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Near-Infrared Spectroscopy Shows Right Parietal Specialization for Number in Pre-Verbal Infants

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Running title: PARIETAL SPECIALIZATION FOR NUMBER IN INFANTS

Near-infrared spectroscopy shows right parietal specialization for number in pre-verbal infants

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Abstract

Bilateral regions of the intraparietal sulcus (IPS) appear to be functionally selective for both rudimentary non-symbolic number tasks and higher-level symbolic number tasks in adults and older children. Furthermore, the ability to mentally represent and manipulate approximate non-symbolic numerical quantities is present from birth. These factors leave open whether the specialization of the IPS develops through the experience of learning a symbolic number system or if it is already specialized before symbolic number acquisition. Using the newly emerging technique of functional Near-Infrared Spectroscopy (fNIRS) over left and right parietal and lateral occipital regions, we show right parietal specialization for number in 6-month-old infants. These results extend the current literature in three ways: by successfully implementing an event-related NIRS design in infants, by showing parietal specialization for number occurs before the acquisition of language, and by suggesting number representation may be initially right lateralized and become bilateral through experience.

1. Introduction

Studies with non-human animals and pre-verbal infants suggest the presence of a non-verbal cognitive system for representing number (see Carey, 2009; Dehaene, 1997; Feigenson, Dehaene, & Spelke, 2004; Gallistel, 1993 for reviews). These numerical representations appear to be innate and abstract, as even newborns can match visual-spatial arrays of objects with auditory sequences of events on the basis of number (e.g. Izard, Sann, Spelke, & Streri, 2009). Although precision in the mental representation of number increases, these representations capture the cardinal values of sets approximately. Across all age ranges tested, discrimination ability is a function of numerical ratio of the sets; the ratio that can be discriminated improves with age, from 1:3 among newborns, 1:2 among 6-month-olds, 2:3 among 9 month olds, 3:4 among preschool children, and 7:8 among adults (e.g. Carey, 2009; Feigenson et al., 2004; Izard et al., 2009; Lipton & Spelke, 2003, 2004; Xu, Spelke, & Goddard, 2005; Xu & Spelke, 2000). The behavioral ratio limit of number comparison in infants, children, and adults has led some to conclude that non-verbal number representation is continuous over development (Carey, 2009; Feigenson et al., 2004; Hyde & Spelke, in press; Xu & Spelke, 2000). If so, we might expect continuity in the neural mechanism underlying number representation over development in the face of vast differences in experience and even number-related conceptual change (Feigenson et al., 2004; Hyde & Spelke, in press). A strong test of the continuity hypothesis would be to find evidence of a specialized brain region for number in pre-verbal infants that corresponds to that previously observed in verbal children and adults.

In adults, both symbolic and non-symbolic number tasks activate bilateral regions of the intraparietal sulcus (IPS) and damage to this region results in a loss of numerical abilities (e.g. Cantlon, Brannon, Carter, & Pelphrey, 2006; Dehaene, Piazza, Pinel, & Cohen, 2003; Holloway,

Price, & Ansari, in press; Piazza, Pinel, Le Bihan, & Dehaene, 2007; Piazza, Izard, Pinel, Le Bihan, & Dehaene, 2004). This region appears to be specific for number, as it responds to number changes but not to other equally salient non-numerical changes (Cantlon et al., 2006; Piazza et al., 2004). However, it is unclear whether number-specialization of the parietal lobe develops through the experience of learning a symbolic number system or if it is already specialized before formal training and symbolic numerical experience. Thus far, localization of such a brain region in pre-verbal infants has been difficult given the spatial resolution of EEG/ERPs, the most common technique employed in measuring the neural correlates of higher-level cognition in infants (see Johnson, de Haan, Oliver, Smith, Hatzakis, Tuker, & Csibra, 2001) In fact, only one study to date has attempted to localize number representation in the infant brain using ERPs (Izard, Dehaene-Lambertz, & Dehaene, 2008). This study applied a source localization algorithm to ERP data and estimated the brain response to number originated from a widespread network of right lateralized brain regions including right inferior parietal, right frontal, and temporal regions. These estimates suggest some degree of specialization for number, as the number response dissociated from that observed for shape in ventral brain regions. While this study provides a rough approximation as to the brain areas that may be important to infants' number processing, the methods used are limited in their spatial resolution and possibly in accuracy and validity (see Luck, 2005 for a review). For instance, some question the current methods for localizing the source of the electrical activity that constitutes ERP data in infants because the current source localization algorithms rest, in part, on largely untested assumptions about infant brain anatomy (Johnson et al., 2001).

