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The involvement of cognitive processing in a perceptual-motor process examined with EEG time–frequency analysis

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ABSTRACT

Objective: For motor activities, visual information is crucial for organizing a movement with respect to a given situation. The present study investigates how cognitive information processing is associated with this visuomotor process.
Methods: Brain dynamics in executing two perceptual-motor tasks were examined in terms of event-related synchronization (ERS) and event-related desynchronization (ERD) of EEG. Those tasks were (1) reaching toward and grasping a visual object with a pinch grip, and (2) matching the pinch grip size with respect to the perceived object size.
Results: According to the aperture size in the task execution, both the tasks were affected by the perceived object size inducing the Ebbinghaus illusion. The alpha-ERD patterns were associated with the movement execution and appeared to be identical in both the tasks, whilst the gamma-ERS appeared only for the grasping motion.
Conclusions: These results suggest that cognitive processing was involved not only in the matching task but also in the grasping task. These ERD/ERS patterns are thought to reflect the similarity and difference in the perceptual-motor processes between the two tasks.
Significance: The analysis of ERD/ERS can provide insight on the qualitative feature in a visuomotor process associated with the involvement of cognitive processing.

1. Introduction

1.1. How cognitive information processing is associated with perceptual-motor process?

For any motor activity in our daily life, perceptual information plays an essential role in organizing the movement with respect to a given situation. Even in the simple example of reaching for a glass on a table, the configuration of a grasping aperture needs to be organized specifically with respect to the size, shape, and orientation of the glass. From a computational or information processing view (Schmidt and Lee, 1999), the cognitive process of recognizing the identity of an object to be grasped and deciding how to move toward it is central for organizing a prehensile movement. As an alternative, an ecological approach to perception and action accounts for the mechanism of movement control without ascribing it to the cognitive process (Lee, 1980; Lee and Young, 1985; Turvey and Kugler, 1984; Warren, 1990). Likewise, in the application of nonlinear dynamics to the study of human motor behaviors (Kelso, 1995; Kelso and Schoner, 1988; Saltzman and Kelso, 1987; Schoner and Kelso, 1988), the spatial and temporal characteristics of upper limb kinematics in a prehensile motion were modeled with nonlinear equations of motion, which include a perceptual variable as a parameter to modulate the dynamics of the movement (Schoner, 1994; Zaal et al., 1998). Thereby it could demonstrate the perceptual-motor organization without involving cognitive information processing. Therefore, understanding how cognitive information processing is associated with the perceptual-motor process is one of the major issues in the study of motor control. The present study addresses this issue by focusing on the perceptual-motor process in organizing a grasping movement with respect to an object.

1.2. The cortical functional systems for perception and action

It has been known that a perceptual-motor deficit due to lesions associated with the dorsal stream in the cortex induces the inability to shape the prehensile aperture for reaching and grasping an object properly but with no difficulty in visually discriminating one such object from another. On the contrary, the lesions associated with the ventral stream lead to the reverse deficit. Therefore, these findings have been regarded as evidence

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of two visual processing routes, one for visuomotor control via the dorsal stream and the other for cognitive visual processing via the ventral stream (Goodale et al., 1994). This dissociation between perception and action led to the idea that the issue of the cognitive processing account versus the ecological account for the perceptual-motor process can be ascribed to these two visual streams (Tresilian, 1995).

The studies on perception of object identity and prehensile movements to an illusory object, which induces misperception about the object identity, have also reported findings that the visual discrimination or perception of an object's size was susceptible to an illusory object, such as the Ebbinghaus figure or the Müller–Lyer figure, but the grasping aperture with respect to it was not (Aglioti et al., 1995; Haffenden and Goodale, 1998). This led to the argument that cognitive perceptual processing and motor production process can be dissociable, and they can be ascribed to the two visual streams (Goodale and Milner, 1992). However, contradictory results have also been reported in which a prehensile movement was also affected by the illusory object (Franz et al., 2000, 2001), and the ventral stream may be involved in a prehensile motion with respect to a complex object (McIntosh et al., 2004). Other studies also suggested that the dissociation is not exclusive but partial (Ellis et al., 1999); a multiple visuomotor process may be involved (Westwod et al., 2000b); and the ventral stream is also associated with the execution of prehensile movements via the supplementary motor areas (Lee and van Donkelaar, 2002). These findings suggest that some integrated function of the cortical networks for the visuomotor control needs to be considered to fully understand the mechanism of the perceptual-motor process.

