

The parietal distance effect appears in both the congenitally blind and matched sighted controls in an acoustic number comparison task

Dénes Szűcs^{a,b,*}, Valéria Csépe^b

^a Centre for Neuroscience in Education, Faculty of Education, University of Cambridge, UK

^b Research Institute for Psychology, Department of Psychophysiology, Hungarian Academy of Sciences, Hungary

Received 10 February 2005; received in revised form 30 March 2005; accepted 13 April 2005

Abstract

Visual world experience is thought to play a significant role in the development of an abstract representation of quantity in the human brain. Nevertheless, some congenitally blind individuals demonstrate excellent numerical abilities. We show that blind adults have a phenomenologically normal semantic representation of number. Electro-encephalography data demonstrate that the numerical distance effect has similar parietal correlates both in the blind and in matched sighted controls. Our interpretation is that number comparison in the blind relies on a compensation network in the initial phase of number comparison. In a second phase, an evolutionarily hardwired parietal system is exploited. The representation of number meaning has both plastic and evolutionarily hardwired components.

© 2005 Elsevier Ireland Ltd. All rights reserved.

Keywords: Number comparison; Distance effect; Numerical processing; Brain plasticity; Event-related spectral perturbation (ERSP); Time-frequency analysis; Cognition in the blind

Animals [4], human infants [19], and adult humans with [11] and without [9] an extensive counting list appear to interpret numerosity in an abstract, amodal, approximate [7] representation in the bilateral parietal lobes of the brain. According to some views, this circuit provides a biological foundation for number sense [15]. According to others, a hard-wired system for something as complex as number representation is untenable [14]. Proponents of both views assume that the development of this numerosity representation depends on the extraction of object-location information via the occipito-parietal pathway involved in the visuo-spatial individuation of objects [15,14,6]. Accordingly, number representation may be different from normal in humans lacking visuo-spatial information.

In blind people, the visuo-spatial individuation of objects is absent. Blind individuals usually have poor mathematical abilities. Yet, 5–10% of blind teenagers in Hungary obtain good or excellent grades in advanced maths examinations.

Moreover, some achieve a university degree (all of our subjects), or may become outstanding mathematicians [10]. There are two interpretations of such achievements: either some blind individuals use sophisticated compensating strategies to overcome the absence of visuo-spatial input in building a system capable of the interpretation of numerical information or this system is hardwired. In Hungary, the blind learn spatial relations and number meaning via tactile input. They learn to interpret numerical distance by placing pegs in a peg board. The distance between pegs representing different numbers is used to convey magnitude information. The blind brain shows a remarkable plasticity in response to altered stimulation [1]. The question addressed here is whether brain plasticity allows the tactile input to build on a dedicated neural and cognitive system, resulting in the classic parietal circuitry for number sense. We investigated whether blind individuals demonstrate the classic properties of normal number representation: (1) the behavioural numerical distance effect (reaction times are longer and accuracy is worse when discriminating numerically closer than further away quantities [11]). (2) Amplitude modulations of

* Corresponding author. Tel.: +44 1223 767636; fax: +44 1223 767602.
E-mail address: ds377@cam.ac.uk (D. Szűcs).

electroencephalographic parameters in function of numerical distance as measured at parietal electrode sites [3,17,13,16].

In experiment 1, 12 sighted subjects (native Hungarians in all experiments) decided whether digits were smaller or larger than 5 (high-school students; six women; mean age: 24.42 ± 4.54 years). All subjects gave informed written consent in all studies. Stimuli were the Arabic digits 1–4 and 6–9. Black stimuli on light-green background appeared for 200 ms at the centre of a 17 in. computer monitor (800×600 pixels) positioned at about 80 cm from the subjects' eyes. Four hundred and eighty stimuli were presented in two blocks, preceded by 72–72 practice stimuli. Responses, counterbalanced across blocks, were given by either the left or right index finger. Possible response priming effects were balanced for each number. The percent of correct responses (PC), individually normalized and raw reaction times (RTs) were assessed by response pattern (left-right versus right-left) \times relation (<5 versus >5) \times distance (from 5) ANOVAs. The analysis of normalized and raw RTs yielded nearly equivalent results, therefore, only results based on raw values are reported. In all experiments, Greenhaus–Geisser epsilon (ϵ) correction of p -values was used when necessary to compensate for the violation of the sphericity assumption. Original F and d.f. values and corrected p -values are reported.

