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Voluntary action modulates the brain response to rule-violating events indexed by visual mismatch negativity

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ABSTRACT

An event-related brain potential (ERP) component called visual mismatch negativity (MMN) is automatically elicited when sequential rules inherent in a visual stimulus sequence are violated. To elucidate whether the visual MMN-generating processes are strictly determined in a bottom-up (i.e., stimulus-driven) manner, or can be modulated by top-down control, we investigated whether or not visual MMN is affected by prior information about the occurrence of rule violation derived from the participant's voluntary action. The participants were required to produce a visual stimulus sequence by pressing one button frequently (about 90%) and another button infrequently (10%) in random order; an oddball sequence consisting of repetition-rule-conforming and -violating stimuli in Experiment 1 and a more complex sequence consisting of change-rule-conforming and -violating stimuli in Experiment 2. Frequently-performed button presses triggered rule-conforming stimuli (81%), but occasionally rule-violating stimuli (9%). In contrast, infrequently-performed button presses triggered rule-violating stimuli (9%), but occasionally rule-conforming stimuli (1%). The results showed that visual MMN was elicited by rule-violating stimuli triggered by frequently-performed button presses, while it was not elicited by physically the same rule-violating stimuli triggered by infrequently-performed button presses. That is, visual MMN was strongly affected by action-based prior information about the occurrence of rule violation. This result suggests that the visual MMN-generating processes can be flexibly controlled in a top-down manner, so that rule violation that can carry significant information is selectively detected.

1. Introduction

1.1. Automatic detection of rule-violating event indexed by mismatch negativity

The external environment contains a number of sensory events. However, the brain cannot analyze all of these events in depth due to its limited capacity. An essential task for the brain is therefore to achieve the effective detection of biologically significant events, even when they are unrelated to the ongoing task. Recent event-related potential (ERP) studies have provided converging evidence that the brain is well organized to automatically detect novel or salient events that violate regular aspects of the environment.

Several ERP studies have reported that, when sequential rules inherent in a sensory stimulus sequence are violated, a negative-going ERP component called mismatch negativity (MMN; Näätänen et al., 1978) is elicited at around 100–300 ms after event onset: i.e., auditory MMN with a fronto-central scalp distribution (for reviews, see Bendixen et al., 2012; Näätänen et al., 2005; Schröger, 2007; Sussman, 2007; Winkler, 2007) and visual MMN with an occipito-temporal scalp distribution (for reviews, see Czigler, 2007; Kimura, 2012; Kimura et al., 2011; Winkler and Czigler, 2012). So far, MMN has been observed in response to repetition-rule-violating stimuli (i.e., deviant stimuli) that are occasionally inserted in a sequence of repetition-rule-conforming stimuli (i.e., standard stimuli in an oddball sequence), as well as change-rule-violating stimuli (i.e., irregular stimuli) that are occasionally inserted in a more complex sequence of change-rule-conforming stimuli (i.e., regular stimuli) (for auditory MMN, see e.g., Alain et al., 1994; Nordby et al., 1988; Paavilainen et al., 1995; Saarinen et al., 1992; for visual MMN, see e.g., Czigler et al., 2006; Kimura et al., 2012; Stefanics et al., 2011). Importantly, these findings have been obtained under experimental conditions in which the participant's ongoing task is unrelated to the stimulus sequence. Therefore, it is widely accepted that brain processes that underlie the elicitation of MMN play a critical role in the automatic detection of rule-violating sensory events.

1.2. Top-down control of MMN-generating processes

The automatic elicitation of MMN has motivated researchers to address whether the MMN-generating processes are strictly

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determined in a bottom-up (i.e., stimulus-driven) manner, or they can be modulated by top-down control; this is similar to the well-known debate of the "automatic attentional capture" (Theeuwes, 1991, 1992; Yantis and Jonides, 1984) versus "contingent attentional capture" hypothesis (Folk et al., 1992, 1994) regarding the "pop-out" phenomenon. An important finding from previous studies in this line is that MMN-generating processes are largely independent of top-down information. A key finding comes from investigations on the effects of the participant's voluntary action on auditory MMN (Nittono, 2006; Rinne et al., 2001; Waszak and Herwig, 2007). Rinne et al. (2001) required the participants to produce an auditory oddball sequence consisting of standard and deviant stimuli by pressing one button frequently and another button infrequently in random order. In one condition, frequently-performed button presses triggered standard stimuli, whereas infrequently-performed button presses triggered deviant stimuli; here, the deviant stimulus is "self-generated", so to speak, and therefore its occurrence can be known in advance. In another condition, each button press triggered a standard or deviant stimulus according to a pre-arranged order; here, the deviant stimulus is "externally-generated", and therefore its occurrence cannot be known in advance. They found that auditory MMN elicited by deviant stimuli in these two conditions did not differ in terms of amplitude, latency, or scalp topography. Nittono (2006) and Waszak and Herwig (2007) also replicated that voluntary action did not significantly influence auditory MMN. This result means that prior information about the occurrence of rule violation did not affect auditory MMN, and therefore strongly suggests that there is no direct top-down control over MMN-generating processes (for associated findings, see Pieszek et al., 2013; Ritter et al., 1999; Sussman et al., 2003).