1.3. The task-dependent involvement of cognitive processing in a movement execution

Given the discussion above, the present study examines the cortical activation pattern during perceptual-motor tasks in which cognitive information processing will be involved depending on task requirements. To this end, perceptual-motor tasks examined were (1) reaching out toward and grasping a visual object with an index–thumb pinch grip, and (2) assessing the size of the same visual object and indicating the estimated size by the same aperture as used to grasp the object.

For these two tasks, the involvement of cognitive process (i.e., recognizing the target object, estimating its size, and deciding the grasping aperture size with respect to the object) is thought to be different, even though both the tasks share a qualitatively similar perceptual-motor process in terms of producing the same aperture configuration based on the same visual information about the target figure. The size-estimation task is cognitive process oriented in the sense that the production of the aperture configuration requires explicit identification of the size of the figure and the particular aperture size needs to be associated arbitrarily with respect to the particular perceived size of the figure (Ranganathan and Carlton, 2007). On the contrary, producing the aperture in the grasping task is more natural and task goal oriented in the sense that the joint motion is organized so as to grasp the figure as the hand reaches it. Therefore, it may not necessarily involve a cognitive process, such as the object identification and the arbitral figure-aperture size association.

From the above perspective, the perception of the target figure and the action with respect to it are mutually dependent in the grasping task, whilst those in the size-estimation task are uncoupled and mediated via the cognitive process. Such qualitative differences in the process of the task execution should be reflected in the pattern of cortical activity. If distinctive activation patterns between the two task performances are observed, it may be attributed to the difference in the perceptual-motor process associated with the involvement of cognitive processing. Conversely, if there is no difference in the cortical activity patterns between the two task conditions, some qualitative similarity in the cortical process between the different task executions needs to be considered. Such a result may imply that the functionally different cortical processes may not be exclusive but achieved by some integrated cortical network that may potentially involve the two visual streams.

For this investigation, it is also necessary to assess the effect of the perception of the target object size on the task execution. To this end, two task movements were produced with respect to a neutral object and an object inducing a size illusion. If the illusion effect is observed in the produced aperture configuration, it would indicate that cognitive processing is involved in the task execution. Thereby, it is possible to interpret the observed cortical activity in terms of the association between cognitive processing and movement execution.

1.4. Examination of the brain dynamics related to task execution

The cortical activity was investigated using EEG with which the change in the EEG frequency power spectrum that is time-locked to the stimulus event was analyzed (for review Pfurtscheller and Lopes da Silva, 1999a). This quantifies the degree to which the amplitude of a particular frequency band of ongoing EEG attenuates or enhances in response to a stimulus event, which is termed event-related desynchronization (ERD) or event-related synchronization (ERS), respectively. ERD is regarded as representing an activated cortical state with which the processing of sensory, motor, or cognitive information is enhanced and the excitability of cortical neurons is increased (Pfurtscheller, 2001; Steriade et al., 1991). Whilst ERS has been regarded as reflecting a deactivated cortical state with reduced information processing or none at all and decreased cortical excitability (Neuper and Pfurtscheller, 2001; Pfurtscheller, 1992), the inhibitory activity of ERS can play a functional role to accentuate a task-related information processing by inhibiting other cortical areas and/or to deactivate some cortical network depending on a task context/situation (Neuper and Pfurtscheller, 2001; Suffczynski et al., 1999). Using this technique has revealed the EEG time–frequency characteristics of cortical activities for executing different perceptual, motor, and cognitive tasks (e.g., Aranibar and Pfurtscheller, 1978; Pfurtscheller, 2001; Pfurtscheller and Aranibar, 1980; Pocock, 1980; van Winsum et al., 1984). This technique has been further generalized to examine broadband EEG frequency spectra as a function of time relative to a stimulus event, and is termed the event-related spectral perturbation (ERSP: Makeig, 1993). Thereby, more information on brain dynamics that involve spectral changes in more than one frequency or frequency band can be made available than with the narrow-banded analysis of ERD/ERS. The present study examines the ERSP during the task performances, thereby attempting to capture the brain dynamics characteristic to the task execution.

2. Methods

2.1. Participants

Ten healthy right-handed (as assessed by the Edinburgh inventory (Oldfield, 1971)) participants volunteered for the experiment (seven males and three females with an average age of 29 ± 6.7 years). All procedures were approved by an Ethics Committee. After the experimenter explained the purpose and procedure of the experiment, each participant signed an informed consent form.