In experiment 2, congenitally blind and gender-, age-, and education-matched sighted control subjects solved a number comparison task with spoken digits. Apart from the acoustic stimulation the procedure and the stimuli was the same as in experiment 1. Subjects were eight congenitally blind (age: 26.62 ± 3.96 ; range: 21–33; four women) and eight control adults (age: 26.5 ± 3.42 ; range: 22–32). All participants were fulfilling or had finished college or university studies. Participants came from working-class or lower middle-class families. Blind participants were born blind or became blind due to perinatal accidents. According to self-reports participants did not have further neurological or psychiatric problems. According to the statement of the Hungarian School of the Blind all of the blind participants were well-functioning with no serious problems except their blindness. Control subjects were blindfolded in all acoustic studies. Stimuli, delivered bilaterally via earphones, were Hungarian number words from 1 to 9, spoken by a native speaker, digitized at 11 025 Hz. Results were assessed by a group \times response side \times relation \times distance ANOVA.

In experiment 3, EEG data was collected. Eight blind (6 subjects were the same as in experiment 2) and eight control subjects decided whether numbers 1, 4, 6 and 9 were smaller or larger than 5; or that letters a, e, f and i stood before or after letter e in the alphabet. The paradigm, EEG recording conditions and the processing of event-related potentials (ERPs) have been described elsewhere [16]. The mean age of the blind group was 26.87 ± 3.65 years (range: 21–31 years; four women), that of the control group was 25.37 ± 2.49 years (range: 21–32 years). Further subject variables were similar to those in experiment 2. Due to EEG artefacts in one of the blind subjects, 7–7 subjects' data was analyzed.

Letters tested for the stimulus-specificity of effects. Behaviourally, the distance \times group interaction was tested by a group \times material (number versus letter) \times distance (distance from 5 is 1 versus distance from 5 is 4) \times magnitude (smaller than 5 versus larger than 5) ANOVA. For clearer interpretability other effects were tested by separate within-subject distance \times magnitude ANOVAs. The percent of accepted epochs was above 75% in all accepted subjects.

The ERP and a generalized measure of event-related synchronization and desynchronization [12], the event-related spectral perturbation (ERSP) transform of the EEG were computed [8]. The ERSP is the mean change of spectral power relative to a baseline. The ERP, computed by averaging brain responses, recorded at each presentation of a certain stimulus class, contains only information both phase-locked and time-locked to the stimulus (evoked activity). The ERSP contains not only phase-locked but also not phase-locked information (both evoked and induced activity). Considering only phase-locked information (the ERP) may not be an adequate representation of the ongoing neural processes [8]. Time-frequency decomposition was performed by short-time Fourier transform in EEGLab [8] using a sliding temporal window of 128 points, applied 200 times providing output frequency bins at about 2 Hz steps. The -100 to 0 ms interval before stimulus presentation served as the baseline for both stimulus-locked and response-locked ERSP computation. One stimulus-locked ERSP analysis included the response-interval (-100 to 900 ms) while (in order to have a better temporal resolution) another analysis focused more on the stimulus-processing phase (-100 to 600 ms). The second analysis was subjected to the reported ANOVAs. Response-locked epochs ranged from -250 to $+100$ ms relative to the response time. Epochs receiving a correct response between 250 and 1000 ms were used.

