

Event-Related Potentials Recorded during Human-Computer Interaction

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Abstract - Event-related brain potentials (ERPs) elicited by a computer's response to a user's voluntary action can be used as an objective index of the user's attention and expectation in human-computer interaction. The present paper summarizes the existing data on this topic and describes the results of a new experiment. Fourteen university students performed a difficult visual discrimination task in two conditions. In the self condition, the stimuli were triggered by participants' voluntary button presses. In the auto condition, the same stimuli were presented automatically with the same interstimulus intervals as those produced in the preceding self condition. Although previous studies showed that voluntary stimulus production enhanced the P3 to perceptually deviant stimuli, P3 amplitude in the present study did not differ between the conditions. This finding suggests that voluntary eye fixation can enhance P3 amplitude even without stimulus triggering movements, and supports the notion that ERPs to self-produced stimuli can be explained in the traditional theoretical framework based on experiments in which stimuli are presented automatically. Actual and potential applications of recording ERPs in human-computer interaction are discussed.

Keywords - Attention, expectation, feedback, physiological measure, voluntary action.

INTRODUCTION

Human-computer interaction (HCI) consists of continuous cycles in which users execute a voluntary action, evaluate its outcomes, and plan the next action [1]. I have proposed that event-related brain potentials (ERPs) can be used as a physiological measure to assess this cognitive activity without changing the task structure [2].

In their applications to engineering psychology, ERPs are usually recorded from probe stimuli that are presented independent of the main task. The data are then analyzed as an indirect index of the amount of attentional resources allocated to the main task, under the assumption that the resources have a limited capacity [3]. On the other hand, task-relevant stimuli are often presented in response to users' voluntary actions in HCI. It is possible to record ERPs from these stimuli that are directly related to the main task. Despite the potential advantages, this method is not widely used. One reason is the lack of basic knowledge about the commonalities and differences between ERPs to stimuli produced by voluntary actions and ERPs to stimuli presented automatically.

Previous studies have shown that the amplitude of the P3 wave to perceptually deviant stimuli is larger when the stimuli are triggered by button presses than when the same

stimuli are presented automatically without button presses [2,4,5,6]. It is assumed that voluntary action enhances the existing ERP components that are essentially independent of action, rather than elicits a new, qualitatively different component [7]. The scalp-recorded P3 wave consists of at least two components, P3a (or novelty P3) and P3b. The P3a component has a shorter peak latency and more anterior scalp distribution than the P3b. The P3a is a part of an orienting response, whereas the P3b is related to event encoding or context updating [8,9]. The increase in the P3 wave by voluntary action is assumed to be due to the increase in the P3a component, because it occurs regardless of task relevance and appears in an earlier part of the P3 wave with a central dominant scalp distribution [2,5,6,7].

In this study, I attempted to replicate and extend the finding that the P3a component is enhanced when a high-deviant stimulus is triggered by voluntary action. To elicit the P3a and P3b components relatively independently, a difficult three-stimulus visual discrimination (oddball) task was used. When the perceptual difference between standard and target stimuli is small and the difference between standard and task-irrelevant deviant stimuli is large, the P3 to high-deviant nontarget stimuli consists mainly of the P3a component, while the P3 to low-deviant target stimuli consists mainly of the P3b component [10]. In a similar task in the auditory modality, it was found that voluntary stimulus production affected only the P3 to high-deviant nontarget stimuli [7]. The present study was conducted to examine whether this finding could be replicated in the visual modality, which is most popular in HCI.

METHOD

Participants

Fourteen right-handed students participated in the study (7 men and 7 women, 20–29 years old, mean 23.1 years). All had normal or correct-to-normal sight according to self-report. All participants signed informed consent.

Stimuli

Three types of geometric figures that were used in the difficult condition of [10] were replicated. Fig. 1 shows the stimuli in a reduced scale. They were 70 ms in duration and presented in blue on a black screen of a 17-inch cathode ray tube (refresh rate 100 Hz). The viewing distance was 1.5 m.

