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Similarities and differences in the coding of numerical and alphabetical order using acoustic stimulation as revealed by event-related potentials in humans

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Abstract

We analyzed event-related potential (ERP) correlates of numerical and alphabetical positional judgements. Sixteen subjects classified whether acoustically presented numbers (1, 4, 6 or 9) were smaller or larger than 5 or whether phonemes (a, d, f or i) stood before or after letter 'e' in the alphabet. Stimulus non-specific effects in the amplitude of P2p and in the latency of N2f and N2p (220–255 ms) were found. In contrast, in the amplitude of the right parietal N2p and in response-locked ERPs, stimulus-specific distance effects were found. The topography of ERPs was similar in both tasks. However, stimulus-specific effects may reflect differences in the ordinal coding of numerical and alphabetical information. Similarity to former results is discussed and a possible scenario of executing magnitude comparison tasks is sketched.

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The (numerical) distance effect (DE) is the phenomenon that in number comparison tasks the reaction time (RT) is longer to numbers closer to a reference number than the RT to numbers further away from it [10]. The DE has been tested extensively and so far it has been demonstrated to be stimulus- and modality-independent. In response to stimuli of various surface formats, amplitude modulation in event-related potentials (ERPs) over parietal electrodes [2,12,14], and intraparietal fMRI activation [12] correlates of numerical distance are considered as evidence for the existence of a supramodal number representation residing in the bilateral intraparietal lobes. In a recent fMRI experiment automatic number-specific activation in the intraparietal sulcus has been shown in response to both visual and auditory stimulation [5]. Kiefer et al. [8] demonstrated an ERP numerical problem size effect over temporo-parietal electrodes in both modalities. However, to our best knowl-

edge the DE has never been tested with acoustically presented symbolic stimuli. This was one of our intentions. Furthermore, not only numbers but also letters have a highly accurate ordinal representation [7] and in comparison tasks they also show the DE [9]. In order to obtain insight into the evaluation of numerical and non-numerical ordinal positions we compared high temporal resolution ERP correlates of number and letter magnitude judgments.

Sixteen healthy high-school students participated in the experiment (mean age 22 ± 3 years; range 19–27 years). Stimuli were the spoken number words of one [egy, duration: 200 ms], four [négy, 350 ms], six [hat, 350 ms] and nine [ki-lenc, 500 ms] and the spoken Hungarian phonemes, 'a' [a, 180 ms], 'd' [de:, 300 ms], 'f' [ef, 200 ms] and 'i' [i, 160 ms], digitized at 11025 Hz. Stimuli were presented in three consecutive blocks (4×104 stimuli in each block). Stimuli were number words in Blocks 1 and 3 and phonemes in Block 2. In Blocks 1 and 3 subjects had to press a button if the presented number was smaller than 5 and another if the number was larger than 5 (number task: NT [2]). In Block 2 subjects classified phonemes as

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preceding or following the letter ‘e’ in the alphabet (letter task: LT). Response hands were counterbalanced between Blocks 1 and 3 in the NT. In Block 2 subjects responded the same way as they did in Block 1, i.e. in the LT half of the subjects responded in different ways. A similar counterbalancing of responding in the two tasks was not possible, as we had to keep the length of the experiment acceptable for the subjects. The distance of the stimuli from the referent number or letter (distance factor) was either 1 (condition CD1) or 4 (condition CD4). In order to avoid response-priming effects half of each kind of stimuli was preceded by stimuli requiring an opposite behavioral response. Twenty practice stimuli preceded each block.

We used a 32-channel electrode-cap with the following standard electrode sites according to the international 10–20 system: Fp1, Fp2, F9, F7, F3, Fz, F4, F8, F10, Fc5, Fc1, Fc2, Fc6, T9, T7, C3, Cz, C4, T8, T10, Cp5, Cp1, Cp2, Cp6, P9, P7, P3, P4, P8, P10, O1 and O2. The raw EEG was referenced to site Pz, band pass filtered between 0.15 and 70 Hz online, digitized at a sampling rate of 500 Hz and then off-line filtered between 0.3 and 30 Hz. The recorded data were recomputed to average reference and baseline-corrected relative to the –100 to 0 ms interval before stimulus onset. Ocular artifacts were monitored on electrodes Fp1, Fp2, F9 and F10. Any of the epochs where voltage exceeded $\pm 80 \mu\text{V}$ on any of the electrodes were excluded from the analysis.