In contrast, the newly emerging technique of functional Near Infrared Spectroscopy (fNIRS), is a method with relatively precise spatial resolution (see Aslin & Mehler, 2005;

Minagawa-Kawai, Mori, Hebden, & Dupoux, 2008).   NIRS allows estimation of the

hemodynamic response on the immediate cortical surface at a maximum depth of about 2.5-3

centimeters from the light source. Thus, at least on the cortical surface, NIRS provides an

alternative method with better spatial resolution to ERPs for measuring the cortical response in

infants (see Aslin & Mehler, 2005 or Minagawa-Kawai et al., 2008 for reviews). Here we used

fNIRS to estimate fluctuations in the hemodynamic response to number changes directly over

occipital and parietal regions as a test of the continuity hypothesis of number representation. As a

first step in exploring the specificity of the response, we also tested whether the brain region(s)

that respond to number change also respond equally to another type of change, namely shape

changes (Cantlon et al., 2006; Izard et al., 2008; Piazza et al., 2004).

2. Methods and Materials

2.1 Subjects

Approval for use of human subjects in this study was obtained through the Partners/MGH

Human Research Committee and informed consent was obtained from a parent or guardian of

each infant participant. Thirty-six infants 5.5 months to 6.5 months of age made up the final data

set. An additional 38 infants came into the lab, but were not included in the analysis for the

following reasons: failure to view at least eight deviant trials because of fussiness or

inattentiveness (16 infants), failure to obtain good measurements due to improper fit of headgear

causing it to move or slip off during the testing (5 infants), signal saturation due to

excessive/dark hair (3 infants), failure to obtain good measurements due to excessive motion

during the experiment (7 infants), or failure of experimenters to record the data due to technical

difficulties with the equipment (7 infants).   This attrition rate is characteristic of studies

measuring the brain response to static visual stimuli in infants using ERPs (e.g. Berger, Tzur, &

Posner, 2006; Izard et al., 2008; Hyde, Jones, Porter, & Flom, 2010; Hyde & Spelke, in press; Libertus et al., 2009; Quinn, Westerlund, & Nelson, 2006).

2.2 Procedure

Infants viewed numerical arrays in an adaptation or oddball paradigm, similar to that used in previous studies of adults and older children (Cantlon et al., 2006; Hyde & Spelke, 2009, in press; Izard et al., 2008; Piazza et al., 2004). In this paradigm, subjects were presented with a sequence of novel images, a majority of which contained 16 circles (adaptation images). Occasionally, embedded within the sequence of adaptation images, deviant test images appeared (randomly every 5th-11th image). The number-change group (n = 18) saw occasional number-deviant test images of increasing (32 circles) and decreasing numerical magnitudes (8 circles). The shape-change group (n = 18) saw occasional shape-deviant test images of 16 squares and 16 triangles. To avoid boredom, presentation of stimuli was broken up into short blocks followed by short rest periods. Four deviant images appeared pseudo-randomly within each block with the constraints that the first test deviant occurred between 9-16.5 seconds after the start of the run and the last deviant image appeared at least 9 seconds before the end of the run. Each block contained new adaptation and deviant images.