Procedure

Participants performed an auditory target detection task in two conditions. In the self condition, the stimuli were presented in response to participants' voluntary button

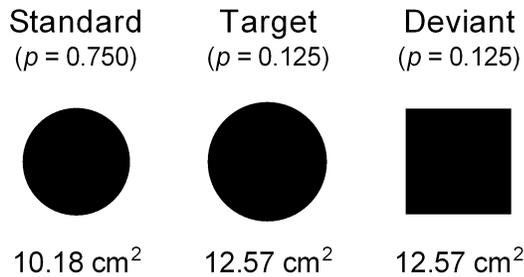


Fig. 1. Visual stimuli used in the present study. They were presented in blue on a black screen.

presses. Each button press triggered one of the three stimuli within 10 ms after microswitch closure. Participants were instructed to press the trigger button with the index finger no quicker than once per 2 s. In the auto condition, the stimuli were presented automatically by the computer at the same interstimulus intervals as those recorded in the preceding self condition. In both conditions, participants were asked to press the response button to the target stimuli with the index finger on the other hand than the triggering finger as quickly and accurately as possible. Each condition consisted of 400 trials, which were divided into 5 blocks with 80 trials each (10 target, 10 deviant, and 60 standard stimuli). Participants performed five sets of the self and auto condition blocks alternately (10 blocks in total). The triggering and responding fingers were counterbalanced across participants. Before the experimental blocks, participants received short practice blocks for voluntary button presses and for stimulus discrimination. At the end of the experiment, participants rated the difficulty of the self and auto conditions on a 9-point scale (1: easy – 9: difficult).

Electrophysiological Recording

An electroencephalogram (EEG) was recorded from three midline sites (Fz, Cz, and Pz) referenced to the linked-earlobes using sintered Ag/AgCl electrodes. An electrooculogram (EOG) was recorded bipolarly from electrodes placed above and below the left eye. The bandpass filter was set at 0.016 Hz (time constant 10 s) to 60 Hz. The data were digitized at 250 Hz and stored on a hard disk for offline processing. The epoch between 200 ms before and 800 ms after stimulus onset was averaged separately for each participant, condition, stimulus, and site. The epochs containing EEG or EOG over $\pm 100 \mu\text{V}$ were removed automatically and those containing muscle artifacts were removed by visual inspection. The first 200-ms period of each waveform served as the baseline.

Data Reduction

Trials that were too close to (< 2 s) or too remote from (> 10 s) the previous trials were excluded from the analysis (3.6 % of the total trials). Button presses occurring 200–1,200 ms after the target stimuli were regarded as correct responses. The mean reaction time was calculated for correct responses only. Button presses after the standard and deviant stimuli were counted as false alarms. Incorrect and

false alarm trials were excluded from the ERP averaging.

To cancel out the movement-related potentials associated with a trigger button press and to eliminate possible differences in the baseline period between conditions, difference waveforms were calculated by subtracting the ERPs to standard stimuli from the ERPs to target and deviant stimuli. This procedure was applied to both the self and auto conditions, which allowed comparison of the deviance-related ERPs between the conditions [6].

The peak latencies of the P3s were measured on the difference waveforms at the most dominant sites (Cz and Pz for the P3s to deviant and target stimuli, respectively). The time windows for peak detection were 300–540 ms and 348–600 ms for the P3s to deviant and target stimuli, respectively. The mean amplitude of five data points (± 8 ms) around each peak was calculated at each electrode site. The N2b, which had a less clear peak, was measured as the mean amplitude of 252–296 ms for target stimuli.

Statistical Analysis

Subjective and behavioral measures were compared between the self and auto conditions using two-tailed paired *t* tests. Amplitudes and latencies of ERP components were submitted to multivariate analyses of variance (MANOVAs) using Pillai's trace statistics. The significance level was set at 0.05. Multiple comparisons were made by the Bonferroni procedure (i.e., two-tailed paired *t* tests with a corrected comparison-wise significance level, $\alpha = 0.05/3 = 0.016$).

