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Effects of Time-on-Task on the Processing of Unexpected Action Effects

Mio Iwanaga and Hiroshi Nittono

Graduate School of Integrated Arts and Sciences, Hiroshima University, Higashi-Hiroshima 739-8521, Japan

E-mail: nittono@hiroshima-u.ac.jp

Abstract

To examine how people perceive their action effects and how they learn by experience, we recorded event-related potentials (ERPs) during a self-paced, random generation task. Sixteen participants pressed one of two buttons randomly with a self-selected regular pace once per 1–2 s. Each button press triggered either a 1000 Hz or a 2000 Hz tone. Five blocks with 160 trials each were conducted. The button–tone combination was fixed in the first block, but it became variable in the subsequent four experimental blocks. In each experimental block, the tone associated with the opposite button was presented infrequently (p = .15). Participants reported that their attention was captured by the unexpected tones only in the first block after the introduction of the mismatch trials. In contrast, ERP indices of perceptual and cognitive mismatch (N2, P300, and a late positive potential) and a behavioral index of attentional distraction (the increased button press interval after mismatched tones) did not show a significant effect of block. The discrepancy between subjective and objective measures suggest that subjective reports can be changed quickly when the users obtain the explicit knowledge of the system behavior, but that the actual effect of the mismatch between expectation and action effect may last for a longer time.

Key words: *Action effects, Action selection, Expectation, Attentional distraction*

Introduction

When users interact with an artifact, such as a computer or appliance, they select and execute an action with the intention to achieve a certain goal. During this operation, users have a certain expectation about the effect of their action. This expectation is based on the users' mental model of the system, which should be revised and updated by receiving feedback from the system. Consequently, the users can expect the behavior of the system more precisely. This learning process can be tracked by subjective reports. However, it is unclear how precisely this retrospective assessment reflects the actual process of learning.

Event-related potentials (ERPs) have been proposed to be a tool of assessing the state of attention in human–computer interaction (Nittono, 2005; Nittono, Hamada, & Hori, 2003). Unexpected events after participants' actions elicit larger ERP responses in several latency ranges. First, infrequent stimuli elicit an N2 component regardless of whether the stimuli follow participants' actions. Second, when the stimuli are produced by participants' button presses, a larger frontocentral P300 is elicited by perceptually deviant, infrequent action effects (Nittono, 2006). And third, a late positive potential (LPP) is elicited by the action effects that deviated from the expectation (Adachi, Morikawa, & Nittono, 2007).

In the present study, we examined how people perceive their action effects and how they learn by experience in a situation when action effects were mismatched with the expectation from the past experience. Unexpected action effects would capture a participant's attention, delay the execution of the next action, and elicit mismatch-related ERP components (N2, P300, and LPP). These signs of cognitive mismatch would weaken when the participant became accustomed to its occurrence.

Methods

Participants

Sixteen university students (5 men and 11 women) participated in the study (20–27 years old, M = 21.7 years old). They were right-handed except one ambidexter. All of them had normal hearing according to the standard audiometry. They gave written informed consent.

Stimuli and Procedure

Participants were asked to press one of the two buttons of a computer mouse randomly with a regular, but self-selected pace once per 1–2 s. Each button press triggered either a 1000 Hz or a 2000 Hz tone immediately within 10 ms. Both tones were 70 ms in duration (including the rise and fall times of 10 ms) and presented at about 60 dB SPL from two loudspeakers. Participants were told that the tones were irrelevant to the random generation task and that they should ignore them.

Five blocks with 160 trials each were conducted. The button–tone combination was fixed in the first block, but it became variable in the subsequent four experimental blocks (Blocks 1–4). In each experimental block, each button press produced the predetermined tone in the first 20 trials, and then, the tone that was associated with the opposite button was presented in 21 of the last 140 trials (p = .15), which we call the cognitive mismatch trials. After each block, participants rated how much attention they directed to the tones on a 9-point scale (1: not at all–9: very much).

Physiological Recording

An electroencephalogram (EEG) was recorded from 38 scalp sites using an electrode cap with Ag/AgCl electrodes. A high-pass filter of 0.016 Hz and a low-pass filter of 60 Hz were used at recording. The sampling rate was 500 Hz.

