committee of the Department of General Psychology (University of Padova).

Stimuli and procedure

The experiment was based on a slow event-related visual enumeration task. The paradigm was created with the E-prime software (Psychology Software Tools Inc., Pittsburgh, PA, USA). Stimuli consisted in white dot arrays (40 cd/m^2) randomly disposed on the screen, with a gray background on a 22″ LCD monitor. Size and location of the dots varied randomly within each trial to minimize the influence of non-numerical visual cues; in particular, the size of each dot was randomly chosen between 3 different sizes (radius of 6, 8 and 10 pixels) both within and between trials in order to prevent a linear covariation between numerosity and total area. During the experiment, each participant was seated in a comfortable chair placed inside a sound-attenuated and dimly lit room, at a distance of 60 cm from the monitor. As shown in Fig. 1, each trial started after a fixation cross, presented for 1 s. After the fixation cross offset, the stimulus was presented for 200 ms and immediately replaced with a mask, consisting in a square matrix of 16 elements (each element was formed by three partially overlapping dots with the radius of 6, 8 and 10 pixels), that stayed on screen for 100 ms. Participants were instructed to maintain their gaze at fixation and to respond fast and accurately by naming the stimulus numerosity: vocal responses were recorded by means of a microphone. Stimuli were replaced with a blank screen upon detection of a response or after 3 s from the stimulus offset. In the latter case, a “no response warning” was presented as feedback. In order to collect the data on accuracy, participants' vocal responses were recorded by the experimenter, who pressed the corresponding numbers on a keyboard connected to the computer controlling the experiment. The response was followed by an interval (randomly chosen between 11, 12 or 13 s) with a blank screen before the beginning of the next trial. The numerosity of dot arrays varied randomly between 2, 3, 4, 5 and 6; these numerosities were chosen to cover the transition between subitizing and estimation, which is typically at 4 dots (e.g., Trick and Pylyshyn, 1994). As a control condition, Arabic digits of numerical magnitude corresponding to the dot arrays (i.e., digits 2 to 6) were presented. The visual enumeration condition was always presented before the control condition. This choice was made to prevent the participants from knowing the precise numerical range used in the visual enumeration task (which would have caused an anchoring effect for the large numerosities). After 5 min of practice, participants performed a sequence of 140 trials (90 dot array trials: 18 for each numerosity; 50 Arabic digit trials: 10 for each numerosity). The experiment duration was approximately 45 min.

fNIRS data acquisition

The recording optical unit was a multi-channel frequency-domain NIR spectrometer (ISS Imagent™, Champaign, Illinois), equipped with 32 laser diodes (16 emitting light at 690 nm, and 16 at 830 nm) modulated at 110.0 MHz. The diode-emitted light was conveyed to the subject's head by multimode core glass optical fibers (heretofore, sources; OFS Furukawa LOWOH series fibers, 0.37 of numerical aperture) with a length of 250 cm and a core diameter of 400 μm. Light that scattered through the brain tissue was carried by detector optical fiber bundles (diameter 3 mm) to 4 photo-multiplier tubes (PMTs; R928 Hamamatsu Photonics). The PMTs were modulated at 110.005 MHz, generating a 5.0 kHz heterodyning (cross-correlation) frequency. To separate the light as a function of source location, the sources time-shared the 4 parallel PMTs via an electronic multiplexing device. Only two sources (one per hemisphere) were synchronously ($t = 4$ ms) active (i.e., emitting light), such that the resulting sampling frequency was $f = 15.0625$ Hz, due to the 64 ms sampling period required to the multiplexing cycle. To stabilize the optical signal, a dual-period averaging was performed, resulting in a final sampling period of 128 ms ($f = 10^3/128 = 7.8125$ Hz).

Following detection and consequent amplification by the PMTs, the optical signal was converted into alternating current (AC), direct current (DC), and phase (Φ) for each source/detector pair, considering separately each light wavelength. These values were then converted into estimates of absorption coefficient variations ($\Delta\mu\alpha$) using the differential-pathlength factor (DPF, (Cope and Delpy, 1988)) method. Temporal variations (Δ) in the cerebral oxy-hemoglobin (ΔHbO) and deoxy-hemoglobin (ΔHbR) concentrations were calculated based on the values of $\Delta\mu\alpha$ at the two wavelengths (Cutini et al., 2008; Franceschini et al., 2000).

Probe placement

A single-distance probe arrangement aimed at maximizing the number of HbO–HbR measurement sites was adopted, as in previous studies (Cutini et al., 2008, 2011a). Each source location (see Fig. 2) comprised 2 source optical fibers, one for each wavelength. The distance between each source/detector pair (hereafter, channel) was $L = 30$ mm, to equate the channels for optical penetration depth (~20 mm) into the cortical tissue (Franceschini et al., 2000). The probe configuration provided 18 channels, each measuring both HbO and HbR. Sources and detectors were held in place on the scalp using a custom-made head-mount system composed of a black rubber foil (external surface) and soft neoprene foam (internal surface, facing the scalp), in order to minimize the potential interference from the environmental light, as in previous studies (Cutini et al., 2008, 2011a, 2012a). The optodes were positioned using a probe placement method (Cutini et al., 2011b) based on a physical model of the head surface of ICBM152 (Mazziotta et al., 2001) (the standard brain template in neuroimaging studies) and a 3D digitizing system (BrainSight™, Rogue Research). This method was used to find the optimal placement of the fNIRS probes in relation to the cerebral regions to be investigated that allowed to place the holder in a reproducible way across participants. This yielded a set of 10–20/10–10 reference points that guided the probe placement on the parieto-occipital cortex, including IPS; more specifically, the middle point between the left source 9 and right source 9 was placed 10 mm below Pz, left source 5 was placed on P3 (while right source 5 was placed on P4), and left source 1 was placed on CP1 (while right source 1 was placed on CP2). The position of sources and detectors on the scalp of the ICBM152 template is shown in Fig. 2a, whereas the channels are shown in Fig. 2b. Sources were numerated from 1 to 7, both on the left (L) and right (R) hemispheres, detectors ranged from A to D, and channels were numerated from 1 to 9, on both hemispheres. Notably, the precision achieved with the probe placement procedure is comparable to that obtained with other methods (Okamoto and Dan, 2005; Okamoto et al., 2004; Singh et al., 2005) and can yield a worst-case average error within the spatial resolution of the present fNIRS setup (Firbank et al., 1998).