2.3 Stimuli

Stimuli were white shapes on a gray background that appeared sequentially for 500 milliseconds and were separated by a gray fixation screen that appeared for a randomly chosen time between 500-1000 milliseconds. Images were constructed using an automated program designed to control for non-numerical parameters such as total area, individual item size, and density across the entire set of images (see www.unicog.org for documentation). Specifically, the intensive parameters (individual item size and inter-item spacing) of the adaptation images

varied with number while the extensive parameters (total occupied area and total luminance) varied randomly within a fixed distribution but were equated on average across adaptation images. In the test images, the reverse was true. Crucially, the smallest and largest values of the distribution used for the extensive parameters of the adaptation images were the smallest and largest values presented in test images. This means that all individual continuous values presented in the test images were equally familiar between experimental conditions, as they were presented equally often in the adaptation images (for more details of controls see Hyde & Spelke, 2009; Izard et al., 2008, Piazza et al., 2004).

2.4 Apparatus

The hemodynamic response was measured over bilateral occipital and parietal sites with Near-Infrared Spectroscopy (NIRS) using a continuous wave machine that emitted light at 690 and 830 nm wavelengths. Light was projected to and detected from the infants' head using fiber optic cables attached to a custom head probe made out of neoprene material. The head probe was fitted to the head by Velcro adjustments on the probe itself and further secured to the head by an adjustable chin strap and two sports-style headbands which were placed over the probe after initial Velcro adjustment. The probe had two light sources and four light detectors. Detectors were spaced 2.5 cm above and below the two sources and placed on the right and left posterior scalp (see Figure 1). The probe was placed over left and right lateral occipital and inferior parietal scalp sites according to the International 10-20 EEG coordinates (Okamoto et al., 2004). Specifically, the head probe was centered with respect to the Oz reference point on each infant (see Figure 1). This placed the left occipital detector 2 cm to the left of Oz and the right occipital detector 2 cm to the right of Oz, locating them just lateral of 10-20 points O1/O2

based on the average head measurements of children this age (www.cdc.gov). Parietal detectors

were 5 cm above the occipital detectors placing them just under the parietal 10-20 points P3/P4.

2.5 Data reduction and analysis

The data processing and analysis routine employed is similar to that used in previous

infant NIRS studies (Wilcox et al., 2008, 2009; Bortfeld et al., 2009; Pena et al., 2003). All

processing was done using HomER and EasyNIRS (available at www.nmr.mgh.harvard.edu/

PMI/resources/homer/home.htm). Raw signals were acquired at 10 Hz. Data were converted to

relative levels of oxy-, deoxy-, and total hemoglobin using the modified Beer-Lambert law (e.g.

Strangman, Boas, & Sutton, 2002). Data were filtered offline at 3 Hz and then subjected to

principal components analysis to remove large physiological and motion artifacts. The brain

response was assessed using a 10 second time window surrounding the presentation of test

images. The 2 seconds before the event was considered the baseline and subtracted from the 8

seconds following to assess the change in hemodynamic response. Individual trial epochs were

rejected automatically if they contained more than 5% intensity change over a 10 ms sample.

Additionally, trials in which infants became fussy, cried, or were inattentive to the displays were

rejected, as indicated by the behavioral notes. Infants that did not complete at least 8 acceptable

trials were excluded from the analysis (see subjects section 2.1 for breakdown).

2.5 Statistical Analysis

Analysis focused on relative OxyHb concentration as previous studies have found it to be

an informative marker of cognitive processing (e.g. Baird, Kagen, Gaudette, Walz, Hershlag, &

Boas, 2002; Bortfeld, Fava, Boas, 2009; Grossmann, Johnson, Lloyd-Fox, Blasi, Deligianni,

Elwell, & Csibra, 2008; Minagawa-Kawai et al., 2008; Pena et al., 2003; Wilcox, Bortfeld,

Woods, Wruck, & Boas, 2008; Wilcox, Bortfeld, Woods, Wruck, Armstrong, & Boas, 2009).

First, the OxyHb responses at all four detectors were tested relative to baseline for significant responses during two time windows characterizing the first and second half of time between test trials (2-5 seconds/5-8 seconds) using a one sample t-test. To compare the relative response across experiments, we performed a mixed ANOVA with the within-subjects repeated factor of Brain Region (Occipital or Parietal) and the between subjects factor of Change Condition (number or shape change). Post hoc testing followed up with paired samples t-test comparing Brain Region (Occipital and Parietal) within each Change Type (number and shape) separately.