Data Reduction

As a behavioral measure of attentional distraction, we calculated the mean button press interval after either the match or mismatch trials of each block and subtracted it from the baseline interval that was defined as the mean button press interval on the first 20 trials of each block. The EEG data were re-referenced to the linked earlobes offline and a digital bandpass filter of 0.05–30 Hz was applied. ERP waveforms were obtained by averaging the 1,000-ms period, starting 200 ms before the stimulus onset. The amplitudes of the N2, P300, and LPP were measured as mean amplitudes of 200–240, 270–390, and 400–700 ms after stimulus onset, respectively. For the sake of simplicity, only the amplitude data at the most dominant site (Fz for N2, Cz for P300, and Pz for LPP) were analyzed statistically. Subjective, behavioral, and ERP data were submitted to repeated measures of analyses of variance (ANOVAs). Whenever the degree of freedom in the numerator in the ANOVAs was more than one, the Greenhouse-Geisser ε correction for the violation for the sphericity assumption was applied. Post hoc multiple comparisons were made with the Bonferroni t tests.

Results

Subjective Ratings

Figure 1 shows the subjective ratings of the attention directed to the tones after button presses. A one-way ANOVA showed a significant main effect of block, $F(4, 56) = 9.12$, $p < .01$, $\varepsilon = .60$. Post hoc comparisons suggest that the score was highest in Block 1, which was the first block after introducing cognitive mismatch trials, and that subjective feelings of attention to the tones were reduced in later blocks.

Behavioral Measures

Figure 2 shows the mean delays in the execution of the next button press after the match and mismatch trials. The data were submitted to a two-way ANOVA with factors of condition (match vs. mismatch) and block (1–4). Button press intervals were longer after the cognitive mismatch trials than after the cognitive match trials. The main effect of condition was significant, $F(1, 15) = 22.44$, $p < .01$, but neither the main effect of block nor the interaction effect was significant.

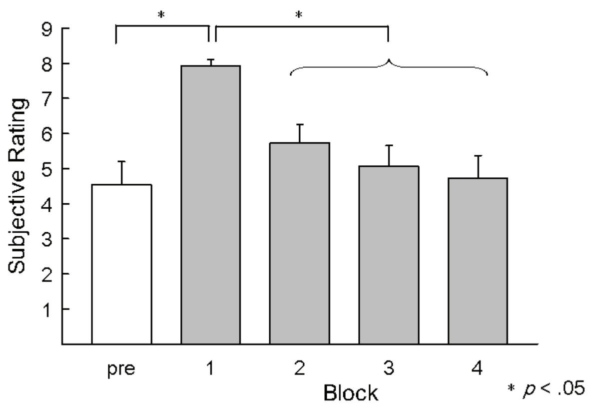

Figure 1. Means and standard errors of the subjective ratings on the attention to the action effect tones.

ERPs

Figure 3 shows the grand average ERP waveforms at three midline electrode sites. Larger ERPs were elicited in the cognitive mismatch trials than in the match trials. Figure 4 shows the topographic maps of the N2, P300, and LPP components in the cognitive mismatch trials. The N2 has a frontocentral distribution, the P300 has a central distribution, and the LPP has a parietal distribution. Figure 5 shows the temporal changes in the amplitudes of these components. The amplitudes were larger in the cognitive mismatch trials than in the match trials through the four blocks. A Condition × Block ANOVA on each amplitude measure showed a significant main effect of condition, $Fs(1, 15) = 14.74$, 12.58, and 18.83, $ps < .01$, for the N2, P300, and LPP, respectively. Neither the main effect of block nor the interaction effect was significant.

