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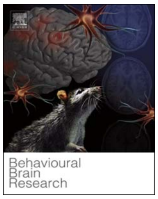

Research report

Bilateral dorsal fronto-parietal areas are associated with integration of visual motion information and timed motor action

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ABSTRACT

Interaction with the environment often involves situations requiring visuomotor integration. For instance, in fast interceptive actions, the brain must integrate visual information of motion with the appropriate motor action. In such dynamic situation, the brain may control movement based on predictions of where the object will be in the future and when it will arrive there. Although previous studies have analyzed brain regions associated with processing visual information of motion, motor control and visuomotor integration with static objects, less is known about visuomotor integration with moving objects. In the present study we used an event-related fMRI experiment to investigate brain areas integrating visual information of motion with motor action in response to moving objects. Twenty healthy volunteers performed an interceptive task where they had to press a button in synchrony with the arrival of a horizontally moving target at a predefined location. They also performed two control tasks—simple reaction and attention to visual motion—in order to identify and exclude brain areas that would be involved in motor or visual motion processing components that are inherent to interceptive tasks. Through a conjunction analysis, we show greater BOLD signal in a bilateral dorsal fronto-parietal network, as well as the intraparietal sulcus, angular gyrus, and human visual motion area hV5+. We discuss these results with respect to their previously identified functions, and suggest they play a role in visuomotor integration with moving objects.

1. Introduction

Interaction with the environment often involves situations requiring visuomotor integration. For instance, to reach for and grasp a cup of coffee, the brain transforms the visual information of the position of the cup into appropriate motor commands [1,2]. Visuomotor integration is even more complicated when we interact with the environment in dynamic situations. We also have to estimate an objects changing position over time, such as catching a flying ball coming towards us, or avoiding to be hit by a car while crossing the street. Many studies have investigated possible optical variables involved in visuomotor integration (see [3,4], for reviews) and the neural basis for the integration of static visual information with reaching and grasping movements (see [5,2], for reviews). However, less attention has been given to the neural underpinnings of the integration of visual information and motor actions in dynamic scenarios.

Dynamic situations with high temporal constraints, such as fast interceptive actions, may be controlled using predictions of where the object will be in the future and *when* it will arrive there [6–8,4]. The building blocks for estimating when an object will be intercepted, such as distance between two objects, velocity and direction of motion, have been thoroughly investigated in primates and humans [9–11]. Only few neuroimaging studies have tried to understand how and in which areas of the brain these elements are integrated to perform temporal prediction of moving objects. For instance, Indovina and collegues [12] have shown that a network comprising bilateral fronto-parietal areas is associated with intercepting moving targets (see also [13–15]). However, these studies fail to precisely identify which regions are associated with visuomotor integration per se because control conditions lack either similar low-level visual or motor information, such as same motor output or visual stimuli [14], or high-level attentional aspects of the task [12,13], such as attending target motion. Another issue is the lack of spatial specificity of the recording method (MEG: [15]). In contrast to interceptive tasks, temporal estimation in perceptual tasks involve a left lateralized network comprising the supramarginal gyrus and the ventral premotor cortex [16–19]. Therefore, it remains to be shown whether the central nervous system relies on a bilateral or left lateralized fronto-parietal network to integrate temporal information extracted from

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target motion in an interceptive task.

In the present study we sought to identify which brain regions are associated with integrating visual information of a moving target and a timed motor action in a coincident anticipation task using fMRI. Coincident anticipation tasks are a class of interceptive actions in which the participant presses a button in synchrony with the arrival of the target at a predetermined position [20]. We hypothesized that the supramarginal gyrus and ventral premotor cortex on the left hemisphere would be associated with this type of visuomotor integration task because it was previously associated with temporal prediction in perceptual tasks [17,18]. We also hypothesized that the borders of the intraparietal sulcus would be involved in the visuomotor integration given that it has been previously associated with visuomotor integration with static visual information [1,2] and given that it has connections with premotor cortex [21–23]. In order to control for low-level—general motor or visual motion processes—and high-level—motor preparation and attention to visual motion—activations, we compared the activation in the coincident anticipation task to reaction time and attention to visual motion conditions. Whenever our initial hypotheses were not met, we explored possible explanations for activity in other brain areas. The comparison of these conditions showed a bilateral dorsal fronto-parietal network, as well as activity in the ascending limb of the inferior temporal sulcus (hV5+ complex; [24,25]) and the angular gyrus.

2. Materials and methods

2.1. Participants

Twenty young healthy adults participated in our study (7 female; 26.1 ± 5.07 years old, mean ± standard deviation). All participants were right handed as assessed by the Edinburgh inventory [26], had normal or corrected to normal vision, and no history of neurological disease prior to this study. All participants provided consent by signing a form approved by the Ethical Committee of the Faculdade de Medicina da Universidade de São Paulo according to the Declaration of Helsinki.