Behavioral and fNIRS data processing

Individual accuracy and mean response were calculated, and absent responses were excluded from analysis. Individual hemodynamic responses were segmented into 15 s trials starting from 1 s before the onset of the fixation cross. Trials were divided into the ten cells of the present experimental design generated by the orthogonal combination of condition (visual enumeration vs. digit naming) and numerosity (2, 3,

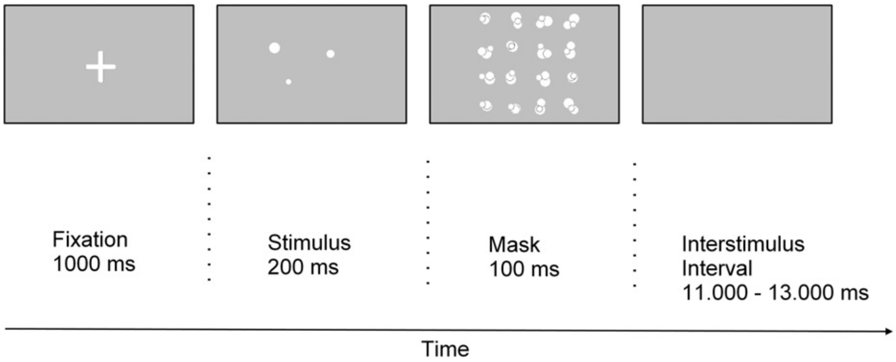


Fig. 1. A schematic illustration of the sequence of events in the present experimental paradigm. In the control condition (i.e., digit naming), the dots were replaced by Arabic digits.

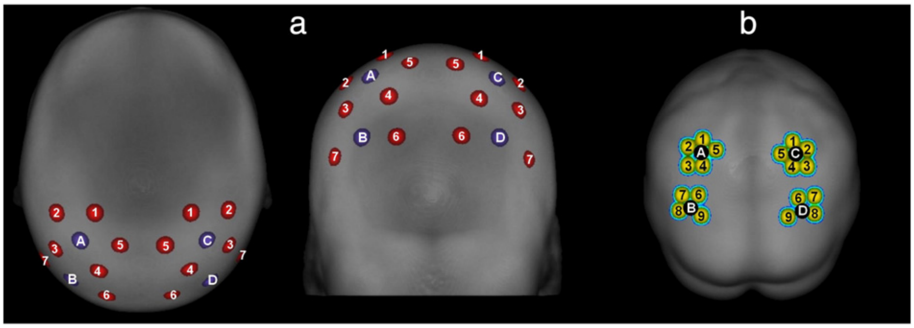


Fig. 2. Illustration of the probe placement. a) Sources (red) and detectors (blue) on the scalp of a template. Left: top view; right: posterior view. b) Cerebral projections of the channels (numbered from 1 to 9 for the left and right hemispheres) on a brain template (inclined posterior view).

4, 5 and 6). A sequence of operations was then performed for each participant, channel and condition. The optical signal of each trial was zero-mean corrected by subtracting the mean intensity of the optical signal recorded during the 15 s period, in order to reduce the effect of low-frequency physiological noise when averaging the trials. Then, artifactual trials were eliminated by using the outlier removal algorithm proposed by Devaraj (2005), which considers variations in concentration of the hemodynamic signal throughout the entire trial. The mean value and the difference between maximum and minimum values (range) were calculated considering all trials in a given condition, as well as for each single trial; single-trial mean and range values were then compared with the mean values of all trials in that condition. Trials characterized by a range or mean value greater than the condition mean ±2.5 SDs were discarded from analysis (~2%). Signal averaging of all remaining trials in each condition was then performed. Noisy channels (with SD > 2500 nM) were discarded from analysis (1%). The averaged hemodynamic signal was smoothed with a Savitzky-Golay's filter (Savitzky and Golay, 1964) with polynomial order equal to 3 and frame size equal to 31 time-points (i.e., ~4 s). The resulting signal was baseline-corrected by subtracting the mean signal intensity in the 0–1 s interval from the stimulus onset from the averaged hemodynamic signal. All the computations were performed using custom software written in Matlab R2010a (The Mathworks, Natick, MA, USA).

Afterwards, we calculated the mean signal intensity during the vascular response for dot arrays (2–5 s after trial onset) and 1–3 s after trial onset for the control condition (see Supplementary Fig. 1). These time intervals were chosen by visual inspection of the vascular response elicited by the two different types of stimuli (Jourdan Moser et al., 2009; Schroeter et al., 2007). By repeating this operation for all participants, channels, conditions and concentrations, we obtained individual HbO and HbR optical maps for each numerosity (both for visual enumeration and Arabic digits). These maps were submitted to the statistical analyses, which were performed with SPSS 18 (SPSS Inc., Chicago, IL, USA) and GraphPad Prism 5.0 (GraphPad Software, San Diego, CA, USA).

In channel-wise analyses of the hemodynamic data (see the Results section), the resulting *t* and *F* scores were corrected with the false discovery rate (FDR) method (Singh and Dan, 2006), with $q = .05$, such that no more than an average 5% of false positives could be included in the set of significantly active channels for each given statistical test. The *t* and *F* scores that survived to the FDR correction were converted into *z* scores to create z-maps as follows. The *z* score of each channel was mapped onto an overlay map (1 mm^3 voxel size) at the correspondent midpoint expressed in Montreal neurological (MNI) coordinates, using the NIfTI toolbox (Neuroimaging Informatics Technology Initiative, nifti.nimh.nih.gov/). A Gaussian blurring filter (SD = 10 mm) was then applied to the overlay map to approximate the area covered by each channel. Finally, the resulting z-map was overlaid onto the reference brain using the MRIcron software (http://www.mccauslandcenter.sc.edu/mricro/mricron/).

Results

Behavior

Performance in visual enumeration was almost errorless until 4 dots, while once above the subitizing range it showed a steep decrease (Fig. 3a), consistently with classical evidence (Kaufman et al., 1949; Revkin et al., 2008; Trick and Pylyshyn, 1994). As shown in Fig. 3b, the mean response was close to the correct numerosity across the entire range, but response variability – a signature of estimation processes – emerged only above the subitizing range. Participants made no errors in the control condition.

fNIRS

A set of statistical analyses was hierarchically organized in order to adhere to a conservative approach. The first group of fNIRS data analyses was aimed at broadly defining the cortical regions involved in visual enumeration while ruling out the activity related to naming. To this aim, we performed a comparison between the hemodynamic activity (pooled across the different numerosities) for non-symbolic stimuli with that recorded for Arabic digits, by carrying out a channel-wise series of one-tailed *t*-tests. This test enabled to highlight the regions that were significantly more activated by dot arrays than Arabic digits. As it can be observed in Fig. 4, the results revealed that visual enumeration elicited a stronger activity in a variety of channels in the parieto-occipital regions (see Table 1). Since the control task (Arabic digits) comprised a lower number of trials with respect to non-symbolic stimuli, we performed another channel-wise series of *t*-tests including only the first 10 trials for each numerosity (thereby matching non-symbolic and symbolic conditions for the number of trials included in the analysis) to rule out any possible confound related to task duration. The results were nearly identical to the previous analysis including all non-symbolic trials: only the modulation of channels L8 and R8 (located among the most posterior part of the recording sites, see Fig. 2b) did not reach significance in this control analysis.

