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Context and hand posture modulate the neural dynamics of tool–object perception

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ABSTRACT

Prior research has linked visual perception of tools with plausible motor strategies. Thus, observing a tool activates the putative action-stream, including the left posterior parietal cortex. Observing a hand functionally grasping a tool involves the inferior frontal cortex. However, tool-use movements are performed in a contextual and grasp specific manner, rather than relative isolation. Our prior behavioral data has demonstrated that the context of tool-use (by pairing the tool with different objects) and varying hand grasp postures of the tool can interact to modulate subjects' reaction times while evaluating tool-object content. Specifically, perceptual judgment was delayed in the evaluation of functional tool-object pairings (Correct context) when the tool was non-functionally (Manipulative) grasped. Here, we hypothesized that this behavioral interference seen with the Manipulative posture would be due to increased and extended left parietofrontal activity possibly underlying motor simulations when resolving action conflict due to this particular grasp at time scales relevant to the behavioral data. Further, we hypothesized that this neural effect will be restricted to the Correct tool-object context wherein action affordances are at a maximum.

64-channel electroencephalography (EEG) was recorded from 16 right-handed subjects while viewing images depicting three classes of tool–object contexts: functionally Correct (e.g. coffee pot–coffee mug), functionally Incorrect (e.g. coffee pot–marker) and Spatial (coffee pot–milk). The Spatial context pairs a tool and object that would not functionally match, but may commonly appear in the same scene. These three contexts were modified by hand interaction: No Hand, Static Hand near the tool, Functional Hand posture and Manipulative Hand posture. The Manipulative posture is convenient for relocating a tool but does not afford a functional engagement of the tool on the target object. Subjects were instructed to visually assess whether the pictures displayed correct tool-object associations. EEG data was analyzed in time–voltage and time–frequency domains. Overall, Static Hand, Functional and Manipulative postures cause early activation (100–400 ms post image onset) of parietofrontal areas, to varying intensity in each context, when compared to the No Hand control condition. However, when context is Correct, only the Manipulative Posture significantly induces extended neural responses, predominantly over right parietal and right frontal areas [400–600 ms post image onset]. Significant power increase was observed in the theta band [4–8 Hz] over the right frontal area, [0–500 ms]. In addition, when context is Spatial, Manipulative posture alone significantly induces extended neural responses, over bilateral parietofrontal and left motor areas [400–600 ms]. Significant power decrease occurred primarily in beta bands [12–16, 20–25 Hz] over the aforementioned brain areas [400–600 ms].

Here, we demonstrate that the neural processing of tool-object perception is sensitive to several factors. While both Functional and Manipulative postures in Correct context engage predominantly an early left parietofrontal circuit, the Manipulative posture alone extends the neural response and transitions to a late right parietofrontal network. This suggests engagement of a right neural system to evaluate action affordances when hand posture does not support action (Manipulative). Additionally, when tool-use context is ambiguous (Spatial context), there is increased bilateral parietofrontal

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activation and, extended neural response for the Manipulative posture. These results point to the existence of other networks evaluating tool-object associations when motoric affordances are not readily apparent and underlie corresponding delayed perceptual judgment in our prior behavioral data wherein Manipulative postures had exclusively interfered in judging tool-object content.

1. Introduction

Research has well shown that tool knowledge is a part of our neural architecture. Previous work has identified class-specific mechanisms of object recognition in the brain (Weisberg, van Turennout, & Martin, 2007), and it is known that viewing tools activates inferior regions of the left intraparietal sulcus and ventral premotor cortex (Chao, Weisberg, & Martin, 2002). Extensive tool-specific activation is also commonly seen at diffuse temporal regions (Beauchamp & Martin, 2007). Although commonly active in response to tool stimuli, there does appear to be specialization in the type of information processed at these regions. Posterior parietal and premotor activation in response to tools may be specialized to convey information related to the motor affordance of a tool rather than simply its identity (Jeannerod, Arbib, Rizzolatti, & Sakata, 1995; Johnson-Frey, 2004). Posterior and inferior temporal activation, however, seems to be of particular importance in tool identification rather than understanding motoric qualities (Martin, 2007). As such, specialized mechanisms seem to link the identification of manipulable objects with information about the actions associated with their use throughout distributed brain areas, an idea that is well supported by previous literature (Grezes & Decety, 2002; Mahon et al., 2007).