3. Results and Discussion

Number-deviant images elicited a significant increase in Oxyhemoglobin concentration (OxyHb) relative to baseline in the right parietal region alone (see Figure 2). This response was at a maximum between 2-5 seconds after stimulus onset ($t(17) = 2.27$, $p = .036$). Based on our probe placement, the localization of the parietal detector showing the response to number is consistent with right IPS activity seen in adults (e.g. Cantlon et al., 2006; Piazza et al., 2004). In contrast, shape-deviant images elicited an increase in OxyHb concentration relative to baseline in the right lateral occipital region alone. This response was at a maximum between 5-8 seconds after stimulus onset ($t(17) = 2.69$, $p = .016$). Based on our probe placement, the localization of the lateral occipital detector is consistent with LOC (lateral occipital complex) activation seen for shape in adults with fMRI (e.g. Cantlon et al., 2006; Grill-Spector & Malach, 2001; Kanwisher, Woods, Iacoboni, & Mazziotta, 1997; Piazza et al., 2004; Shuman & Kanwisher, 2004).

Because there were no effects of either shape change or number change in our left hemisphere probes, these were not analyzed further.   A more focused analysis examined whether the responses in the right lateralized regions to shape changes or to number changes

were significantly different from each other. A multi-factor ANOVA examining the effects of

the within-subjects variable of Brain Region (occipital vs. parietal) and the between-subjects

variable of Change Type (shape vs. number) on change in OxyHb concentration revealed a

significant interaction between Brain Region and Change Type (F (1, 17) = 6.87, p = .013, partial

eta squared = .17).   Post-hoc tests revealed that this interaction was due to number changes

eliciting a larger hemodynamic response in right parietal areas compared to right occipital areas

(t (17) = -2.49, p = .024), whereas the difference (in the other direction) between brain regions in

the case of shape changes was not significant (t (17) = 1.01, p = .326) (see Figure 3).

5. Conclusions

        Our application of NIRS to study infant numerical cognition makes four main

contributions. First, we successfully implemented an event-related adaptation design with rapid

stimulus presentation (< 1 second), in contrast to the slow, block-designs employed by most

using NIRS with infants to date (e.g. Aslin & Mehler, 2005; Baird et al, 2002; Bortfeld et al.,

2009; Grossmann et al., 2008; Minagawa-Kawai et al., 2008; Pena et al., 2003; Wilcox et al.,

2008; Wilcox et al., 2009).   The success of this paradigm with infants will enable researchers to

expand the range of stimuli used and corresponding research questions asked to those that

require rapid stimulus presentation and/or more subtle differences between experimental

conditions. For example, and second, we found that the response to shape change occurred later

(5 to 8 sec. after the change), relative to that for number change (2 to 5 sec. after the change).

Block designs, in contrast, may not be sensitive to such subtle timing differences in the response.

One interpretation of this difference is that the occipital response to shape change is the result of

feedback rather than initial processing of shape. This interpretation could be confirmed through

the use of a NIRS system with more scalp coverage, allowing simultaneous monitoring of more brain regions.

Third, our results overcome the previous limits to brain localization of number in infants by using a technique with relatively precise spatial resolution (Hyde & Spelke, in press; Izard et al., 2008; Libertus, Pruitt, Woldorff, & Brannon, 2009) and show that the right inferior parietal region is, in fact, functionally responsive to number by 6 months of age. Furthermore, our results, coupled with those from previous fMRI studies of adults and older children and ERP localization research with infants, suggest that the neural response to number in the right parietal lobe is continuous across development despite vast differences in training and experience with symbolic numbers between pre-verbal infants, older children, and adults (Cantlon et al., 2006; Piazza et al., 2004; Izard et al., 2008) That is, the same experimental conditions used in the previous studies with older children and adults reveal a similar degree of specialization for number in the infant brain that arises independently of formal numerical experience, education, or even language.

