

The Temporal Dynamic Relationship between Attention and Crowding: Electrophysiological Evidence from an Event-Related Potential Study

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Supplementary Methods

Continuous EEG data were re-referenced, filtered and segmented just the same as descriptions in the formal text. Ocular artifacts were removed using the Independent Component Analysis (ICA) (Jung et al., 2000a, 2000b). Moreover, epochs containing voltage deviation that exceeds $\pm 75 \mu\text{V}$ were also removed (Ronconi et al., 2016). On average, 1.54% of trials, ranging from 0.06% to 8.00% were rejected. No participant was excluded from the analysis.

The P1, N1, and P2 amplitudes were measured from the mean amplitude of the 40-ms window centered at the grand average ERP peak latency separately determined for each condition (Supplementary Figure 2). ERP amplitudes at the F1, F2, F3, F4, F5, F6, and Fz electrode sites were averaged as measures of the frontal cluster, and those at the O1, O2, Oz, PO7, PO8, P7, and P8 electrode sites were averaged as measures of the occipital cluster. A three-way repeated measures analysis of variance (ANOVA) was conducted on mean amplitudes of each component (P1, N1, and P2). ANOVA factors were attention (attended vs. unattended), crowding (crowded vs. uncrowded), and regions (frontal vs. occipital).

To further assess whether attention modulates crowding, difference amplitudes were obtained by subtracting the amplitudes of uncrowded ERP components from that of crowded ERP components in the attended and unattended conditions, respectively. If crowding \times attention or/and crowding \times attention \times regions interactions were significant, a two-way repeated measures ANOVA was conducted on difference amplitudes during each component stage. ANOVA factors were attention (attended vs. unattended) and regions (frontal vs. occipital). A Greenhouse-Geisser correction was used to correct for any violations of sphericity (Greenhouse and Geisser, 1959), and the partial eta squared (η_p^2) was used to estimate the ANOVA effect size (Levine and Hullett, 2002).

Supplementary Results

Behavioral results. The accuracy was computed for each participant in the crowded, uncrowded, and auditory conditions. A one-way repeated measures ANOVA performed on the accuracy revealed a significant main effect of conditions [$F(2, 34) = 26.533$, $p < 0.001$, $\eta_p^2 = 0.609$]. The accuracy was significantly lower in the crowded ($0.565 \pm 0.030 \mu\text{V}$) than in the uncrowded condition ($0.811 \pm 0.037 \mu\text{V}$) [$t(17) = -7.760$, $p < 0.001$, Cohen's $d = -1.829$], and the difference of accuracy between uncrowded and auditory ($0.807 \pm 0.054 \mu\text{V}$) conditions was not significant [$t(17) = 0.105$, $p > 0.05$, Cohen's $d = 0.025$]. The results indicated that crowding declined performance significantly; the identification of uncrowded targets had the same level of difficulty as in the auditory task.

EEG results. Supplementary Figure S1 and S2 shows ERP waveforms elicited by

crowded and uncrowded targets in both attended and unattended conditions. A repeated measures ANOVA conducted on the P1 amplitude found a significant main effect of crowding [$F(1, 17) = 5.313, p < 0.05, \eta_p^2 = 0.238$] and a significant interaction of attention \times regions [$F(1, 17) = 17.539, p < 0.01, \eta_p^2 = 0.508$]. The other main effects and interactions were not significant (p values > 0.05). Crowded targets evoked a more positive P1 component ($-0.119 \pm 0.118 \mu\text{V}$) compared with uncrowded targets ($-0.321 \pm 0.112 \mu\text{V}$). A simple effects analysis on attention \times regions interaction revealed that the difference of P1 amplitude between attended and unattended conditions was not significant over the frontal region ($p > 0.05$), whereas the P1 amplitude was more positive in the attended condition ($0.149 \pm 0.187 \mu\text{V}$) than that in the unattended condition ($-0.306 \pm 0.166 \mu\text{V}$) over the occipital region [$F(1, 17) = 18.354, p < 0.01, \eta_p^2 = 0.519$; Supplementary Figure S3A].

For N1 peak amplitude, a repeated measures ANOVA revealed significant interactions of attention \times regions [$F(1,17) = 4.728, p < 0.05, \eta_p^2 = 0.218$], crowding \times regions [$F(1,17) = 50.982, p < 0.001, \eta_p^2 = 0.750$] and crowding \times attention \times regions [$F(1,17) = 43.623, p < 0.001, \eta_p^2 = 0.720$]. The other main effects and interactions were not significant (p values > 0.05). A simple effects analysis on crowding \times attention \times regions interaction revealed that the crowded targets elicited a more negative N1 amplitude compared with the uncrowded targets in the attended [$F(1, 17) = 24.421, p < 0.001, \eta_p^2 = 0.590$] and unattended [$F(1, 17) = 12.281, p < 0.01, \eta_p^2 = 0.419$] conditions over the frontal region. The crowded targets elicited a less negative N1 amplitude compared with the uncrowded targets in the attended [$F(1, 17) = 34.114, p < 0.01, \eta_p^2 = 0.667$] and unattended [$F(1, 17) = 10.878, p < 0.01, \eta_p^2 = 0.390$] conditions over the occipital region (Supplementary Figure S3B).