The comparison illustrated in Fig. 4 (see also Table 1) suggests a right hemisphere dominance and a strong engagement of the bilateral IPS. In contrast with HbO results, HbR results did not reveal any significant difference between the activity observed for non-symbolic and symbolic stimuli, although the visual inspection suggested that the HbR response profile was consistent with that of HbO. Thus, HbR was not considered in the following analyses. We then investigated the impact exerted by visual enumeration on the hemodynamic activity of the parieto-occipital regions in terms of hemispheric dominance. We compared the number of activated channels between the left and right hemispheres by means of the Kolmogorov–Smirnov non-parametric test. The results confirmed the presence of a significant dominance of the right hemisphere ($D = 0.4556$, $p = .0104$, one-tailed).

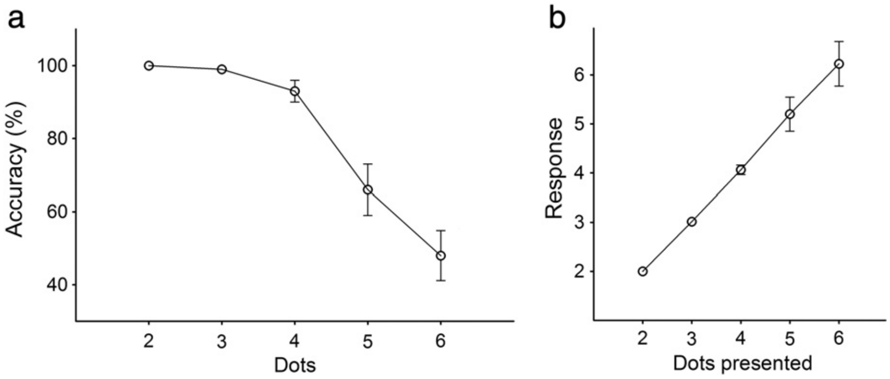


Fig. 3. Behavioral results. a) Accuracy in the numerosity naming task (mean ± standard error); as expected, there was a sudden decrease in accuracy with numerosities beyond the subitizing range (>4 dots). b) Response (mean ± standard deviation) as a function of the numerosity of the dot array; note that response variability emerges beyond 4 dots.

We then performed a channel-wise analysis devised to detect which regions were more sensitive to numerical magnitude in visual enumeration. For each active channel found in the dots vs. digits comparison, a repeated-measures ANOVA was performed with dot numerosity as a within-subjects factor (5 levels: 2–6) in order to identify the regions that were modulated by numerical magnitude. The series of ANOVAs revealed a specific pattern of hemodynamic activity, showing a modulation of more channels of the right PPC, and the left IPS (Fig. 5). Interestingly, the highest z score was observed in the right IPS (channel R4: $z = 3.66$), followed by left IPS (channel L4: $z = 2.50$); see Table 1 for more information.

As it can be noted from the response profile of the right IPS in relation to the dot numerosity (Fig. 6a), there was a striking magnitude-dependent modulation of hemodynamic activity. What is less clear, however, is whether such modulation is linear or non-linear. Indeed, the hemodynamic response was low for 2 and 3 dots, while it showed a sudden increase for 5 dots and a plateau (i.e., with no further increase for 6 dots). Crucially, 4 dots elicited an intermediate hemodynamic response, likely reflecting the transition between subitizing and estimation. To specifically characterize the exact nature of the magnitude-dependent modulation exerted on the activity of parieto-occipital regions, the response profile was fitted (linear vs. sigmoid) in relation to the number of dots; the best fit was then established by computing the Akaike's Information Criteria (AIC) (Akaike, 1974). The sigmoid fit significantly better explained the modulation for all the channels investigated ($p < .05$) (see Fig. 6b), even if the sigmoid curve fitting was limited by two stringent constraints (i: start curve at position $x = 2$ with value $y = 0$; ii: end curve at position $x = 6$ with value $= 1$). To further characterize the nature of the modulation, we carried out a series of one-tailed t-tests restricted to right IPS activity for all the pairs of adjacent numerosities (3 vs. 2; 4 vs. 3; 5 vs. 4; 6 vs. 5): crucially, only the comparison between the activity observed with 5 vs. 4 dots yielded a significant difference ($t(10) = 2.159$, $p = .0281$), while all the other comparisons were not significant (note that 4 vs. 3 showed a non-significant trend, $t = 1.56$; $p = .0744$; in contrast, the apparently higher activity for 5 over 6 dots visible in Fig. 6b was far from being significant, $t < 1$).

Finally, in order to assess possible differences in the temporal pattern of the IPS hemodynamic activity within and beyond the subitizing range, a cross-correlation analysis was performed on the pooled response profiles for 2–4 dots vs. 5–6 dots. The cross-correlation was computed for each participant on the response profiles in the time interval between 0 and 6 s after onset, and the resulting individual lag values were statistically analyzed by means of a one-sample t-test vs. 0. The analysis revealed that the hemodynamic response beyond the subitizing range was significantly delayed ($t(10) = 1.866$, $p < .05$, one-tailed) with respect to that observed for numerosities within the subitizing range (see Fig. 7).

Discussion

The primary scope of the present investigation was to test with fNIRS a set of specific hypotheses related to the neural substrate of non-symbolic numerical magnitude processing during visual enumeration of dot arrays. We investigated in detail the functional involvement of the parieto-occipital cortex in the processing of small numerosities, within and beyond the subitizing limit, providing clear-cut neuroimaging results.