For the evaluation of distance and magnitude effects within-subject distance \times magnitude ANOVAs were run on each point of the time-frequency landscape, separately for number and letter tasks. To compensate for multiple testing a conservative ($p < 0.004$) significance level was used. As 115 sampling points (120 – 450 ms) \times 25 frequency bins (2 – 48 Hz) were of interest, at a p -level of 0.004, 11.5 points could be detected as significant due to chance at each electrode. This is considerably less than the number of points interpreted as showing significant effects. Effects with an area of less than 16 data points were overall discarded. The six largest area effects (per electrode) were selected for analysis. Effects showing great overlap across electrodes were counted as one.

In experiment 1, the behavioural distance effect was replicated in Hungarians (RT: $F(3, 33) = 87.85$; $\epsilon = 0.681$; $p < 0.0001$. PC: $F(3, 33) = 26.571$; $\epsilon = 0.605$; $p < 0.0001$. Table 1. Normalized reaction times for all experiments are shown in supplementary Fig. 1). In experiment 2, both congenitally blind and sighted control subjects showed robust distance effects (Table 1, RT: $F(3, 42) = 177.912$; $\epsilon = 0.611$; $p < 0.0001$. PC: $F(3, 42) = 10.681$; $\epsilon = 0.396$; $p = 0.0033$. dis-

Table 1
Reaction time (RT) and the percent of correct responses (PC) in experiment 1 (visual) and experiment 2 (control and blind)

Group		Numbers			
		1	2	3	4
RT	Visual	401.6 ± 39.3	400.9 ± 45.4	413.5 ± 46.2	440.0 ± 46.1
	Control	495.6 ± 66.8	534.3 ± 67.3	567.2 ± 70.4	634.8 ± 69.0
	Blind	440.9 ± 67.8	487.4 ± 71.5	503.1 ± 78.6	583.4 ± 59.8
PC	Visual	96.7 ± 2.7	96.8 ± 2.3	95.6 ± 2.2	90.4 ± 6.0
	Control	98.7 ± 2.6	99.2 ± 0.9	98.8 ± 1.9	94.6 ± 5.4
	Blind	98.5 ± 1.8	98.6 ± 1.4	98.4 ± 3.1	93.6 ± 7.7
Group		Distance			
		9	8	7	6
RT	Visual	409.6 ± 42.6	408.5 ± 45.1	421.2 ± 43.1	432.0 ± 40.7
	Control	541.9 ± 70.2	580.1 ± 67.9	564.3 ± 77.6	578.0 ± 73.6
	Blind	486.9 ± 86.7	524.5 ± 68.6	509.5 ± 65.7	510.6 ± 74.1
PC	Visual	96.9 ± 2.0	95.7 ± 3.3	94.1 ± 3.1	92.2 ± 3.4
	Control	99.0 ± 1.5	99.5 ± 0.6	98.2 ± 3.4	97.1 ± 4.3
	Blind	99.2 ± 1.2	98.4 ± 2.1	98.5 ± 1.3	95.9 ± 4.3
Group		Distance			
		4	3	2	1
RT	Visual	405.6 ± 40.9	404.7 ± 45.2	417.3 ± 44.7	436.0 ± 43.4
	Control	518.7 ± 68.5	557.2 ± 67.6	565.8 ± 74.0	606.4 ± 71.3
	Blind	463.9 ± 77.2	505.9 ± 70.1	506.3 ± 72.1	547.0 ± 67.0
PC	Visual	96.8 ± 2.3	96.2 ± 2.8	94.9 ± 2.6	91.3 ± 4.7
	Control	98.8 ± 2.1	99.3 ± 0.8	98.5 ± 2.6	95.8 ± 4.9
	Blind	98.8 ± 1.5	98.5 ± 1.8	98.5 ± 2.2	94.7 ± 6.0

tance × group interactions: n.s.), and performed at a similar level (97.6% and 98.1% correct). Further, responses were faster when subjects responded to numbers above 5 with their right hand and numbers below 5 with their left hand than vice versa ($F(1, 14) = 9.473$; $p = 0.0081$; response pattern: left is smaller, right is larger: 507.1 ms. Right–left: 530.2 ms). Thus both groups showed the so-called spatial-numerical association of response-codes, which is thought to be an index of a number-line like organization of number representation [5]. Blind subjects responded 58 ms faster than the controls ($p = 0.06$).