2.2. Experimental design and procedures

Participants practiced the experimental task before entering in the scanner for 6 min. They sat in a room with one of the researchers (R.M.A.N) and practiced the task in a 13-inches MacBook Pro laptop (Mac OS X 10.10) and custom made response box connected to the USB port. Irrespective of the experimental condition, participants saw two black vertical bars (0.33° width; 3.5° height) separated by 10° of visual angle, and one black dot (0.33° diameter) positioned at the middle of the screen throughout the entire experiment. During the training period, participants were instructed to fixate their gaze at a dot in the center of the screen for the entire run. One researcher (R.M.A.N.) visually inspected whether participants were not moving their eyes during practice, and if they did move, the researcher repeated the instructions. Participants were able to follow these instructions before entering the scanner.

In order to investigate which areas of the brain are associated with the integration of visual motion and timed motor action, we conducted an event-related fMRI experiment with three conditions: Intercept, Observe and React (Fig. 1). Before each trial began, participants saw a word with the name of the condition that would be performed next. This instruction was shown just above the fixation dot for 500 ms. In the Intercept condition, as soon as the trial began, a red square target (0.33° width) appeared on the screen right beside one of the vertical bars, and started to move towards the opposite bar. Participants were instructed to press a button with their right thumb at the exact moment the target would hit the opposite bar at the end of its trajectory (Fig. 1). The time-to-contact from one bar to the other varied between 0.5 s and 1.7 s, with increments of 0.3 s. In the Observe condition, participants were required to pay attention to the displacement of the target, without producing any motor response. Time-to-contact in the Observe and Intercept conditions were the same. In the React condition, participants were required to press a button with their right thumb as fast as possible after they perceived that the fixation dot had transformed into a hollow black ring. The transformation of the fixation dot could occur after intervals between 0.5 and 1.7 s, with increments of 0.3 s, after the warning cue disappeared.

Both time-to-contact and time to fixation dot transformation were randomized according to a uniform distribution with the hard constraint that two trials in a row could not be the same. The direction of motion in the Intercept and Observe conditions were randomized across trials. Participants performed 40 trials in each condition. The three conditions were randomized across the run using a script based on the Genetic Algorithm [27]. Trials were separated by inter-trial intervals between 2.3 s and 5 s (increments of 0.3 s). Participants did not receive any feedback about their performance throughout the experiment. The run took 12 min and 12 s to be completed. Participants saw the stimuli projected in a screen positioned in front of the scanner by means of a mirror system (Projector DELL, 60 Hz, 1024 × 768 resolution). Behavioral data were collected by means of an MR compatible custom-made button box (1000 Hz frequency of acquisition). Experimental stimuli, behavioral acquisition and synchronization with the MRI scanner were made using Psychophysics toolbox 3 [28,29] in MATLAB® (version 7.13.0, MathWorks).

2.3. fMRI acquisition

Data were acquired using a 3-T Philips (Achieva, Philips Medical Systems, The Netherlands) using a 32-channel coil. Images were acquired using echo-planar T2*-weighted imaging, with an ascending sequence covering the whole brain, with a voxel size of 3 × 3 x 3 mm (TR = 2000 ms, TE = 30 ms, flip angle = 90°, FOV = 240 mm, slice thickness of 3 mm aligned with the anterior and posterior commissures, between slice gap of 0.3 mm, matrix = 80 × 80). One run consisted of 366 volumes and each volume acquired with 40 slices. The first five volumes were collected in the absence of any task to allow for signal stabilization and were excluded from additional processing and analysis.

2.4. Behavioral data analysis

We recorded subjects' responses to the tasks using an MRI compatible button-press system (Zurc & Zurc, Brazil). Variables measured included temporal error (Intercept condition), reaction time (React condition) and error percentage in all three conditions. These measures were processed using custom made scripts in MATLAB® (Mathworks, version 7.13.0), and further statistical analysis were performed using R (version 2.15.2). Temporal error is the difference between the moment the target hits the vertical bar and the moment participants press the button. This measure indicates the temporal bias of the participants. Negative values indicate anticipation and positive values indicate they were late. Reaction time is the difference of time between the moment participants press the button and the moment the fixation dot transforms into a ring. We considered as errors in the Intercept condition if participants pressed the button more than 500 ms before or after the target hit the vertical bar. In the React condition, we considered as an error if participants pressed the button before the fixation dot transformed into a ring or if they did not press the button 500 ms after the ring was presented. In the Observe condition, we considered as an error if participants pressed the button. In addition, we also considered as errors when the button box system failed to register a response in the Intercept and React conditions. In order to evaluate if participants were using different strategies in the Intercept and React conditions, we performed a Wilcoxon signed rank test comparing temporal error and