1.3. Present study

While the effect of voluntary action on auditory MMN has been investigated, no previous study has addressed this issue in the visual domain. Visual and auditory MMN have similar sensitivities to several experimental manipulations (see e.g., Kimura et al., 2010b; Sussman and Gumenyuk, 2005; Sussman et al., 1998), which have led to the proposal that the MMN-generating processes in the auditory and visual domains would basically follow the same principle (Kimura, 2012; Kimura et al., 2011). From this standpoint, visual MMN is expected to be unaffected by voluntary action. However, considering that the MMN-generating processes in the auditory domain may operate more robustly than those in the visual domain (see e.g., Berti and Schröger, 2001; Boll and Berti, 2009), it is also possible that visual MMN is significantly affected by voluntary action, unlike auditory MMN.

To answer this question, the present study investigated the effects of voluntary action on visual MMN by applying the design developed by Rinne et al. (2001). The participants produced a visual stimulus sequence by pressing one button frequently and another button infrequently in random order; an oddball sequence consisting of standard and deviant stimuli was produced in Experiment 1 according to previous auditory studies, and a more complex sequence consisting of regular and irregular stimuli was produced in Experiment 2 (for details, see the following sections). Frequently-performed button presses triggered rule-conforming stimuli, but occasionally triggered rule-violating stimuli (i.e., externally-generated rule violation, the occurrence of which cannot be known in advance). In contrast, infrequently-performed button presses triggered rule-violating stimuli (i.e., self-generated rule violation, the occurrence of which can be known in advance), but occasionally triggered rule-conforming stimuli. If there is top-down control over visual MMN-generating processes, then visual MMN would be elicited by rule-violating stimuli triggered by frequently-performed button presses, whereas no (or at least reduced) visual MMN would be elicited by rule-violating stimuli triggered by infrequently-performed button presses. In contrast, if there is no top-down control, then visual MMN should be similarly elicited by these two types of rule-violating stimuli.

2. Experiment 1

2.1. Methods

2.1.1. Participants

Twenty-three young adults (3 women, 20 men; age range = 19–27 years, mean = 22.0 years) participated in this experiment. Twenty-one participants were right-handed and two were left-handed. All participants had normal or corrected-to-normal vision and were free of neurological or psychiatric disorders. Written informed consent was obtained from each participant after the nature of the study had been explained. The experiment was approved by the Safety and Ethics committee of the National Institute of Advanced Industrial Science and Technology (AIST).

2.1.2. Stimuli and procedure

The experiment was controlled by programs written in MATLAB (Mathworks) with the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997) installed on a computer (Apple, MacBook Pro 8,2; AMD, Radeon HD 6770M). Fig. 1 shows a schematic illustration of the stimuli and procedure. The participants' task was to produce a visual stimulus sequence on a computer display (17-inch cathode ray tube display; Sony, Trinitron Multiscan G220) by pressing the left and right buttons of a gamepad (Logitech, RumblePad 2). The participants were required to frequently press one (e.g., left) button with the forefinger of one (left) hand and infrequently press another (right) button with the forefinger of the other (right) hand. There were five constraints regarding the button press: (1) the interval between the current and preceding button press had to be within a range of 500–800 ms, (2) the percentages of frequently-performed and infrequently-performed button presses had to be about 90% and 10%, respectively, (3) an infrequently-performed button press could not be made twice (or more times) in a row, (4) the two types of button presses had to be made in random order, and (5) the two types of button presses should not be made according to a fixed sequential pattern (e.g., every tenth action was an infrequently-performed button press). Each button press triggered a visual stimulus on the display, with a constant delay interval (i.e., from button press to stimulus onset) of 50 ms.

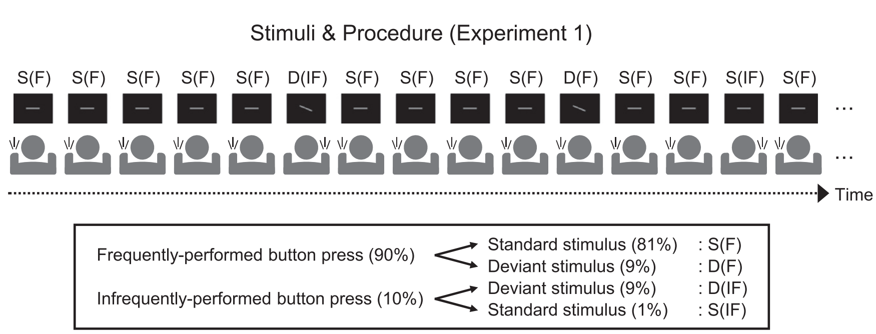

Fig. 1. Schematic illustration of the stimuli and procedure in Experiment 1. The participants produced an oddball sequence consisting of standard and deviant stimuli by pressing one button frequently and another button infrequently in random order.