RESULTS

Subjective and Behavioral Measures

Mean trigger button press intervals, which were equal to the onset-to-onset stimulus intervals, ranged from 2,382 to 3,197 ms across participants (Mean 2,772 ms, SD 299). Table I shows the subjective and behavioral measures. Target stimuli were missed more frequently in the auto condition than in the self condition, $t(13) = 4.12$, $p < 0.005$. The mean

TABLE I
SUBJECTIVE AND BEHAVIORAL MEASURES AND P3 LATENCIES
IN THE SELF AND AUTO CONDITIONS

	Condition	
	Self	Auto
Difficulty rating (1: easy – 9: difficult)	6.3 (1.9)	6.7 (1.8)
Error rate (%)		
No response to target	9.4 (7.3)	17.3 (11.1) ^a
False alarm to standard	2.3 (3.6)	2.9 (4.6)
False alarm to deviant	0.1 (0.5)	0.0 (0.0)
Mean reaction time (ms)	572 (91)	544 (72)
P3 latency (ms)		
Deviant	437 (26)	440 (31)
Target	511 (47)	521 (59)

Note. Standard deviations are shown in parentheses.

^a Significant difference between the self and auto conditions, $p < 0.05$.

reaction time was slightly longer in the self condition, but the difference was not significant, $t(13) = 1.68$, $p = 0.12$. The other measures did not differ significantly between the conditions.

ERPs

Fig. 2 shows grand mean ERP waveforms. In both conditions, deviant and target stimuli elicited large P3 waves. ERP differences between the self and auto conditions started from the baseline period.

Fig. 3 shows the difference waveforms calculated by subtracting the ERPs to standard stimuli from the ERPs to deviant and target stimuli, which are assumed to be free from the effects of movement-related potentials and possible ERP differences in the baseline. The P3 to deviant stimuli was largest at the central site (Cz), whereas the P3 to target stimuli was largest at the parietal site (Pz). There were few ERP differences between the conditions, although P3 amplitude was slightly larger in the self condition.

Fig. 4 illustrates the peak amplitudes of the P3s to deviant and target stimuli. A Stimulus \times Condition \times Site MANOVA on P3 amplitude showed no significant main and interaction effects of condition, $F_s < 1.55$. The main effect of site and the interaction between stimulus and site were significant, $F_s(2, 12) = 16.23$ and 13.66 , $p_s < 0.001$. Multiple comparisons showed that the P3 to deviant stimuli had a central dominant scalp distribution ($Fz < Cz$), whereas the P3 to target stimuli had a parietal dominant distribution ($Fz < Cz < Pz$).

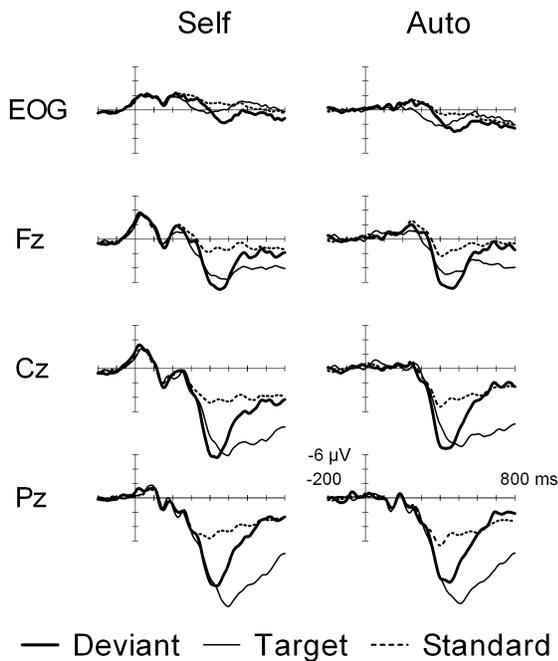


Fig. 2. Grand mean ERP waveforms in the self and auto conditions ($N = 14$). Vertical lines indicate the onset of stimuli. In the self condition, the stimuli were presented within 10 ms after the microswitch closure of the trigger button.