In order to exclude the possibility that the distance effect was seriously confounded by word-length effects [3], in a complementary analysis individual reaction times were pooled across subjects. Word-length, estimated minimum identification time of words and the number of phonemes in words were taken as partial variables in calculating correlations between numerical distance and response time (parameters from 1 to 9 are: Word-length (ms): 200, 450, 450, 350, 350, 400, 500, 500. Estimated minimum identification time (ms): 140, 350, 350, 300, 180, 250, 400, 450. Number of phonemes: 2, 4, 5, 3, 3, 3, 4, 6). The minimum identification time was the average of the estimation of 12 Hungarian speakers. The effect of distance remained significant in all of the partial correlations (reaction time–distance partial correlations: $-0.36 < r < -0.47$; $p < 0.0001$, in all cases).

Experiment 2 showed that the phenomenological organization of numerical representation was similar in both groups.

In experiment 3, we asked whether the two subject groups recruited similar brain circuits in numerical comparison. Accuracy was the same in both groups (98.4%) and the blind were faster than the controls (416 versus 529 ms; $F(1, 14) = 10.331$; $p = 0.006$. See data in Table 2). The behavioural distance effect was significant and similar in both groups (number task: RT: $F(1, 14) = 109.131$; $p < 0.0001$. PC: $F(1, 14) = 8.501$; $p = 0.0112$. Letter task: $F(1, 14) = 75.778$; $p < 0.0001$. PC: n.s.). The magnitude effect was not significant.

Guided by prior studies [3,17,13,16], the EEG analysis was focused on the 120–450 ms interval after stimulus onset. The EEG of both groups was dominated by a clear stimulus-locked effect between 100 and 300 ms (supplementary Fig. 2). The P3 accompanying the response was more expressed between 300 and 400 ms in the blind than in the control group due to shorter and less scattered reaction times in the blind. Apart from a general amplitude difference showing a maximum at central electrodes (see supplementary Fig. 2); there were no apparent morphological or distribution discrepancies in ERPs between subject groups. Moreover, at around 200 ms, we found similar lateral parietal (N2p component at electrodes P9, P7, P8 and P10) and frontal (P2 component at electrodes F3, Fz and F4) ERP deflections and distance effects in the amplitude of ERPs in both subject groups as in our former study [16]. The peak amplitude of the N2p (Fig. 1; measured between 150 and 300 ms) was more negative in case of numerical distance 4 than in case of distance 1 ($F(1, 14) = 17.724$; $p = 0.0009$). The amplitude of the frontal

Table 2
Reaction time in milliseconds (RT) and the percent of correct responses (PC) in experiment 3

Group	Number task				Letter task			
	1 ^a	4 ^a	6 ^a	9 ^a	a ^a	d ^a	i ^a	f ^a
Control								
RT								
Mean	478.6	581.2	551.7	509.2	481.5	585.6	519.5	527.7
Standard deviation	72.7	90.7	83.6	88.2	88.1	77.3	76.8	70.7
Minimum	371.7	428.0	425.7	379.3	385.2	461.6	401.3	439.4
Maximum	578.1	688.7	667.4	624.4	656.8	706.4	620.3	638.7
PC								
Mean	99.3	98.0	97.7	99.1	99.6	97.3	99.0	97.3
Standard deviation	1.2	2.5	2.7	2.1	0.8	2.2	1.8	1.9
Blind								
RT								
Mean	369.2	464.2	426.2	408.4	369.9	462.3	418.3	416.9
Standard deviation	44.5	40.1	52.3	45.7	45.5	48.5	55.2	52.5
Minimum	313.6	410.8	374.9	354.5	299.4	380.7	331.8	346.3
Maximum	449.9	533.2	512.5	468.4	427.7	535.2	495.5	487.4
PC								
Mean	99.4	97.8	97.7	99.5	99.0	97.8	98.6	97.8
Standard deviation	0.5	1.4	1.1	0.7	1.4	1.7	2.2	2.2

^a Stimuli.

