NeuroImage 48 (2009) 696–706

Contents lists available at ScienceDirect

NeuroImage

journal homepage: www.elsevier.com/locate/ynimg

FMRI adaptation during performance of learned arbitrary visuomotor conditional associations

Philippe A. Chouinard *, Melvyn A. Goodale

CIHR Group on Action and Perception, Department of Psychology, University of Western Ontario, 1151 Richmond Street, London, Ontario, Canada N6A 5B8

ARTICLE INFO

Article history:
Received 1 April 2009
Revised 8 July 2009
Accepted 9 July 2009
Available online 18 July 2009

Keywords:
Arbitrary visuomotor conditional associations
Functional magnetic-resonance imaging
Adaptation
Dorsal premotor cortex
Object perception
Response selection

ABSTRACT

In everyday life, people select motor responses according to arbitrary rules. For example, our movements while driving a car can be instructed by color cues that we see on traffic lights. These stimuli do not spatially relate to the actions that they specify. Associations between these stimuli and actions are called arbitrary visuomotor conditional associations. Earlier fMRI studies have tried to dissociate the sensory and motor components of these associations by introducing delays between the presentation of arbitrary cues and go-signals that instructed participants to perform actions. This approach, however, also introduces neural processes that are not necessarily related to the normal real-time production of arbitrary visuomotor responses, such as working memory and the suppression of motor responses. We used fMRI adaptation as an alternative approach to dissociate sensory and motor components. We found that visual areas in the occipital–temporal cortex adapted only to the presentation of arbitrary visual cues whereas a number of sensorimotor areas adapted only to the production of response. Visual areas in the occipital–temporal cortex do not have any known connections with parts of the brain that can control hand musculature. Therefore, it is conceivable that the brain areas that we report as having adapted to both stimulus presentation and response production (namely, the dorsal premotor area, the supplementary motor area, the cingulate, the anterior intra-parietal sulcus area, and the thalamus) are involved in the multiple steps between processing visual stimuli and activating the motor commands that these cues specify.

Introduction

The brain transforms sensory input into motor output. In the case of grasping visually-presented objects, people pre-shape their hand to match their three-dimensional structure. This behavior requires a standard visuomotor transformation from the object's geometrical properties to the motor commands acting on the muscles of the hand. According to Goodale and Milner's (1992) two-stream hypothesis, standard visuomotor transformations such as these take place in the dorsal stream of visual processing. But there are many examples of behavior in which people select motor responses according to arbitrary rules rather than on the basis of geometrical properties of objects. For example, our movements while driving a car can be instructed by color cues that we see on traffic lights (e.g. stepping on the breaks after seeing a red light). These stimuli do not spatially relate to the actions that they specify. Such associations are sometimes called arbitrary visuomotor conditional associations and are thought to involve neural processes that differ from the ones that are used in standard visuomotor transformations (Wise and Murray, 2000; Wise et al., 1996).

Although functional neuroimaging studies have identified a number of brain areas that are invoked during arbitrary visuomotor conditional associations (for review, see Chouinard and Paus, 2006), it is still unclear as to which part of this network processes the stimuli, which part transforms the sensory information into the appropriate action, and which part generates the required motor response. To address this issue, Toni et al. (1999, 2002a) used event-related functional magnetic-resonance imaging (fMRI) to dissociate the sensory and motor components of these associations by introducing a delay between the presentation of arbitrary cues and the go-signals that instructed participants to perform actions that the cues specified. There is, however, an important limitation in this approach. The introduction of delays also introduces neural processes that are not necessarily related to the normal real-time production of arbitrary visuomotor responses, such as working memory and the suppression of motor responses. In this study, we used fMRI adaptation as an alternative approach to dissociate sensory and motor components without introducing artificial delays. This approach allows participants to perform arbitrary visuomotor responses in real time, which better simulates how these actions would normally be performed in everyday life.

Adaptation has been studied extensively at the level of both cortical neurons in monkeys and local hemodynamic changes in the brain of both monkeys and humans (Grill-Spector et al., 2006). In the

* Corresponding author.
E-mail address: pchouin@uwo.ca (P.A. Chouinard).

1053-8119/$ – see front matter © 2009 Elsevier Inc. All rights reserved.
doi:10.1016/j.neuroimage.2009.07.020

case of neuroimaging, if a given brain area contains neurons that code for a particular stimulus or action, then the hemodynamic response would be expected to be higher during conditions in which the stimulus or the action changes across trials as compared to conditions in which the stimulus or the action remains the same. FMRI adaptation has proved to be an effective way of determining what is and what is not processed by a particular brain area in vision (e.g. Grill-Spector et al., 2006; Chouinard et al., 2008) and motor control (e.g. Dinstein et al., 2007; Chouinard et al., 2009) as well as in high-level cognitive operations such as those involved in memory and language (for review, see Schacter et al., 2007), action recognition (Chong et al., 2008; Lingnau et al., 2009), and illusory percepts (Chouinard et al., 2009). Therefore, given the proven effectiveness of this technique in mapping functions to specific brain areas, we thought it would be an excellent way of parcellating the areas in the brain that are involved during arbitrary visuomotor conditional associations into those that adapted only to the presentation of the stimuli, those that adapted only to the production of the responses, and those that adapted to both.