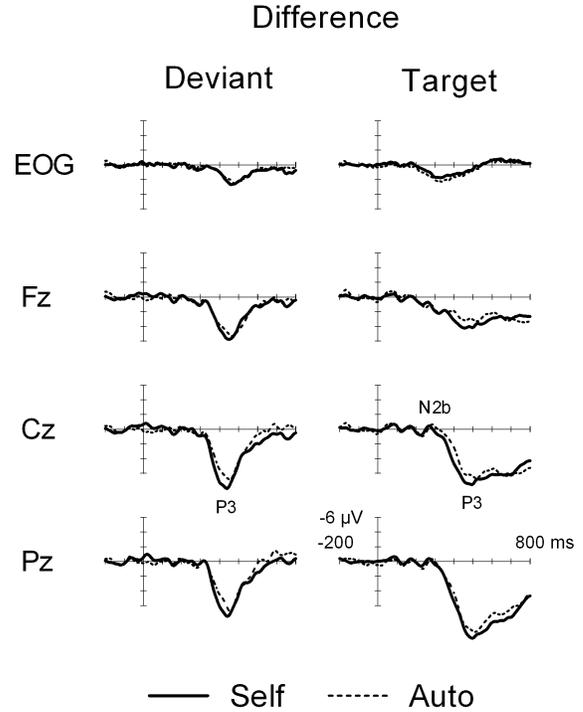


Fig. 3. Difference waveforms calculated by subtracting the ERPs to standard stimuli from the ERPs to deviant and target stimuli.

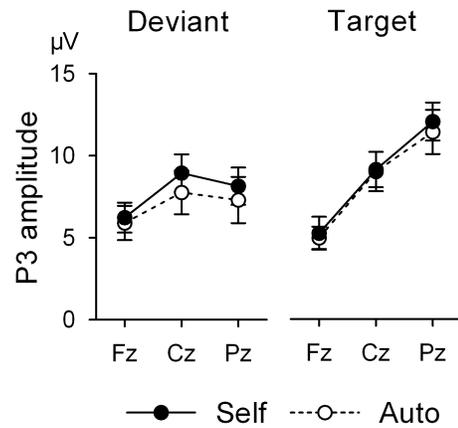


Fig. 4. P3 amplitudes for deviant and target stimuli. Vertical bars indicate standard errors.

Peak latencies of the P3s are shown in Table I. A Condition \times Stimulus MANOVA showed a significant effect of stimulus, $F(1, 13) = 50.80$, $p < 0.0001$, indicating that the P3 to deviant stimuli had a shorter peak latency than did the P3 to target stimuli. No significant main and interaction effects of condition were found, $F_s(1, 13) = 1.30$ and 0.31 , respectively.

A Condition \times Site MANOVA on N2b amplitude showed no significant main and interaction effect of condition, $F_s < 1$. The effect of site was significant, $F(2, 12) = 8.74$, $p < 0.01$. Multiple comparisons showed that the amplitude was significantly less negative at Fz than at Cz and Pz.

DISCUSSION

High-deviant nontarget stimuli elicited a P3 with a shorter peak latency and more anterior scalp distribution than the P3 to low-deviant target stimuli. These results are consistent with the assumption that the P3s elicited by the deviant and target stimuli used in the present study consist mainly of the P3a and P3b components, respectively [10]. However, voluntary stimulus production did not affect P3 amplitude significantly. This result is inconsistent with the result obtained in a similar task in the auditory modality, and does not support the hypothesis that the P3 (P3a) to perceptually deviant stimuli is enhanced by voluntary stimulus production [7].