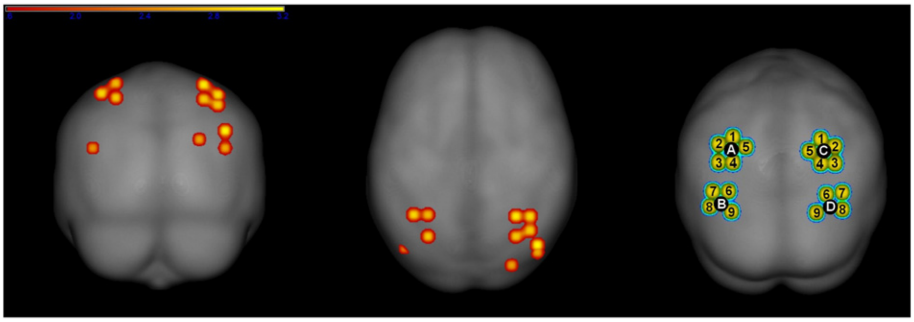


Fig. 4. Statistical (z) maps in the visual enumeration vs. digit naming comparison. Visual inspection indicates strong bilateral activity of IPS, the broad involvement of parieto-occipital regions and a slight right hemispheric dominance. Left: posterior view; center: top view. On the right: cerebral projections of the channels (numbered from 1 to 9 for the left and right hemispheres) on a brain template (inclined posterior view).

Table 1
Statistical results and brain regions investigated. From left to right: channels, statistical values, best fit, MNI coordinates, region and hemisphere, Brodmann Area.

Ch.	Dots vs. digits (HbO) *z* scores	Dot modulation (HbO) *z* scores	Fit	MNI coordinates			Region		BA
				x	y	z			
L1	2.80			−30	−53	74	Left	SPL	7
L2	2.99			−40	−53	67	Left	IPS	7/40
L3				−40	−63	59	Left	SMG	40
L4	2.91	2.50	Sigmoid	−30	−68	64	Left	IPS	7/40
L5				−21	−62	73	Left	SPL	7
L6				−33	−78	46	Left	SPL/IOS	7/19
L7				−44	−73	41	Left	AG/IOS	19/39
L8	2.55			−46	−76	29	Left	IOS/TOS	19/40
L9				−31	−87	35	Left	TOS	19/18
R1	3.13			31	−54	73	Right	SPL	7
R2	3.02	2.13	Sigmoid	41	−54	66	Right	IPS	7/40
R3	2.92	1.65	Sigmoid	41	−64	59	Right	SMG	40
R4	2.90	**3.66**	Sigmoid	31	−68	63	Right	IPS	7/40
R5				23	−64	71	Right	SPL	7
R6				35	−81	46	Right	SPL/IOS	7/19
R7	3.20	1.72	Sigmoid	46	−74	41	Right	AG/IOS	19/39
R8	2.70	2.21	Sigmoid	46	−79	29	Right	IOS/TOS	19/40
R9	2.65	1.84	Sigmoid	28	−88	35	Right	TOS	19/18

Abbreviations: SPL (superior parietal lobule); IPS (intraparietal sulcus); SMG (supramarginal gyrus); AG (angular gyrus); TOS (transverse occipital sulcus); IOS (intraoccipital sulcus). Note that statistical results for "dots vs. digits (HbO)" and "dot modulation (HbO)" refer to the *t* and *F* values, respectively; both *t* and *F* values have been converted in *z* scores: only the statistical values that survived FDR correction are reported. The bold value represents the highest *z* score for the parametric modulation due to dot numerosity.

From a behavioral standpoint, we observed a steep decrease in accuracy above the subitizing range which was the expression of increasing response variability. This is the typical pattern of performance that is thought to reflect the transition between subitizing and estimation processes (e.g., Revkin et al., 2008). By comparing the hemodynamic activity elicited by dot arrays with Arabic digits by means of a channel-wise series of *t*-tests, we excluded any confound that might have been introduced by the different vocal responses to the numerical stimuli as well as by the number naming process itself. Indeed, we are confident that the comparison with digit naming is more stringent than with any control condition which does not involve number naming/verbal number processing. This contrast also allows us to exclude that the recorded activity results from spurious systemic effects (Franceschini et al., 2006; Saager et al., 2011) or task-unrelated physiological oscillations (Julien, 2006; Sassaroli et al., 2012). The comparison showed a broad involvement of the parieto-occipital cortex during non-symbolic magnitude processing. This is consistent with the notion that numerosity is a primary visual property, as previously shown in other investigations (Burr and Ross, 2008; Stoianov and Zorzi, 2012).

The results of the Kolmogorov–Smirnov test on HbO changes with the pooled numerosities showed that, although both hemispheres seem to be involved in the task, there is a right hemispheric dominance in non-symbolic numerical magnitude processing (Castelli et al., 2006; Dehaene et al., 2003; Hubbard et al., 2005; Piazza et al., 2002). The final series of the channel-by-channel analyses confirmed and extended these results: notably, we detected a functional dissociation between subitizing and estimation. This was particularly evident for the bilateral IPS, with a slight predominance for the right IPS (see Fig. 5). These novel results are broadly consistent with a seminal fMRI study on subitizing and counting (Piazza et al., 2003), which has shown that attention-related regions of the posterior parietal cortex exhibited a sudden increase in activity only from numerosity four upwards, confirming a dichotomy between number processing within and beyond the subitizing range. Interestingly, single-trial measures of parietal activations could be used to detect whether attentive processes were employed for subitizing or serial counting.

In the present study, AIC results allowed to characterize more specifically the non-symbolic magnitude-dependent pattern of modulation: once the subitizing limit was exceeded, hemodynamic activity showed a steep increase and tended to plateau immediately afterwards. It is plausible that the intermediate level of activity observed for arrays with a numerosity of 4 might reflect both individual and within-trial variability in the subitizing limit (cf. Piazza et al., 2003). Interestingly, no region showed the reverse trend (i.e., higher activity in subitizing range), consistently with the idea that the entire parieto-occipital cortex contributes to some extent in the visual processing of non-symbolic numerical magnitudes. On top of that, the amplitude modulation is largely consistent with the temporal difference observed in the hemodynamic

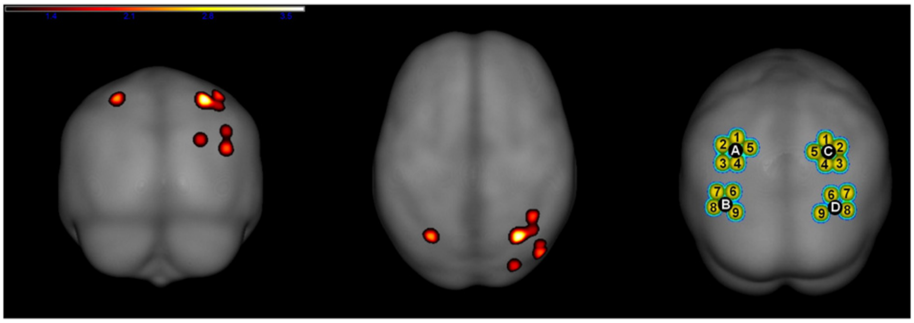


Fig. 5. Statistical (z) maps obtained by the channel-wise ANOVAs aimed at detecting a modulation of cortical activity in relation to numerical magnitude. The highest statistical value was located in the right IPS (channel R4), followed by the left IPS (L4). Left: posterior view; center: top view. On the right: cerebral projections of the channels (numbered from 1 to 9 for the left and right hemispheres) on a brain template (inclined posterior view).