Similar to a number of earlier fMRI adaptation studies (e.g. Huettel and McCarthy, 2000; Huettel et al., 2004; Valyear et al., 2006; Chouinard et al., 2008), a slow event-related design was used to examine adaptation. Pairs of stimuli were presented close together (2 s apart) so that we could examine the effects of repetition suppression on the BOLD response driven by the second stimulus. We presented two objects in succession that consisted of the same object presented twice in a row, which required the same response to be made a second time (Same Stimulus and Same Response), two different objects that required the same response to be made a second time (Different Stimuli and Same Response), or two different objects that required two different responses to be made (Different Stimuli and Different Responses). By presenting pairs of objects in which the stimulus and/or the response properties were repeated, BOLD to the first object could be assumed to be equivalent across conditions and any differences in BOLD between conditions would be driven by whether or not the stimulus and/or the response properties were repeated in the second object.

Methods

Overview

Fourteen volunteers (7 females, age range 24–35 years, mean = 28.4 years) participated in the study. Participants had a right-hand preference as determined by a questionnaire (Oldfield, 1971) and provided informed written consent. Participants also had corrected-to-normal visual acuity and no history of neurological impairments. The Research Ethics Board of the University of Western Ontario (London, Ontario, Canada) approved all procedures. Prior to scanning, participants had to learn a set of conditional associations between different non-sense objects and different hand gestures (Fig. 1). Stimuli for non-sense objects were taken from Kroll and Potter (1984). Five different objects cued participants to perform one of five different hand gestures for a total of twenty-five different conditional associations. Participants were first required to study these associations at home (they were given a sheet of paper to study that depicted the stimuli and the associated hand gestures in manner similar to what is shown in Fig. 1). Then, the day before scanning, they came to the laboratory for a training session in which they performed the task until they met the criterion for learning (learning was achieved when

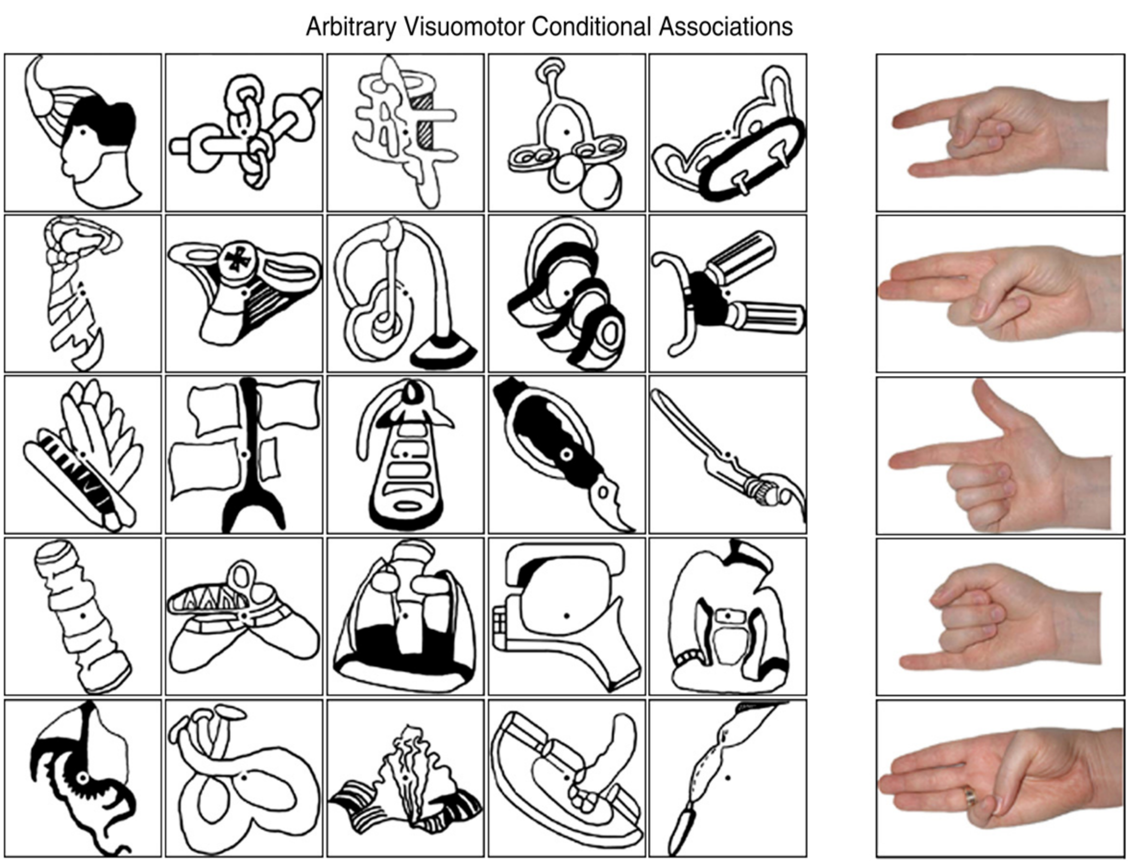

Fig. 1. Arbitrary visuomotor conditional associations. Prior to scanning, participants had to learn conditional associations between the non-sense objects (taken from Kroll and Potter, 1984) and the hand gestures shown in this figure. Five different objects cued participants to perform one of five different hand gestures for a total of twenty-five different conditional associations. Participants were first required to study these associations at home (they were given a sheet of paper to study similar to what is shown in this figure). Then, one day prior to scanning, they came to the laboratory for a training session in order to meet our criterion for learning.