However, tool-use movements are often not performed in isolation, but are reliant on specific context-use and grasp-use knowledge. Previous neuroimaging studies have shed light on the neural substrates underlying perceptual judgment of contextual relationships between tools and objects (Mizelle & Wheaton, 2010b, 2010c). However, little is known on how the combination of tool-grasp and tool-use contexts is neurally encoded. For example, to eat soup out of a bowl, we must be able to recognize the advantage of using a spoon with the cup instead of a key (context-use), and further understand that the spoon is to be grasped by the stem rather than the bowl (grasp-use). Such knowledge may be formed by our prior experiences with these tools, allowing for the differentiation of utility (spoon versus key for use with the soup bowl) and proper grasp (stem versus bowl). In this case, tool-use must involve understanding not only proper tool–object interactions, but also proper grasping postures to use tools (Jacquet, Chambon, Borghi, & Tessari, 2012). For the purposes of this work, we define a "tool" as an object used by an actor to act on something, which in this case is an "object". Further, we can interact with tools using different basic postures. "Functional" grasp identifies a grasp for the purposes of using the tool, while "Manipulative" grasp is not convenient for engaging in functional use but may be convenient for other actions, such as relocating the tool. For a similar distinction, we point to Bub, Masson, and Cree (2008), Costantini, Ambrosini, Scorolli, and Borghi (2011), Pellicano, Iani, Borghi, Rubichi, and Nicoletti (2010).

We extended our conceptual relationships findings of previous studies (Mizelle & Wheaton, 2010b, 2010c) with a behavioral paradigm focusing on interference of grasp postures on judgment. The behavioral paradigm (Borghi, Flumini, Natraj, & Wheaton, 2012) revealed that perceptual judgment of tool-use is affected by the context of tool-object relationships and the hand posture of the tool grasp. We had focused on three levels of tool object relationships: Correct (e.g., coffee pot–coffee cup), Incorrect (e.g., coffee pot–marker) and Spatial (e.g., coffee pot–milk). The Spatial context was based on two items that are commonly together, but do not work together to create a tool–object action. These three levels were then modified based on hand interaction: No Hand, Static Hand (at the bottom of the picture roughly equidistant from tool and object), Functional posture of hand, and Manipulative posture of the hand. Specifically, we found that Manipulative postures elongated the decision process of judging if tool–object relationships were correct, compared to other hand postures (Functional, Static Hand or No Hand). Importantly, this effect was most pronounced when the tool-object context was Correct. The Spatial tool-object context always elicited the longest judgment times and within this context, the Manipulative and Functional postures were slower than No Hand, with the Manipulative posture eliciting the longest judgment times. Thus, Manipulative postures exclusively interfered with the decision about tool–object usage. Our goal in this current study was to identify the neural architecture underlying the results from the behavioral study, notably assessing parietofrontal circuit activity (with electroencephalography, EEG) at time scales relevant to the behavioral data.

Our overall hypothesis was that the behavioral interference seen with the Manipulative posture would be due to increased and extended event related potential activity over left parieto-frontal areas known to be involved in tool-use knowledge and action encoding (Chao & Martin, 2000; Johnson-Frey, Newman-Norlund, & Grafton, 2005; Johnson-Frey, 2004; Kroliczak & Frey, 2009). This may relate to underlying motor simulations to resolve tool–object action interfered by the Manipulative grasp. Further, we hypothesized that the increased parietofrontal activation would be limited to the Correct context wherein action affordances are at a maximum. Other contexts (Incorrect and Spatial) serve to evaluate if hand postures affect action encoding over left parietofrontal areas when the tools and objects do not afford mutual action themselves. Specifically, we hypothesized that unique to the Correct context, (a) Manipulative postures would uniquely evoke stronger left parieto-frontal-motor activation compared to the No Hand condition with corresponding beta band spectral differences indicating motoric processing of the stimulus (Mizelle, Tang, Pirouz, & Wheaton, 2011; Van Elk, Van Schie, Van Den Heuvel, & Bekkering, 2010; Wheaton, Nolte, Bohlhalter, Fridman, & Hallett, 2005) and (b) Manipulative posture activations would be prolonged relative to the comparisons of No Hand versus Static Hand, or No Hand versus Functional posture, with the latter two showing differences earlier in time indicative of more rapid processing to tool-use. Our previous work suggests this prolonged response may be due to an interference effect of the Manipulative posture (Borghi, et al., 2012), possibly underlying action decoding.

2. Materials and methods

2.1. Subjects

Sixteen (16) right-handed adult subjects (8 male, mean age, 21.2; SD, 1.3) were recruited for this research study. The experimental protocol was approved by the Institutional Review Board at Georgia Institute of Technology and each subject provided their written informed consent before the start of the experimental