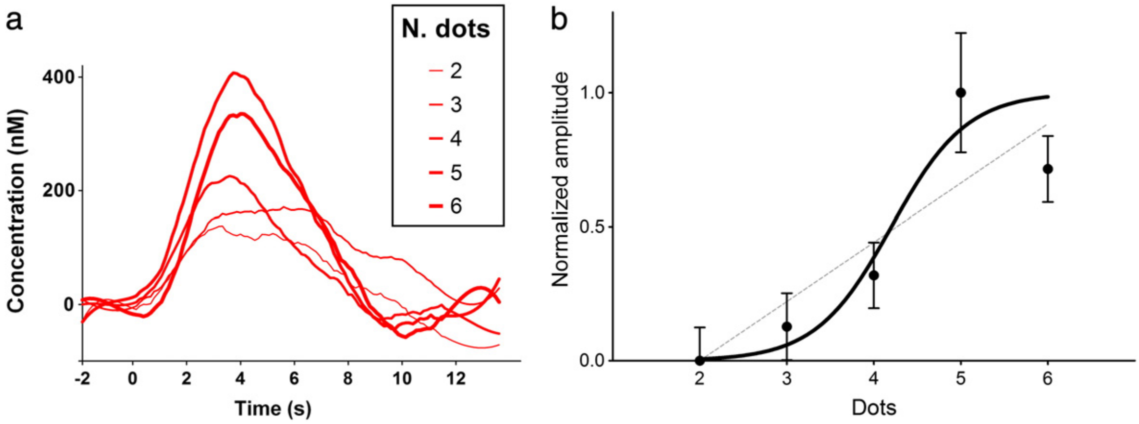


Fig. 6. a) Hemodynamic response profiles in right IPS (channel R4) related to dot numerosity. The thicker the line, the higher the numerosity. b) Sigmoid fit (black solid line; linear fit: gray dotted line) of the mean values of normalized hemodynamic response profiles in right IPS for the different dot numerosities (bars represent standard error).

peak latencies for numerosities within and beyond the subitizing range: the non-linearity observed in the amplitude of hemodynamic activity is supported by a temporal dissimilarity between response profiles within and beyond the subitizing range, as shown by the cross-correlation analysis. In this sense, the present results are complementary to the recent view suggesting that the rTPJ might be the attentional bottleneck involved in subitizing (Vetter et al., 2011). Our results also confirm the critical role of the IPS in numerical magnitude processing, because the magnitude-dependent modulation effect had a *z*-maximum in the right IPS, closely followed by left IPS.

Though the nonlinear pattern of hemodynamic modulation in IPS seems to be directly connected to visual enumeration, it is worth to consider other potential accounts of the data that do not draw on the distinction between two processes (subitizing vs. estimation) and that might be in fact non-numerical. One hypothesis is that the total amount of visual input might be the main driving source of the hemodynamic modulation, mainly because larger numerosities were, on average, associated to a larger total area. Therefore, one could argue that the observed modulation of the parieto-occipital activity might be directly generated by the increase in total area of dot arrays. However, this explanation has several shortcomings; given that the size of each dot was randomly chosen between 3 different sizes both within and between trials, the range of cumulative area for the different numerosities was largely overlapping: for instance, the range of cumulative area for stimuli with 6 dots overlapped with that of all the other numerosities presented (including 2 dots). For this reason, cumulative area could not have been strategically used as a cue to judge numerosity, thereby dampening its potential impact on parieto-occipital activity; moreover, while a tight control of non-numerical visual properties like total area is important for studies that employ comparison of large numerosities to investigate the ANS (e.g., the neural adaptation study of Piazza et al., 2004), continuous visual properties are likely to be far less influent in a simple visual enumeration task with relatively few items (such as those used in the present experiment). It is also worth noting that continuous visual properties such as cumulative area do not affect the activity of intraparietal neurons during stimulus viewing (Roitman et al., 2007). Finally, the visual impact of one single dot on the parieto-occipital hemodynamic response can be considered negligible, especially with respect to the much stronger stimulation exerted by the visual mask that immediately followed all numerosity stimuli. A second alternative explanation of the present hemodynamic data may invoke task difficulty: given that task difficulty increases with dot numerosity, the observed hemodynamic modulation might simply reflect the task demands. However, the different trends shown by behavioral and hemodynamic data are not consistent with this hypothesis (compare Fig. 3 with Fig. 6): while enumeration accuracy (Fig. 3) decreased systematically with increasing numerosity (reaching its minimum for 6 dots), hemodynamic activity reached a plateau for 5 dots (i.e., HbO concentrations for 5 and 6 dots were not significantly different), thus showing a diverging pattern from what one should expect if the modulation was driven by task difficulty. On the other hand, this issue might be definitely settled by extending the investigation to numerosities larger than those examined in the present study (e.g., including 7 and 8 dots), in order to have more detailed information regarding the response modulation beyond the subitizing range.

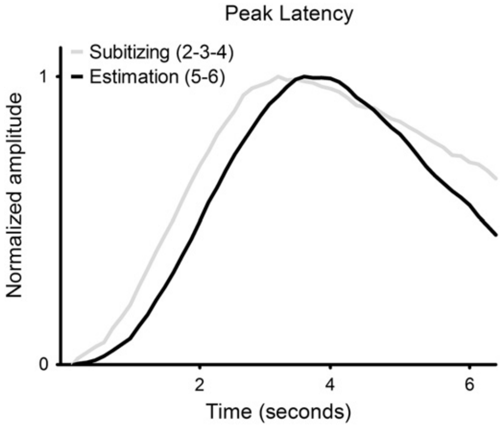


Fig. 7. Normalized hemodynamic response profiles in right IPS (channel R4) for pooled concentrations of numerosities up to the subitizing limit (2–3–4 dots, gray line), and those beyond subitizing limit (5 and 6 dots, black line). The visible temporal difference of the peak latency between the two response profiles is statistically confirmed by cross-correlation analysis.