In the NT a response hand \times magnitude (1–4 vs. 6–9) \times distance ANOVA was used. The RT was longer in CD1 than in CD4 ($P < 0.001$; Table 1). The DE was stronger between 1 and 4 (Tukey $P < 0.001$) than between 6 and 9 ($P = 0.025$; magnitude \times distance: $P < 0.001$). Subjects committed more errors in CD1 than in CD4 ($P < 0.001$). In the LT a magnitude \times distance ANOVA was used. The DE in RTs was significant only between a and d ($P < 0.001$) but not between f and i ($P = 0.9$; magnitude \times distance: $P < 0.001$). Subjects committed more errors in CD1 than in CD4 in the case of a–d ($P = 0.022$) but not in the case of f–i ($P = 0.9$).

The number of accepted epochs per stimuli was cc. 2850 (85–88%) in the NT and cc. 1400 (84–86%) in the LT. ERPs (Fig. 1) in the two tasks were analyzed both separately and also in a common ANOVA. A lateral parietal N1p (60–120 ms), P2p (70–200 ms) and N2p (150–300 ms) was

measured on electrodes P9, P7, P8 and P10. A frontal N2f (80–220 ms) and P2f (180–280 ms) was measured over electrodes F3, Fz and F4. Peak latencies and amplitudes (the average voltage of the peak ± 4 ms interval) shown in Table 2 were tested by (task \times) magnitude \times distance ANOVAs on each electrode.

In the NT, the latency of N1p was shorter to 1 than to 4 over electrodes P9 (69 vs. 92 ms; Tukey $P < 0.001$), P10 (67 vs. 97 ms; $P < 0.001$), P8 ($P = 0.003$) and P7 ($P = 0.01$). The latency of the P2p was shorter to 1 than to 4 ($P < 0.001$). The amplitude of the P2p was more positive in CD4 than in CD1 over P7 ($P = 0.008$) and there was a similar marginal DE over P9 ($P = 0.08$). The latency of the N2f was shorter in CD4 than in CD1 ($P < 0.003$). The amplitude of the N2f was more negative in CD4 than in CD1 ($P < 0.04$). The latency of the N2p was shorter in CD4 than in CD1 over electrodes P10 ($P = 0.003$) and P9 ($P = 0.037$). Due to the enhanced latency to ‘4’, an additional magnitude effect was found over P10 ($P = 0.031$). The amplitude of N2p was more negative in CD4 than in CD1 over electrodes P10 ($P = 0.02$) and P8 ($P = 0.045$). On these electrodes amplitudes were more negative above 5 than below 5 ($P < 0.005$).

In the LT, the latency of N1p was shorter to ‘a’ than to ‘d’ over electrodes P9 (77 vs. 93 ms; $P = 0.01$) and P7 ($P = 0.025$). The latency of the P2p was shorter to ‘a’ than to ‘d’ ($P < 0.005$). The amplitude of the P2p was more positive in CD4 than in CD1 over P7 ($P = 0.036$), P8 and P10 (both $P = 0.002$). The latency of N2f was shorter in CD4 than in CD1 ($P < 0.003$). The latency of N2p was shorter in CD4 than in CD1 over electrodes P7 ($P = 0.001$), P9 ($P = 0.005$) and P10 ($P = 0.01$). However, a magnitude \times distance interaction ($P < 0.008$) revealed a significant DE only below ‘e’ over electrodes P7 and P9. The amplitude of N2p was more negative in CD1 than in CD4 over electrodes P8 ($P = 0.007$) and P10 ($P = 0.002$) and this effect was marginal over P9 ($P = 0.065$).

In both tasks, DEs of opposite directions were detected in the amplitude of the N2p in the NT and in the LT over electrodes P8 ($P = 0.003$) and P10 ($P = 0.002$). This interaction was marginally present over P7 and P9 (both $P = 0.07$). Response-locked averages were analyzed over electrode Cz. Below 5/e there was a DE from –250 to –100 ms in both tasks (NT: $0.24 \mu\text{V}$; LT: $0.29 \mu\text{V}$; $P < 0.02$). Above 5/e the above effect was present in both tasks from –60 to 0 ms (NT: $0.85 \mu\text{V}$; LT: $0.92 \mu\text{V}$; $P < 0.01$). The direction of the effect was the opposite in the two tasks (task \times distance: $P < 0.004$).