P2 (140–260 ms) was more positive for distance 4 than for distance 1 ($F(1, 14) = 15.300$; $p = 0.0015$).

In fact, apart from general amplitude differences, we could not demonstrate any divergence in the ERP topographies and in the ERP distance effects in the blind and in the control subjects. A feasible interpretation is that that number comparison relied on similar neural circuits in both groups as reflected by ERPs [17]. Wishing to further refine our understanding of the underlying processes, we analyzed additional information provided by the ERSP. Between 200 and 500 ms, the ERSP of the controls was dominated by a posterior-peaking ERSP decrease (desynchronization [12]), while that of the blind was characterized by a centro-parietal ERSP increase (synchronization) (Fig. 2). These landscapes were clearly distinct from later, movement-related effects focusing over electrodes C3 and C4 [12], onsetting at certain frequency ranges at about 3–400 ms in the blind and at 500 ms in the controls. Distance effects in the time-frequency landscapes are summarized in Fig. 3. Two phases of number comparison were identified

according to the timing of the bursts of distance effects and differences in their topography. From here on, these are called phase 1 and phase 2 (see phase boundaries in Fig. 3).

In the controls, the locality of left and right frontal and parietal ERSP distance effects corresponded to the localization of formerly reported ERP effects [3,17,13] and to fMRI activations [2] characteristic of number comparison tasks. In phase 1, the blind failed to show similar effects to controls but showed a left-parietal effect. In phase 2, both groups showed similar parietal effects and the blind demonstrated a left frontal effect as found in controls in phase 1. Most importantly, initially the topography of the distance effects was rather different in the two groups but later both groups showed similar expected parietal effects. It is to note that the definition of phases is mainly a convenient way of describing the data and it is somewhat arbitrary. Phase definition is based on the temporal overlap of effects at certain electrodes, the larger between-group similarity at the second burst of effects than at the first burst, and on the similar temporal relation of the second burst of effects to the reaction time in both groups (see also later). Speculatively, task-execution phases may index recurrent, increasingly refined processing of information.

In the controls, phase 1 parietal distance effects coincided with alpha and beta range ERSP decrease, and frontal effects coincided with gamma range ERSP decrease. In phase 2, the controls showed an left-parietal ERSP decrease. Interestingly, at 600 ms, the gamma range ERSP decrease at frontal sites turned into ERSP increase. This may signal a kind of “idling” of previously engaged brain areas as put forward by [12]. The blind initially showed a centro-parietal ERSP increase. At 600 ms, the blind showed an ERSP increase in the

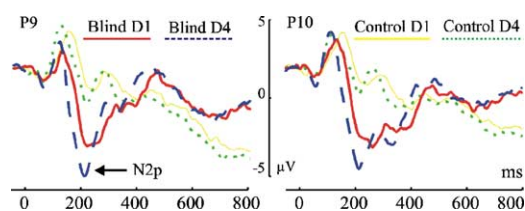


Fig. 1. Event-related potentials in the number task at parietal electrode sites for the blind and for the control subjects. The N2p component is labelled. D1 and D4 stand for numerical distance 1 and numerical distance 4, respectively.