Table II summarizes the results of the previous and present studies. The increase in P3 amplitude by voluntary stimulus production has been found not only in the auditory modality but also in the visual modality. Even in the present study, the mean amplitude value trended in the expected direction. The effect of voluntary stimulus production on the P3a is explained by a theory that holds action and perception have a common representation [11]. The frequent experience of a perceptual event after a certain action strengthens the association between action and event through associative learning mechanisms [12]. As a result, action (or action planning) comes to activate the perceptual representation of a forthcoming event that depends largely on frequent stimuli. This anticipatory activation would make a deviant stimulus more salient in the context and elicit a larger orienting response, which is reflected in a larger P3a [7].

The visual discrimination task used in this study was difficult and had long interstimulus intervals. In the auto condition, participants had to fixate intensively on the screen position where the stimuli were to be presented. This difficulty is reflected in a higher error rate and a higher (though not significantly) subjective rating in the auto condition. Such a fixation required voluntary control, which was followed by a stimulus. Although there was no causal relation between fixation and stimulus presentation, this contingency might strengthen the association between them. Consequently, the voluntary fixation might activate the perceptual representation of a forthcoming stimulus. Given that there was a covert voluntary action before stimulus presentation in the auto condition, it is plausible that the P3a component was already increased in the auto condition, so no further increase occurred in the self condition. In the auditory modality, the P3a was increased in the self condition even using an equally demanding task with equally long interstimulus intervals [7]. This is probably because no voluntary control of fixation was required in the auditory task.

The finding of the present study suggests that there are no substantial differences between ERPs elicited by stimuli presented in response to button presses and ERPs elicited by stimuli presented automatically. This idea supports the notion that ERPs elicited by a computer's response to a user's voluntary action can be explained in the traditional theoretical framework based on experiments in which stimuli are presented automatically.

TABLE II
SUMMARY OF THE INCREASE IN P3 AMPLITUDE IN THE SELF CONDITION

Stimulus modality	N	Task	Mean intervals ^a	Standard stimulus	Eliciting stimulus	Prob.	Relative amplitude % at Cz ^b	
							Self/Auto	Self/Preceding
Auditory								
McCarthy and Donchin [4]	8	Counting	3.4 – 9.8 s	1000 Hz	Target (1500 Hz)	0.100	>100 ^c	–
Nittono and Ullsperger [5]	14	RT	1.2 – 1.9 s	1000 Hz	Target (2000 Hz)	0.100	160	150
					Nontarget (novel sounds)	0.100	183	118
Nittono [6]	16	RT	1.0 – 1.6 s	1000 Hz	Target (2000 Hz)	0.250	168	–
Nittono [7]	16	RT	2.5 – 3.5 s	1940 Hz	Target (2000 Hz)	0.125	109 ^d	–
					Nontarget (500 Hz)	0.125	151	–
Visual								
Nittono et al. [2]	12	Counting	1.2 – 1.5 s	“S” ^e	Target (“H”) ^e	0.125	145	145
					Nontarget (“O”) ^e	0.125	358	199
Nittono [6]	16	RT	1.0 – 1.7 s	“O”	Target (“X”)	0.250	143	–
Present study	14	RT	2.4 – 3.2 s	Circle	Target (large circle)	0.125	101 ^d	–
					Nontarget (large square)	0.125	115 ^d	–

^a Range of the mean onset-to-onset stimulus interval produced by each participant.

^b Compared with the amplitude in the Auto condition or in the preceding condition where stimuli were presented automatically with different intervals.

^c The exact value is not available.

^d The increase was not significant.

^e The combination of the letters to stimulus categories was counterbalanced across participants.