Presenting stimuli visually Dehaene [2] found that for number words the behavioral DE was weaker between 9 and 6 than between 1 and 4. We found the same using acoustic stimulation. Dehaene plausibly attributed the difference to a word-length effect. The sequential nature of acoustic stimulation does not allow us to determine exactly when subjects had enough information to identify a given stimulus. However, all the number words and letter names

Table 1
Reaction times and percentages of correct responses

	Reaction time (ms)				Percent correct (%)			
	1/a	4/d	9/f	6/i	1/a	4/d	9/f	6/i
Number task								
Mean	565.9	666.7	599.2	635.9	99.0	97.3	98.7	97.1
SD	122.6	129.6	140.1	129.7	1.42	3.05	2.02	3.35
Letter task								
Mean	571.0	689.5	637.5	638.7	99.0	96.9	97.6	97.8
SD	131.9	144.1	134.2	136.0	1.45	3.15	2.07	2.45

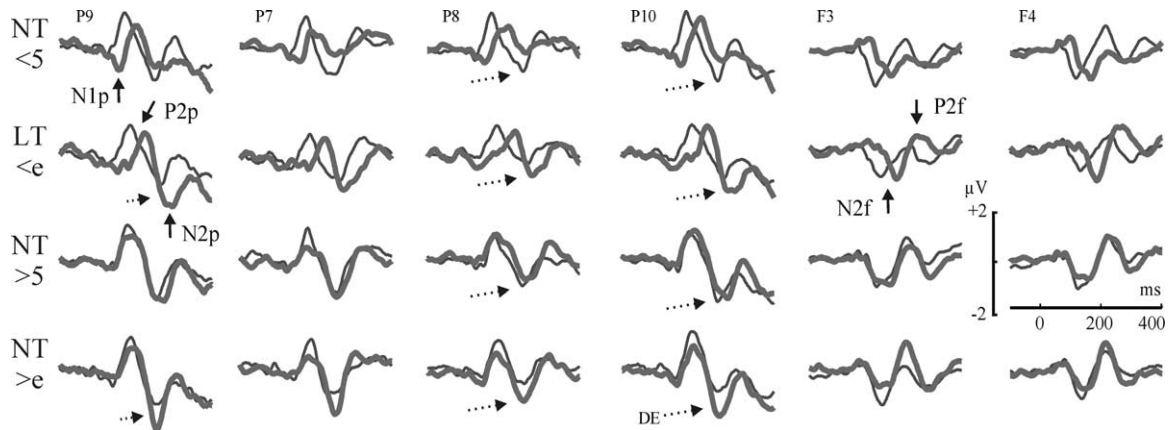


Fig. 1. ERPs in the number and letter tasks below and above 5/e. Stimulus-specific DEs are marked by dotted horizontal arrows. Marginal effects are marked by short arrows (P9). Thick lines: CD1; thin lines: CD4.

began with different phonemes that made their early identification possible. Moreover, the RT to 6 was longer than the RT to 9 and there was no difference in the latency of any of the ERP components between 6 and 9, contrary to the fact that 9 was 150 ms longer than 6. Therefore, it is more reasonable to assume that number meaning rather than word-length affected RTs and the latency of ERPs. Alternatively, a smaller DE between 6 and 9 than between 1 and 4 is in line with the hypothesis that numbers are represented by spreading activation on a compressed ‘mental number line’ [4], therefore the subjective distance between smaller numbers should be larger than between larger numbers.

DEs in ERPs were similar in the NT and in the LT. In former studies the earliest DEs were found in the transition from the parietal N1 to P2p (174 ms; 0.42 μV) over electrodes P3P/P4P [2,12,14]. Here a similar DE appeared earlier (P2p amplitude), potentially supporting our former finding [13] that acoustically presented stimuli have faster

access to magnitude information than visually presented ones. However, the visual DE was not tested in the same population here. ERPs may reflect communication processes in a fronto-parietal network involved in magnitude processing [3,11]. However, it is unknown to what extent poor spatial resolution ERPs reflect contributions from correlating non-numerical processes.