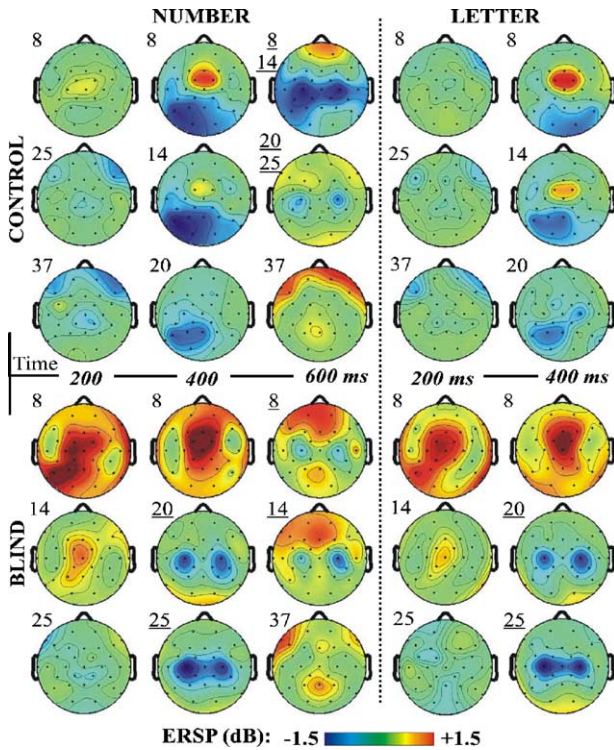


Fig. 2. The temporal course of ERSP topographies at certain frequencies. The selected frequencies are shown to the upper left of each map. Where motor effects are seen, frequencies are underlined. The mean ERSP of three consecutive time points centred on the given times were used for the maps. Mean ERSP values for all four numbers and letters are given.

gamma range over similar frontal and parietal areas as the controls. This may be a further sign of functional similarity in frontal areas in the blind and in the control group.

Between-group similarity was much more striking in the distance effect in the number task compared to the letter task (showing a different pattern of the distance effect), and in the distance effect than in the (behaviourally non-significant) magnitude effect. First, all this supports the specificity of the numerical distance effect. Second, the assessment of letter serial position was accompanied by different ERSP-effect topographies in the blind and in the controls. There may be several reasons for this. For example, the blind never explicitly encounter with a visually represented alphabet. Further, the representation of letter shape and phoneme information probably substantially differs in the blind relative to sighted subjects [1].

The temporal relation of phase 2 distance effects to the reaction time was similar in both groups. This suggests that these effects indexed a similar cognitive decision stage in both groups. In order to explore whether these stages are more related to stimulus-processing or response-organization, response-locked EEG epochs were subjected to ERSP analysis. Apart from a small effect in the controls (at P4, -200 to -50 ms; 6–12 Hz) no effect of distance similar to the stimulus-locked effects were found, suggesting that the formerly described distance effects were locked to stimulus-processing and not to response-organization (electrodes showing distance effects before the response