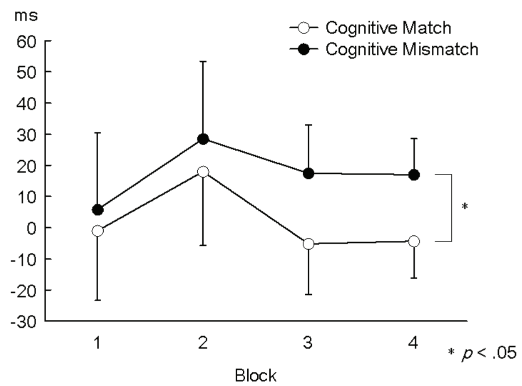

Figure 2. Means and standard errors of the delays in the subsequent action execution after the cognitive match and mismatch trials.

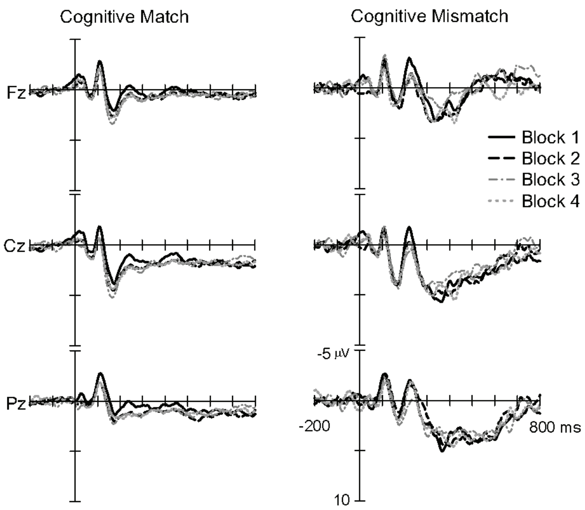

Figure 3. Grand average ERP waveforms at three midline electrode sites ($N = 16$).

Discussion

According to subjective reports, participants directed their attention to the action effect tones in the first block after introducing cognitive mismatch trials. The subjective attention to the tones then decreased in the later blocks, which suggests that participants felt that they could ignore the mismatched tones in early trials. As expected, cognitive mismatches delayed the execution of the next action and elicited a larger N2, P300, and LPP. However, there were no effects of block in either behavioral and ERP measures.

This discrepancy between subjective and objective measures suggests that subjective reports can be changed quickly when participants obtain the explicit knowledge of the system behavior, but the actual effect of the mismatch between expectation and action effect may last for a longer time. Behavioral and physiological measures are valuable in usability research because they can complement subjective measures.

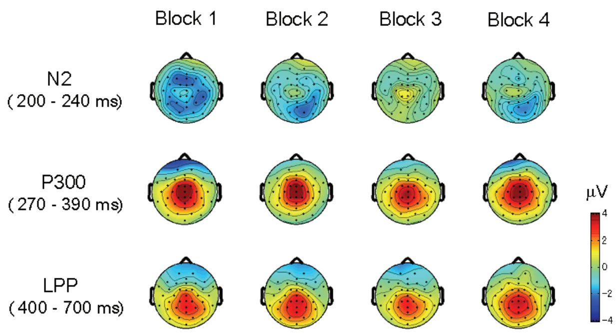

Figure 4. Topographic maps of the N2, P300 and LPP amplitudes in the cognitive mismatch trials.

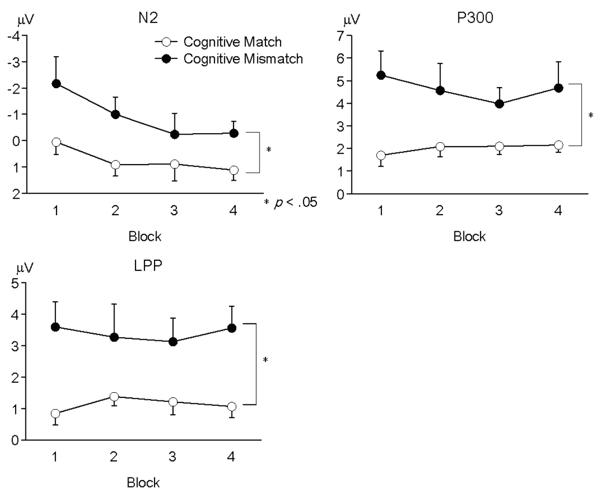

Figure 5. Temporal changes in the amplitudes of the N2 at Fz, P300 at Cz, and LPP at Pz.

Acknowledgments

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