Four distinct phases of executing the comparison task were identified. First, the latency DE in the exogenous component N1p is probably a consequence of acoustic properties of ‘ne:gy’ (4) and ‘d’ relative to other stimuli, and it may accompany the identification process of letters [6] and numbers in the left and right [12] inferior parietal cortex. Second, the somewhat upside-down localization of the DE in the amplitude of P2p (NT: left; LT: right hemisphere) may reflect resource allocation: number meaning is accessed automatically whereas coding of the ordinal position of letters may need extra right-hemispheric [1] resources. Third, the latency DEs in N2f and in the right

Table 2
Peak latencies and amplitudes of ERP components in the number (1–6) and letter tasks (a–f)

		1	4	9	6	a	d	i	f
Latency									
P2p	P9	119 ± 18	144 ± 29	131 ± 15	139 ± 20	128 ± 20	136 ± 35	126 ± 23	135 ± 26
	P10	114 ± 16	152 ± 22	130 ± 15	135 ± 19	138 ± 16	143 ± 23	133 ± 18	133 ± 28
N2f	F3	126 ± 33	167 ± 17	136 ± 29	147 ± 24	140 ± 24	176 ± 25	137 ± 30	149 ± 24
	F4	135 ± 28	158 ± 26	139 ± 34	149 ± 24	143 ± 26	173 ± 34	135 ± 15	146 ± 33
N2p	P9	221 ± 23	227 ± 23	224 ± 19	237 ± 17	234 ± 18	255 ± 10	221 ± 23	225 ± 14
	P10	220 ± 15	237 ± 20	228 ± 17	242 ± 18	234 ± 21	253 ± 9	221 ± 24	229 ± 16
P2f	F3	234 ± 36	252 ± 40	237 ± 30	239 ± 26	234 ± 32	261 ± 23	235 ± 37	221 ± 13
	F4	223 ± 34	251 ± 42	226 ± 24	235 ± 22	221 ± 24	266 ± 28	235 ± 32	221 ± 25
Amplitude									
P2p	P9	2.5 ± 1.5	1.9 ± 1.9	2.5 ± 1.3	2.2 ± 1.3	2.1 ± 1.6	0.9 ± 1.8	2.4 ± 1.4	2.4 ± 1.3
	P10	2.4 ± 1.7	1.9 ± 1.4	2.0 ± 1.6	2.1 ± 1.3	1.9 ± 1.9	1.2 ± 1.3	2.7 ± 1.3	1.8 ± 1.8
N2f	F3	-2.6 ± 1.3	-1.8 ± 1.1	-2.1 ± 1.5	-2.0 ± 1.3	-2.1 ± 1.3	-1.8 ± 1.3	-2.3 ± 1.3	-1.6 ± 1.4
	F4	-2.2 ± 1.3	-2.0 ± 1.4	-2.3 ± 1.3	-1.6 ± 1.2	-1.5 ± 1.5	-1.8 ± 1.4	-1.9 ± 1.5	-1.7 ± 1.2
N2p	P9	-2.2 ± 1.9	-1.8 ± 3.1	-2.6 ± 2.2	-2.9 ± 1.7	-2.3 ± 1.7	-3.0 ± 2.5	-2.8 ± 1.5	-3.5 ± 2.7
	P10	-2.1 ± 1.9	-1.1 ± 1.6	-2.9 ± 2.2	-2.7 ± 1.7	-1.9 ± 1.8	-2.3 ± 1.3	-1.7 ± 1.5	-3.0 ± 2.1
P2f	F3	1.1 ± 1.5	0.2 ± 1.3	1.7 ± 1.7	1.1 ± 1.3	1.0 ± 1.7	1.6 ± 1.6	0.9 ± 1.6	2.0 ± 2.1
	F4	1.6 ± 1.7	0.5 ± 1.2	1.8 ± 1.7	1.6 ± 1.6	1.4 ± 2.0	2.1 ± 1.3	1.7 ± 1.5	2.0 ± 1.8