A repeated measures ANOVA conducted on difference amplitude during N1 stage revealed a significant main effect of regions [$F(1, 17) = 50.982, p < 0.001, \eta_p^2 = 0.750$] and a significant interaction of attention \times regions [$F(1, 17) = 43.623, p < 0.001, \eta_p^2 = 0.720$]. The main effect of attention was not significant ($p > 0.05$). A simple effects analysis on attention \times regions interaction revealed that the difference amplitude was more negative in the attended ($-1.252 \pm 0.253 \mu\text{V}$) than in the unattended condition ($-0.494 \pm 0.141 \mu\text{V}$) over the frontal region [$F(1, 17) = 11.512, p < 0.01, \eta_p^2 = 0.404$]. Further, the difference amplitude was more positive in the attended ($1.463 \pm 0.251 \mu\text{V}$) than in the unattended condition ($0.686 \pm 0.208 \mu\text{V}$) over the occipital region [$F(1, 17) = 15.037, p < 0.01, \eta_p^2 = 0.469$].

For P2 amplitude, repeated measures ANOVA revealed a significant main effect of crowding [$F(1, 17) = 8.273, p < 0.05, \eta_p^2 = 0.327$] and significant interactions of crowding \times regions [$F(1,17) = 18.020, p < 0.01, \eta_p^2 = 0.515$] and crowding \times attention \times regions [$F(1,17) = 26.757, p < 0.001, \eta_p^2 = 0.611$]. The other main effects and interactions were not significant (p values > 0.05). A simple effects analysis on crowding \times attention \times regions interaction revealed that the crowded targets elicited less positive P2 amplitudes compared with the uncrowded targets in the attended [$F(1,17) = 19.180, p < 0.001, \eta_p^2 = 0.530$] and unattended [$F(1,17) = 14.283, p < 0.01, \eta_p^2 = 0.457$] conditions over the frontal region. Over the occipital region, the crowded

targets elicited a more positive P2 amplitude as compared with the uncrowded targets in the attended condition [$F(1,17) = 15.189, p < 0.01, \eta_p^2 = 0.472$], whereas there was no significant difference between the crowded and uncrowded targets in the unattended condition ($p > 0.05$; Supplementary Figure S3C).

A repeated measures ANOVA conducted on difference amplitude during the P2 stage revealed a significant main effect of regions [$F(1, 17) = 18.020, p < 0.01, \eta_p^2 = 0.515$] and a significant attention \times regions interaction [$F(1, 17) = 26.757, p < 0.001, \eta_p^2 = 0.611$]. The main effect of attention was not significant ($p > 0.05$). A simple effects analysis on attention \times regions interaction revealed that the difference amplitude was more negative in the attended ($-2.129 \pm 0.486 \mu\text{V}$) than in the unattended condition ($-1.041 \pm 0.275 \mu\text{V}$) over the frontal region [$F(1, 17) = 7.213, p < 0.05, \eta_p^2 = 0.298$], whereas it was more positive in the attended ($1.251 \pm 0.321 \mu\text{V}$) than in the unattended condition ($-0.135 \pm 0.279 \mu\text{V}$) over the occipital region [$F(1, 17) = 33.210, p < 0.001, \eta_p^2 = 0.661$].

Supplementary References

- Greenhouse, S. W., and Geisser, S. (1959). On methods in the analysis of profile data. *Psychometrika* 24, 95–112. doi:10.1007/BF02289823.
- Jung, T. P., Makeig, S., Humphries, C., Lee, T. W., McKeown, M. J., Iragui, V., et al. (2000a). Removing electroencephalographic artifacts by blind source separation. *Psychophysiology* 37, 163–78. doi:10.1111/1469-8986.3720163.
- Jung, T. P., Makeig, S., Westerfield, M., Townsend, J., Courchesne, E., and Sejnowski, T. J. (2000b). Removal of eye activity artifacts from visual event-related potentials in normal and clinical subjects. *Clin Neurophysiol* 111, 1745–58. doi:10.1016/S1388-2457(00)00386-2.
- Levine, T. R., and Hullett, C. R. (2002). Eta squared, partial eta squared, and misreporting of effect size in communication research. *Hum. Commun. Res.* 28, 612–625. doi: 10.1111/j.1468-2958.2002.tb00828.x.
- Ronconi, L., Bertoni, S., and Bellacosa Marotti, R. (2016). The neural origins of visual crowding as revealed by event-related potentials and oscillatory dynamics. *Cortex* 79, 87–98. doi:10.1016/j.cortex.2016.03.005.

Figure Captions

Supplementary Figure S1. Butterfly plots of grand average event-related potentials and topographies. Crowded (A) and uncrowded (B) targets in the attended condition; crowded (C) and uncrowded (D) targets in the unattended condition.

Supplementary Figure S2. The average event-related potentials for crowded and uncrowded targets in the attended and unattended conditions. The analysis windows for crowded and uncrowded conditions were marked with magenta and black rectangles respectively.

Supplementary Figure S3. Amplitude of P1 (A), N1 (B), and P2 (C) components in the attended and unattended conditions over the frontal and occipital regions. Error bars indicate standard error.