In summary, both total visual area and task difficulty can potentially account for a nonspecific increase in hemodynamic activity related to dot numerosity, but none of them can be straightforwardly reconciled with the non-linearity observed in the hemodynamic modulation profile. Although these alternative accounts cannot be completely dismissed, we believe that the most plausible explanation for the peculiar modulation profile for IPS, characterized by a marked discontinuity around the subitizing limit, concerns the hypothesis that subitizing and estimation are supported by two different mechanisms, the OTS and the ANS, respectively. While the dots within a small set are individuated as objects that can be tracked simultaneously by the OTS (Mazza and Caramazza, 2011; Melcher and Piazza, 2011; Piazza et al., 2011), the numerosity of larger sets is a high-order statistical summary computed by the ANS (Stoianov and Zorzi, 2012) and it is internally coded in a noisy and compressed fashion (Dehaene, 2003). The dissociation between subitizing and estimation is also suggested by EEG findings (Hyde and Spelke, 2009) and by recent behavioral studies showing that increasing attentional load (i.e., dual task condition) disrupts subitizing without affecting estimation (Burr et al., 2010; Feng et al., 2012; Piazza et al., 2011), indicating that only subitizing requires attentional resources. We note that the dissociation between subitizing and estimation might be inextricably rooted in the mechanisms of visual attention: the OTS is domain-general and is characterized by an intrinsic attentional nature, emerging from the ability to simultaneously allocate attention over multiple individual items, whereas the ANS, being specifically devoted to number representation, is a more direct expression of the number sense (Piazza, 2010). How the pattern of activity in IPS observed in the present study may reflect the interplay between OTS and ANS still remains an outstanding question. Nevertheless, a conjecture can be drawn by examining in detail the overall picture coming from theoretical, behavioral and neural data: our working hypothesis is that the pattern of hemodynamic activity in IPS might be complementary to the pattern of TPJ activity found in fMRI studies (Ansari et al., 2007; Vetter et al., 2011), with a selective involvement of TPJ for the processing of small numerosities. Notably, TPJ is a critical node of the ventral attention network for stimulus-driven orienting (Corbetta and Shulman, 2002) and it is thought to act as a "circuit breaker" on the fronto-parietal network for top-down attention. In this light, it is conceivable that TPJ activity induced by small numerosities would turn into suppression of IPS activity. This would allow OTS and ANS to work in concert, because ANS-related activity would be suppressed whenever object tracking/subitizing is engaged. This hypothesis can be used to generate a specific prediction: under attentional load, a significant intraparietal activity can be expected also for small numerosities; indeed, when subitizing is precluded because OTS limited capacities are consumed by a competing attentional task, small numerosities (that would normally be subitized) would bear upon the ANS, as it can be inferred by considering the reduced accuracy for small numerosities in these conditions (e.g., Burr et al., 2010). Thus, the IPS should be strongly activated even by small numerosity processing when TPJ is engaged by a concurrent, attention-demanding task. Unfortunately, in our study we were unable to cover both the parieto-occipital cortex and the TPJ because of instrumental limitations, but we believe that the simultaneous optical recording in IPS and TPJ is an intriguing avenue for future research that might lead to detecting a functional double dissociation between the neural mechanisms involved in subitizing and estimation, which would unequivocally show the presence of two distinct mechanisms for subitizing and estimation.

In conclusion, the present study provides the first demonstration that numerosities within and beyond the subitizing range elicit distinct hemodynamic patterns, both in terms of amplitude modulation and temporal profile. This suggests that subitizing and estimation are neurally dissociable in the IPS, although the present data do not allow to doubly dissociate the neural substrates underlying those processes. Nonetheless, this result confirms that fNIRS can be successfully used to detect subtle temporal differences in hemodynamic activity and to produce inferences on the neural mechanisms underlying cognitive functions.

Acknowledgments

This study was supported by grants from the Cariparo Foundation (Progetti di Eccellenza 2007) and European Research Council (no. 210922) to M.Z.; S.C. was suppported by a Senior Research Fellowship (Assegno Senior) from the University of Padova.

Conflict of interest

The authors declare no conflict of interest.

Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.neuroimage.2013.08.027.

References

Agrillo, C., Piffer, L., Bisazza, A., Butterworth, B., 2012. Evidence for two numerical systems that are similar in humans and guppies. PLoS One 7, e31923.

Akaike, H., 1974. A new look at the statistical model identification. IEEE Trans. Autom. Control. 19, 716–723.

Ansari, D., Dhital, B., Siong, S.C., 2006. Parametric effects of numerical distance on the intraparietal sulcus during passive viewing of rapid numerosity changes. Brain Res. 1067, 181–188.

Ansari, D., Lyons, I.M., Van Eimeren, L., Xu, F., 2007. Linking visual attention and number processing in the brain: the role of the temporo-parietal junction in small and large symbolic and nonsymbolic number comparison. J. Cogn. Neurosci. 19, 1845–1853.

Arsalidou, M., Taylor, M.J., 2011. Is $2 + 2 = 4$? Meta-analyses of brain areas needed for numbers and calculations. NeuroImage 54, 2382–2393.

Beran, M.J., 2007. Rhesus monkeys (*Macaca mulatta*) enumerate large and small sequentially presented sets of items using analog numerical representations. J. Exp. Psychol. Anim. Behav. Process. 33, 42–54.

Brannon, E.M., Terrace, H.S., 1998. Ordering of the numerosities 1 to 9 by monkeys. Science 282, 746–749.

Brigadoi, S., Cutini, S., Scarpa, F., Scatturin, P., Dell'Acqua, R., 2012. Exploring the role of primary and supplementary motor areas in simple motor tasks with fNIRS. Cogn. Process. 13, 97–101.

Burr, D., Ross, J., 2008. A visual sense of number. Curr. Biol. 18, 425–428.

Burr, D.C., Turi, M., Anobile, G., 2010. Subitizing but not estimation of numerosity requires attentional resources. J. Vis. 10, 1–10.

Castelli, F., Glaser, D.E., Butterworth, B., 2006. Discrete and analogue quantity processing in the parietal lobe: a functional MRI study. Proc. Natl. Acad. Sci. U. S. A. 103, 4693–4698.

Cohen Kadosh, R., Henik, A., Rubinsten, O., Mohr, H., Dori, H., Van De Ven, V., Zorzi, M., Hendler, T., Goebel, R., Linden, D.E.J., 2005. Are numbers special? The comparison systems of the human brain investigated by fMRI. Neuropsychologia 43, 1238–1248.

Cope, M., Delpy, D.T., 1988. System for long-term measurement of cerebral blood and tissue oxygenation on newborn infants by near infra-red transillumination. Med. Biol. Eng. Comput. 26, 289–294.