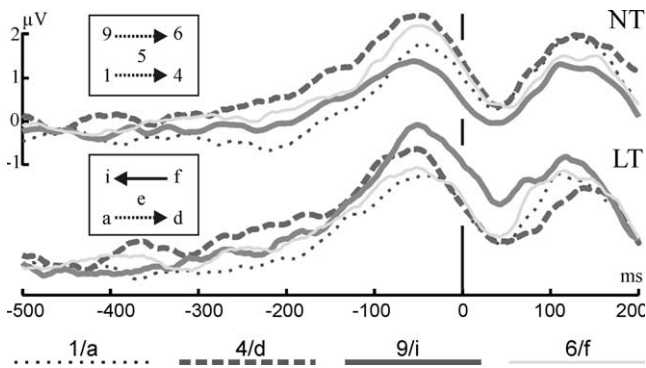


Fig. 2. Response-locked ERPs over electrode Cz. Inserts schematically represent relations between ERPs.

hemisphere N2p, both below and above 5/e, are clear correlates of non-stimulus-specific ordinal information resolution. However, the relation of the latency change to number-specific and to more general processes is not known.

Fourth, and most importantly, the stimulus-specific right parietal DE in the N2p amplitude reflects substantial differences in the encoding of the ‘magnitude’ of numbers and letters. Imaging studies show that the right hemisphere is more involved in numerical magnitude processing than the left one [1,2]. Therefore, similar magnitude representations may participate differentially in coding number and letter magnitude. Response-locked ERPs confirm categorization differences between numerical and alphabetic magnitude. The direction of the DE was the same for 1–4 and 9–6 but it was opposite between a–d and f–i (see inserts in Fig. 2). Our results support Jou et al.’s [7] conclusion that letter position judgments are not translated into an exactly equivalent numerical form.

A possible explanation for the pattern of results is that categories are resolved via automatic magnitude evaluation of numerical distance in the case of numbers, while for letters serial position is a more determining factor. Although latency DEs in the N2f and N2p show that identifying letter and number positions is based on similarly fast processes, the highly insignificant behavioral DE between f and i may mean that letter serial position is not represented by such a robust automatically elicited activation pattern, resulting in involuntary response inhibition in case of 6 relative to 9, as with that of numbers. This is further supported by a lacking letter magnitude effect in N2p, shown for numbers.

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References

- [1] 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) 617–630.
- [2] S. Dehaene, The organization of brain activations in number comparison: event-related potentials and the additive factors method, *J. Cogn. Neurosci.* 8 (1996) 47–68.
- [3] S. Dehaene, Single-neuron arithmetic, *Science* 297 (2002) 1652–1653.
- [4] S. Dehaene, G. Dehaene-Lambertz, L. Cohen, Abstract representations of numbers in the animal and human brain, *Trends Neurosci.* 21 (1998) 355–361.
- [5] E. Eger, P. Sterzer, M.O. Russ, A.L. Giraud, A. Kleinschmidt, A supramodal number representation in human intraparietal cortex, *Neuron* 37 (2003) 719–725.
- [6] J.E. Joseph, A.D. Gathers, G.A. Piper, Shared and dissociated cortical regions for object and letter processing, *Cogn. Brain Res.* 17 (2003) 56–67.
- [7] J. Jou, J.W. Aldridge, Memory representation of alphabetic position and interval information, *J. Exp. Psychol. Learn. Mem. Cogn.* 25 (1999) 680–701.
- [8] M. Kiefer, S. Dehaene, The time course of parietal activation in single-digit multiplication: evidence from event-related potentials, *Math. Cogn.* 3 (1997) 1–30.
- [9] E. Lovelace, R. Snodgrass, Decision times for alphabetic order of letter pairs, *J. Exp. Psychol.* 88 (1971) 258–264.
- [10] R.S. Moyer, T. Landauer, The time required for judgements of numerical inequality, *Nature* 215 (1967) 1519–1520.
- [11] A. Nieder, D.J. Freedman, E.K. Miller, Representation of the quantity of the visual items in the primate prefrontal cortex, *Science* 297 (2002) 1708–1711.
- [12] P. Pined, S. Dehaene, D. Riviere, D. LeBihan, Modulation of parietal activation by semantic distance in a number comparison task, *Neuroimage* 14 (2001) 1013–1026.
- [13] D. Szűcs, V. Csépe, Access to numerical information is dependent on the modality of stimulus presentation in mental addition: a combined behavioral and ERP study, *Cogn. Brain Res.* 19 (2004) 10–27.
- [14] E. Temple, M.I. Posner, Brain mechanisms of quantity are similar in 5-year-old children and adults, *Proc. Natl. Acad. Sci. USA* 95 (1998) 7836–7841.