Actual or potential applications of this method include the evaluation of a user's attention and expectation in HCI by physiological signals from the central nervous system. For example, it is known that an unexpected long delay or omission of a computer's feedback makes users frustrated and causes detectable autonomic responses in electrodermal activity and peripheral blood volume [13]. However, autonomic activity is slow to react and it takes several seconds to change. ERPs can provide a more rapid measure. Actually, I found that infrequent omission of expected stimuli after mouse clicks elicited a negative potential dominant at the right temporoparietal site about 200 ms after stimulus omission [14]. This kind of signal may be used as a sign of a gap between a user's expectation and a computer's response.

Thanks to modern biomedical engineering, ERPs can be recorded with a much shorter preparation time than ever before. High input-impedance amplifiers and digital filtering techniques enable us to record high-quality EEG without skin abrasion [15]. ERP recording during HCI is now a practicable method in real-life situations outside laboratories.

REFERENCES

- [1] D.A. Norman, "Cognitive engineering," in *User Centered System Design*, D.A. Norman and S.W. Draper, Eds. Hillsdale, NJ: Erlbaum, 1986, pp. 31-61.
- [2] H. Nittono, A. Hamada, and T. Hori, "Brain potentials after clicking a mouse: a new psychophysiological approach to human-computer interaction," *Hum. Factors*, vol. 45, no. 4, pp. 591-599, Winter 2003.
- [3] A.F. Kramer and T. Weber, 2000, "Applications of psychophysiology to human factors," in *Handbook of Psychophysiology*, 2nd ed., J.T. Cacioppo, L.G. Tassinari, and G.G. Berntson, Eds. New York: Cambridge University Press, 2000, pp. 794-814.
- [4] G. McCarthy and E. Donchin, "The effects of temporal and event uncertainty in determining the waveforms of the auditory event related potential (ERP)," *Psychophysiology*, vol. 13, no. 6, pp. 581-90, November 1976.
- [5] H. Nittono and P. Ullsperger, "Event-related potentials in a self-paced novelty oddball task," *Neuroreport*, vol. 11, no. 9, pp. 1861-1864, June 2000.
- [6] H. Nittono, "The action-perception paradigm: a new perspective in cognitive neuroscience," *Int. Congr. Ser.*, vol. 1270, pp. 26-31, August 2004.
- [7] H. Nittono, "Voluntary stimulus production enhances deviance processing in the brain," unpublished.
- [8] S. Debener, S. Makeig, A. Delorme, and A.K. Engel, "What is novel in the novelty oddball paradigm? Functional significance of the novelty P3 event-related potential as revealed by independent component analysis," *Brain Res. Cogn. Brain Res.*, vol. 22, no. 3, pp. 309-321, March 2005.
- [9] J. Dien, K.M. Spencer, and E. Donchin, "Parsing the late positive complex: mental chronometry and the ERP components that inhabit the neighborhood of the P300," *Psychophysiology*, vol. 41, no. 5, pp. 665-78, September 2004.

[10] M.D. Comerchero and J. Polich, "P3a and P3b from typical auditory and visual stimuli," *Clin. Neurophysiol.*, vol. 110, no. 1, pp. 24-30, January 1999.

[11] W. Prinz, "Perception and action planning," *Eur. J. Cogn. Psychol.*, vol. 9, no. 2, pp. 129-154, June 1997.

[12] B. Elsner and B. Hommel, "Contiguity and contingency in action-effect learning," *Psychol. Res.*, vol. 68, nos. 2-3, pp. 138-154, April 2004.

[13] J. Scheirer, R. Fernandez, J. Klein, and R.W. Picard, "Frustrating the user on purpose: a step toward building an affective computer," *Interact. Comput.*, vol. 14, no. 2, pp. 93-118, February 2002.

[14] H. Nittono, "Missing-stimulus potentials associated with a disruption of human-computer interaction," unpublished.

[15] T.C. Ferree, P. Luu, G.S. Russell, and D.M. Tucker, "Scalp electrode impedance, infection risk, and EEG data quality," *Clin. Neurophysiol.*, vol. 112, no. 3, pp. 536-544, March 2001.