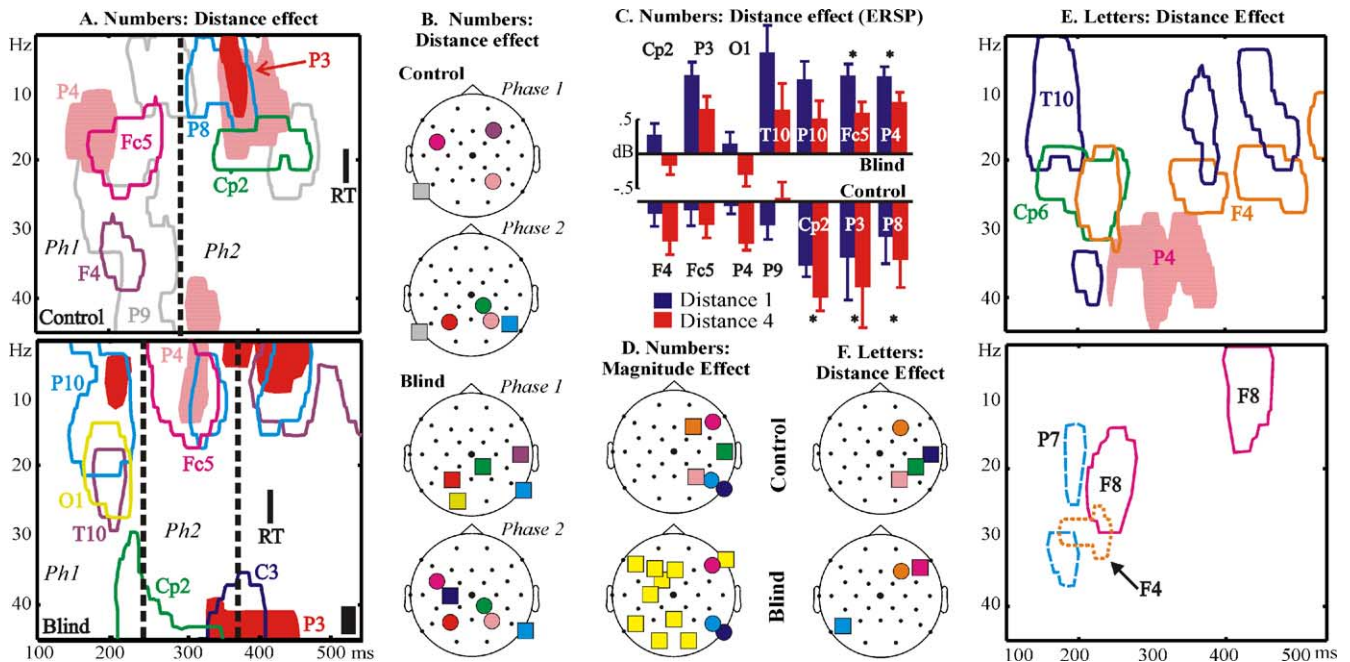


Fig. 3. Distance and magnitude effects in the ERSP landscape. (A) Contour lines mark significant distance effects at different electrodes ($p < 0.004$). Electrode names are next to the contour lines. Areas for electrodes P3 and P4 are shaded. Phase boundaries are marked by the long dashed vertical lines crossing the landscapes. Ph1 and Ph2 stand for phases 1 and 2, subsequently. Short bold vertical markers denote reaction time (RT). (B) Topography of electrode sites showing distance effects in phases 1 and 2. Circles stand for similar, squares for different effects in the blind and control groups. The black bold dot in the middle of the maps marks electrode Cz. (C) Mean ERSP and standard errors at all points showing significant distance effect in phase 1 (no marker) and in phase 2 (marker: “*”). (D) Electrode sites showing magnitude effects in the number task. (E) Distance effects in the letter task. (F) Topography of distance effects in the letter task. Contour lines mark significant distance effects ($p < 0.004$).

were F10 and T10 in the blind; and P4 and T3 in the controls).

Differences found in the overall ERSP landscape, electrodes, and in the frequency ranges demonstrating distance effects point to general and specific functional reorganization in the blind participants relative to the controls. Our results suggest that in the initial phase of number comparison, the blind participants utilized a unique compensation network. One possibility is that they may have interpreted numbers by initially translating them into somatosensory representations. However, no distance effects were found at electrodes placed over the motor cortex. Contrary to phase 1, the considerable between-group overlap at parietal electrodes exhibiting ERSP distance effects in phase 2 suggests that in phase 2, the blind used a similar parietal network to controls for representing numerical information. It is highly probable that after initial “group-specific” interpretation, the blind utilized an ancient hardwired network [4,7] for the evaluation of numerical meaning. We can conclude that first; a phenomenologically normal number representation can be developed by the blind brain; and second, that a *partially* normal number processing network can be shaped in the absence of ontogenetic visual information.

The demonstration of intact behavioural and parietal distance effects in the absence of visual input suggests that the number sense [4] has biological roots [4,7]. Recent evidence suggests that the dorsal visual pathway is activated during visuo-spatial imagery tasks in congenitally blind subjects [18]. Hence, there is a possibility that the preservation of a parietal number processing network in the blind is not number-specific, but derives instead from more domain-general genetic programming. One caveat is that our participants are not representative of the general blind population. In the latter, there may be crucial external or genetic factors hindering the development of the number sense, or other variables (e.g. IQ) may affect arithmetic skills. Further, it remains to see how similar are the neural substrates underlying more demanding arithmetic tasks other than the simple comparison used here, in the well-performing blind and normal population.