Fourth, in contrast to bilateral activity routinely observed in non-symbolic number tasks with adults and older children (Cantlon et al., 2006; Piazza et al., 2004), the brain response to number in infants was only observed in the right hemisphere. These results accord with the right lateralization estimates from scalp ERP data in response to number in infants (Izard et al., 2008). It should be noted that our measurements were restricted to the cortical surface, given the limitations of NIRS to probe deeper cortical activity; our measurements were also limited by the significant variations in brain/head size between infants at this age (see www.cdc.gov). Given these limitations, it is possible that activity may have been present in other portions of the monitored regions but not detected by our measurements. Nonetheless, previous fMRI studies

comparing older children and adults have shown age-related increases in left IPS activity during both symbolic and non-symbolic numerical tasks, suggesting number-specific activation may be initially isolated to the right hemisphere and becomes bilateral over development (Ansari & Dhital, 2006; Cantlon et al., 2004; Cohen-Kadosh, Lammertyn, & Izard, 2008). Our results build on these to provide the strongest evidence to date that numerical processing is initially lateralized to the right hemisphere. Future work should investigate exactly what experiences drive increases in left IPS activity over development.

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Figure Captions

Figure 1. Schematic of optical probe and placement in reference to the international 10-20 EEG system. (A). Lateral view of the 10-20 measurements and superimposed probe placement. The red circle represents the light emitter and the blue squares represent the light detectors. (B). Top view of 10-20 system and superimposed probe placement. (C). Schematic representation of the probe including distances between light emitters and detectors.

Figure 2. Summary of fNIRS results for number and shape changes. (A). Hemodynamic response observed for number changes from 2 seconds before to 8 seconds after deviant image onset. The "*" indicates a significant difference from baseline ($p < .05$). Y axis reflects relative change in oxygenated hemoglobin concentration (micromolars) (B). Hemodynamic response observed for shape changes on the same scale.