Corbetta, M., Shulman, G.L., 2002. Control of goal-directed and stimulus-driven attention in the brain. Nat. Rev. Neurosci. 3, 201–215.

Cordes, S., Gelman, R., Gallistel, C.R., Whalen, J., 2001. Variability signatures distinguish verbal from nonverbal counting for both large and small numbers. Psychon. Bull. Rev. 8, 698–707.

Cutini, S., Bonato, M., 2012. Subitizing and visual short-term memory in human and non-human species: a common shared system? Front. Psychol. 3, 469.

Cutini, S., Scatturin, P., Menon, E., Bisiacchi, P.S., Gamberini, L., Zorzi, M., Dell'Acqua, R., 2008. Selective activation of the superior frontal gyrus in task-switching: an event-related fNIRS study. NeuroImage 42, 945–955.

Cutini, S., Scarpa, F., Scatturin, P., Jolicœur, P., Pluchino, P., Zorzi, M., Dell'acqua, R., 2011a. A hemodynamic correlate of lateralized visual short-term memories. Neuropsychologia 49, 1611–1621.

Cutini, S., Scatturin, P., Zorzi, M., 2011b. A new method based on ICBM152 head surface for probe placement in multichannel fNIRS. NeuroImage 54, 919–927.

Cutini, S., Basso Moro, S., Bisconti, S., 2012b. Functional near infrared optical imaging in cognitive neuroscience: an introductory review. J. Near Infrared Spectrosc. 20, 75–92.

Cutini, S., Scarpa, F., Scatturin, P., Dell'acqua, R., Zorzi, M., 2012a. Number–space interactions in the human parietal cortex: enlightening the SNARC effect with functional near-infrared spectroscopy. Cereb. Cortex. http://dx.doi.org/10.1093/cercor/bhs321.

Dehaene, S., 2003. The neural basis of the Weber–Fechner law: a logarithmic mental number line. Trends Cogn. Sci. 7, 145–147.

Dehaene, S., Piazza, M., Pinel, P., Cohen, L., 2003. Three parietal circuits for number processing. Cogn. Neuropsychol. 20, 487–506.

Demeyere, N., Rotshtein, P., Humphreys, G.W., 2012. The neuroanatomy of visual enumeration: differentiating necessary neural correlates for subitizing versus counting in a neuropsychological voxel-based morphometry study. J. Cogn. Neurosci. 24, 948–964.

Devaraj, A., 2005. Signal processing for functional near-infrared neuroimaging. Unpublished MS Thesis. Drexel University.

Dresler, T., Obersteiner, A., Schecklmann, M., Vogel, A.C., Ehlis, A.C., Richter, M.M., Plichta, M.M., Reiss, K., Pekrun, R., Fallgatter, A.J., 2009. Arithmetic tasks in different formats and their influence on behavior and brain oxygenation as assessed with near-infrared spectroscopy (NIRS): a study involving primary and secondary school children. J. Neural Transm. 116, 1689–1700.

Eger, E., Sterzer, P., Russ, M.O., Giraud, A.L., Kleinschmidt, A., 2003. A supramodal number representation in human intraparietal cortex. Neuron 37, 719–725.

Feigenson, L., Dehaene, S., Spelke, E., 2004. Core systems of number. Trends Cogn. Sci. 8, 307–314.

Feng, J., Pratt, J., Spence, I., 2012. Attention and visuospatial working memory share the same processing resources. Front. Psychol. 3, 103.

Ferrari, M., Quaresima, V., 2012. A brief review on the history of human functional near-infrared spectroscopy (fNIRS) development and fields of application. NeuroImage 63, 921–935.

Firbank, M., Okada, E., Delpy, D.T., 1998. A theoretical study of the signal contribution of regions of the adult head to near-infrared spectroscopy studies of visual evoked responses. NeuroImage 8, 69–78.

Franceschini, M.A., Toronov, V., Filiaci, M., Gratton, E., Fantini, S., 2000. On-line optical imaging of the human brain with 160-ms temporal resolution. Opt. Express 6, 49–57.

Franceschini, M.A., Joseph, D.K., Huppert, T.J., Diamond, S.G., Boas, D.A., 2006. Diffuse optical imaging of the whole head. J. Biomed. Opt. 11, 054007.

Halberda, J., Mazzocco, M.M.M., Feigenson, L., 2008. Individual differences in nonverbal number acuity predict maths achievement. Nature 455, 665–668.

Hubbard, E.M., Piazza, M., Pinel, P., Dehaene, S., 2005. Interactions between number and space in parietal cortex. Nat. Rev. Neurosci. 6, 435–448.

Hyde, D.C., 2011. Two systems of non-symbolic numerical cognition. Front. Hum. Neurosci. 5, 150.

Hyde, D.C., Spelke, E.S., 2009. All numbers are not equal: an electrophysiological investigation of small and large number representations. J. Cogn. Neurosci. 21, 1039–1053.

Hyde, D.C., Boas, D.A., Blair, C., Carey, S., 2010. Near-infrared spectroscopy shows right parietal specialization for number in pre-verbal infants. NeuroImage 53, 647–652.

Jourdan Moser, S., Cutini, S., Weber, P., Schroeter, M.L., 2009. Right prefrontal brain activation due to Stroop interference is altered in attention-deficit hyperactivity disorder — a functional near-infrared spectroscopy study. Psychiatry Res. 173, 190–195.

Julien, C., 2006. The enigma of Mayer waves: facts and models. Cardiovasc. Res. 70, 12–21.

Kaufman, E.L., Lord, M.W., Volkmann, J., 1949. The discrimination of visual number. Am. J. Psychol. 62, 498–525.

Mandler, G., Shebo, B.J., 1982. Subitizing: an analysis of its component processes. J. Exp. Psychol. Gen. 111, 1–22.

Mazza, V., Caramazza, A., 2011. Temporal brain dynamics of multiple object processing: the flexibility of individuation. PLoS One 6, e17453.

Mazziotta, J., Toga, A., Evans, A., Fox, P., Lancaster, J., Zilles, K., Woods, R., Paus, T., Simpson, G., Pike, B., Holmes, C., Collins, L., Thompson, P., MacDonald, D., Iacoboni, M., Schormann, T., Amunts, K., Palomero-Gallagher, N., Geyer, S., Parsons, L., Narr, K., Kabani, N., Le Goualher, G., Boomsma, D., Cannon, T., Kawashima, R., Mazoyer, B., 2001. A probabilistic atlas and reference system for the human brain: International Consortium for Brain Mapping (ICBM). Philos. Trans. R. Soc. Lond. [Biol.] 356, 1293–1322.