Acknowledgements

We are indebted to Usha Goswami for reviewing the manuscript. We are grateful to the enthusiastic blind participants and to Márta Temmel, Venczel Orbán and Lajosné Bors on behalf of the Hungarian School of the Blind. We thank two anonymous reviewers for their helpful comments and Fruzsina Soltész and Gabriella Baliga for their assistance. Our research was supported by grants OTKA T 049345 and T 04381.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at [doi:10.1016/j.neulet.2005.04.050](https://doi.org/10.1016/j.neulet.2005.04.050).

References

- [1] A. Amedi, N. Raz, P. Pianka, R. Malach, E. Zohary, Early visual cortex activation correlates with superior verbal memory performance in the blind, *Nat. Neurosci.* 6 (2003) 758.
- [2] F. Cochon, L. Cohen, P.F. Moortele, S. Dehaene, Differential contributions of the left and right inferior parietal lobules to number processing, *J. Cogn. Neurosci.* 11 (1999) 617.
- [3] S. Dehaene, The organization of brain activations in number comparison: event-related potentials and the additive factors method, *J. Cogn. Neurosci.* 8 (1996) 47.
- [4] S. Dehaene, *The Number Sense*, Oxford University Press, New York, 1997.
- [5] S. Dehaene, S.P. Bossini, P. Giraux, The mental representation of parity and number magnitude, *J. Exp. Psychol. Gen.* 122 (1993) 371.
- [6] S. Dehaene, J.P. Changeaux, Development of elementary numerical abilities: a neuronal model, *J. Cogn. Neurosci.* 5 (1993) 390.
- [7] S. Dehaene, E. Spelke, P. Pinel, R. Stanescu, S. Tviskin, Sources of mathematical thinking: behavioral and brain imaging evidence, *Science* 284 (1999) 970.
- [8] A.S. Delorme, S. Makeig, EEGLAB: an open source toolbox for analysis of single-trial EEG dynamics including independent component analysis, *J. Neurosci. Methods* 134 (2004) 9.
- [9] P. Gordon, Numerical cognition without words: evidence from Amazonia, *Science* 306 (2004) 496–499.
- [10] A. Jackson, The world of blind mathematicians, *Not. Am. Math. Soc.* 49 (2002) 1246.
- [11] R.T. Moyer, T. Landauer, The time required for judgements of numerical inequality, *Nature* 215 (1967) 1519–1520.
- [12] G. Pfurtscheller, F.H. Lopes da Silva, Event-related EEG/MEG synchronization and desynchronization: basic principles, *Clin. Neurophys.* 110 (1999) 1842.
- [13] P. Pinel, S. Dehaene, D. Riviere, D. LeBihan, *Neuroimage* 14 (2001) 1013.
- [14] T.J. Simon, The foundations of numerical thinking in a brain without numbers, *Trends Cogn. Sci.* 3 (1999) 363.
- [15] E. Spelke, S. Dehaene, Biological foundations of numerical thinking, *Trends Cogn. Sci.* 3 (1999) 365.
- [16] D. Szűcs, V. Csépe, Similarities and differences in the coding of numerical and alphabetical order using acoustic stimulation as revealed by event-related potentials in humans, *Neurosci. Lett.* 360 (2004) 65.
- [17] E. Temple, M.I. Posner, Brain mechanisms of quantity are similar in 5-year-old children and adults, *Proc. Natl. Acad. Sci.* 95 (1998) 7836.
- [18] A. Vanlierde, A.G. De Volder, M.C. Wanet-Defalque, C. Veraart, Occipito-parietal cortex activation during visuo-spatial imagery in early blind humans, *Neuroimage* 19 (2003) 698.
- [19] F. Xu, E.S. Spelke, Large number discrimination in 6-month-old infants, *Cognition* 74 (2000) B1–B11.