Figure 3. Relative OxyHb response for number changes and shape changes at right occipital and parietal sites. Y axis reflects relative change in oxygenated hemoglobin concentration (micromolars) relative to baseline. The "*" indicates statistical significance ($p < .05$).
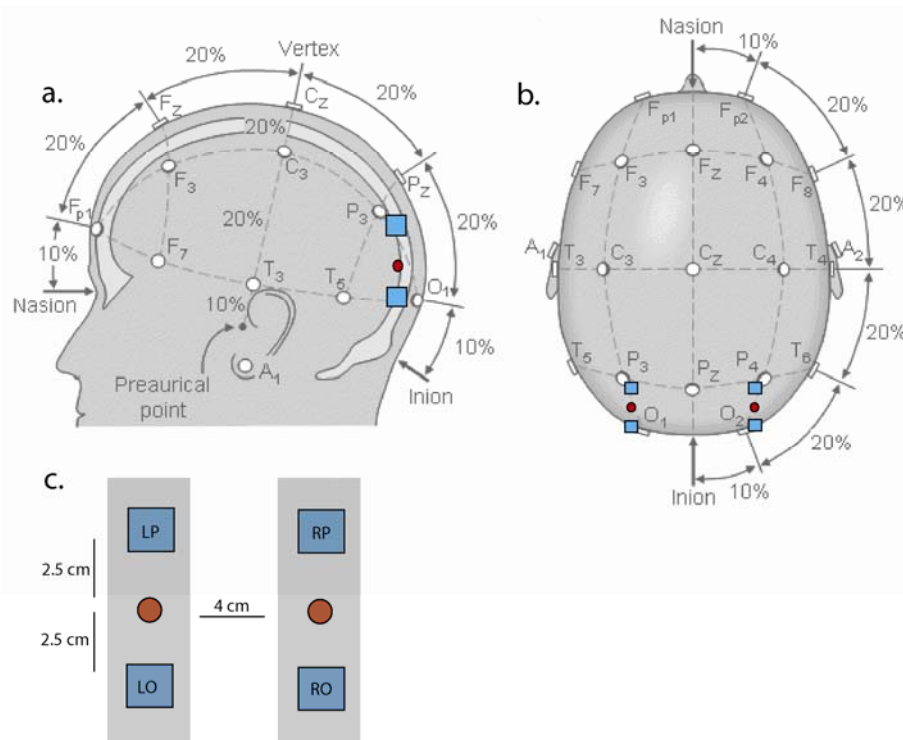
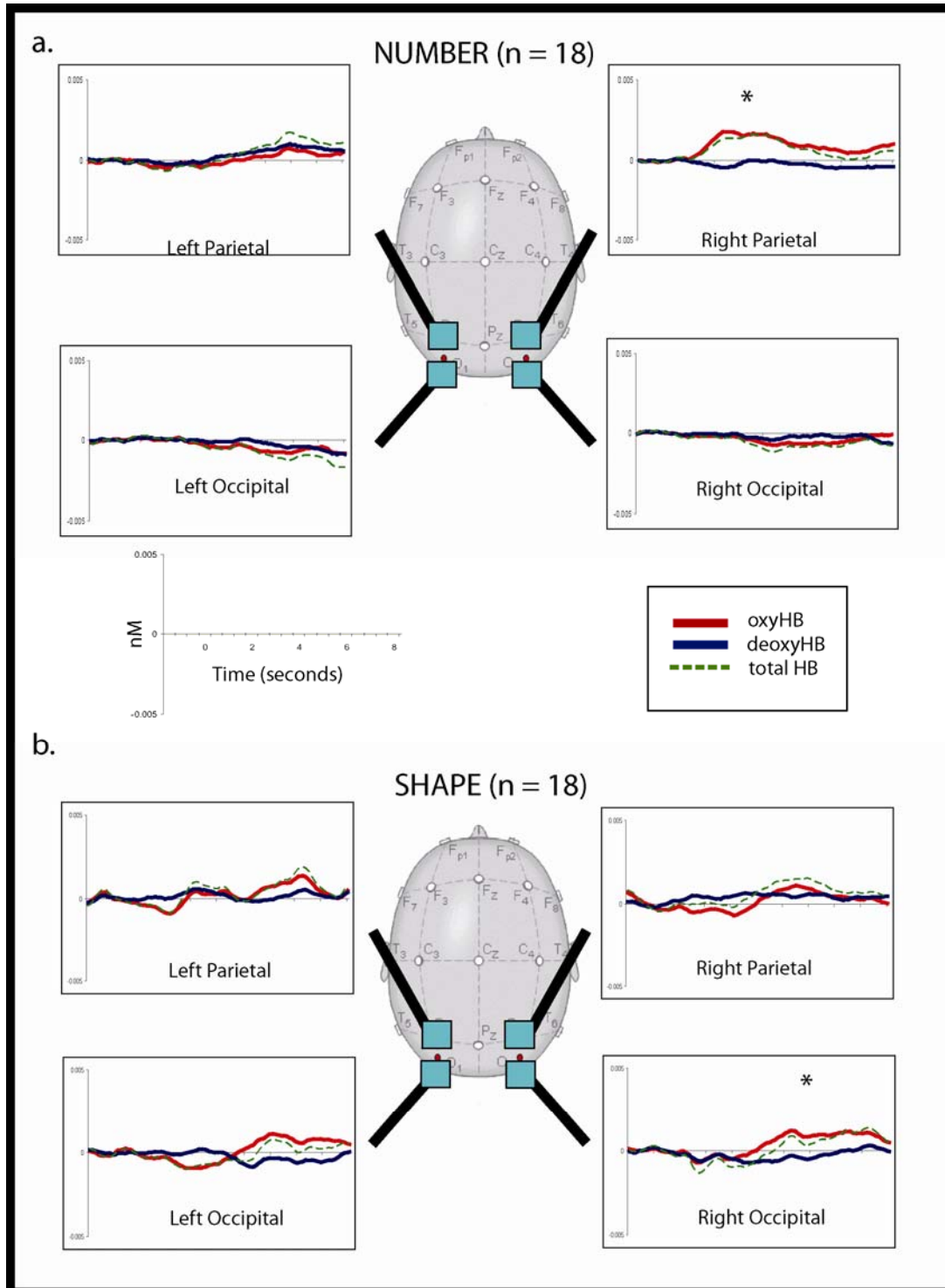Figure 1.

Figure 2.

Figure 3.