Mazzocco, M.M.M., Feigenson, L., Halberda, J., 2011. Impaired acuity of the approximate number system underlies mathematical learning disability (dyscalculia). Child Dev. 82, 1224–1237.

Melcher, D., Piazza, M., 2011. The role of attentional priority and saliency in determining capacity limits in enumeration and visual working memory. PLoS One 6, e29296.

Nieder, A., 2005. Counting on neurons: the neurobiology of numerical competence. Nat. Rev. Neurosci. 6, 177–190.

Okamoto, M., Dan, I., 2005. Automated cortical projection of head-surface locations for transcranial functional brain mapping. NeuroImage 26, 18–28.

Okamoto, M., Dan, H., Sakamoto, K., Takeo, K., Shimizu, K., Kohno, S., Oda, I., Isobe, S., Suzuki, T., Kohyama, K., Dan, I., 2004. Three-dimensional probabilistic anatomical cranio-cerebral correlation via the international 10–20 system oriented for transcranial functional brain mapping. NeuroImage 21, 99–111.

Paterson, S.J., Girelli, L., Butterworth, B., Karmiloff-Smith, A., 2006. Are numerical impairments syndrome specific? Evidence from Williams syndrome and Down's syndrome. J Child Psychol. Psychiatry 47, 190–204.

Piazza, M., 2010. Neurocognitive start-up tools for symbolic number representations. Trends Cogn. Sci. 14, 542–551.

Piazza, M., Mechelli, A., Butterworth, B., Price, C.J., 2002. Are subitizing and counting implemented as separate or functionally overlapping processes? NeuroImage 15, 435–446.

Piazza, M., Giacomini, E., Le Bihan, D., Dehaene, S., 2003. Single-trial classification of parallel pre-attentive and serial attentive processes using functional magnetic resonance imaging. Philos. Trans. R. Soc. Lond. [Biol.] 270, 1237–1245.

Piazza, M., Izard, V., Pinel, P., Le Bihan, D., Dehaene, S., 2004. Tuning curves for approximate numerosity in the human intraparietal sulcus. Neuron 44, 547–555.

Piazza, M., Mechelli, A., Price, C.J., Butterworth, B., 2006. Exact and approximate judgements of visual and auditory numerosity: an fMRI study. Brain Res. 1106, 177–188.

Piazza, M., Pinel, P., Le Bihan, D., Dehaene, S., 2007. A magnitude code common to numerosities and number symbols in human intraparietal cortex. Neuron 53, 293–305.

Piazza, M., Facoetti, A., Trussardi, A.N., Berteletti, I., Conte, S., Lucangeli, D., Dehaene, S., Zorzi, M., 2010. Developmental trajectory of number acuity reveals a severe impairment in developmental dyscalculia. Cognition 116, 33–41.

Piazza, M., Fumarola, A., Chinello, A., Melcher, D., 2011. Subitizing reflects visuo-spatial object individuation capacity. Cognition 121, 147–153.

Pinel, P., Dehaene, S., Rivière, D., LeBihan, D., 2001. Modulation of parietal activation by semantic distance in a number comparison task. NeuroImage 14, 1013–1026.

Revkin, S.K., Piazza, M., Izard, V., Cohen, L., Dehaene, S., 2008. Does subitizing reflect numerical estimation? Psychol. Sci. 19, 607–614.

Richter, M.M., Zierhut, K.C., Dresler, T., Plichta, M.M., Ehlis, A.C., Reiss, K., Pekrun, R., Fallgatter, A.J., 2009. Changes in cortical blood oxygenation during arithmetical tasks measured by near-infrared spectroscopy. J. Neural Transm. 116, 267–273.

Roitman, J.D., Brannon, E.M., Platt, M.L., 2007. Monotonic coding of numerosity in macaque lateral intraparietal area. PLoS Biol. 5 (8), e208.

Saager, R.B., Telleri, N.L., Berger, A.J., 2011. Two-detector corrected near infrared spectroscopy (C-NIRS) detects hemodynamic activation responses more robustly than single-detector NIRS. NeuroImage 55, 1679–1685.

Sassaroli, A., Pierro, M., Bergethon, P.R., Fantini, S., 2012. Low-frequency spontaneous oscillations of cerebral hemodynamics investigated with near-infrared spectroscopy: a review. IEEE J. Sel. Top. Quantum Electron. 18, 1478–1492.

Savitzky, A., Golay, M.J.E., 1964. Smoothing and differentiation of data by simplified least squares procedures. Anal. Chem. 36, 1627–1639.

Schroeter, M.L., Cutini, S., Wahl, M.M., Scheid, R., von Cramon, D.Y., 2007. Neurovascular coupling is impaired in cerebral microangiopathy: an event-related Stroop study. NeuroImage 34, 26–34.

Sella, F., Lanfranchi, S., Zorzi, M., 2013. Enumeration skills in Down syndrome. Res. Dev. Disabil. http://dx.doi.org/10.1016/j.ridd.2013.07.038 (in press).

Singh, A.K., Dan, I., 2006. Exploring the false discovery rate in multichannel NIRS. NeuroImage 33, 542–549.

Singh, A.K., Okamoto, M., Dan, H., Jurcak, V., Dan, I., 2005. Spatial registration of multichannel multi-subject fNIRS data to MNI space without MRI. NeuroImage 27, 842–851.

Stoianov, I., Zorzi, M., 2012. Emergence of a "visual number sense" in hierarchical generative models. Nat. Neurosci. 15, 194–196.

Szűcs, D., Killikelly, C., Cutini, S., 2012. Event-related near-infrared spectroscopy detects conflict in the motor cortex in a Stroop task. Brain Res. 1477, 27–36.

Trick, L.M., Pylyshyn, Z.W., 1994. Why are small and large numbers enumerated differently? A limited-capacity preattentive stage in vision. Psychol. Rev. 101, 80–102.

Vetter, P., Butterworth, B., Bahrami, B., 2008. Modulating attentional load affects numerosity estimation: evidence against a pre-attentive subitizing mechanism. PLoS One 3, e3269.

Vetter, P., Butterworth, B., Bahrami, B., 2011. A candidate for the attentional bottleneck: set-size specific modulation of the right TPJ during attentive enumeration. J. Cogn. Neurosci. 23, 728–736.

Zorzi, M., Di Bono, M.G., Fias, W., 2011. Distinct representations of numerical and non-numerical order in the human intraparietal sulcus revealed by multivariate pattern recognition. NeuroImage 56, 674–680.