Neuropsychologia 69 (2015) 232–241

Contents lists available at ScienceDirect

Neuropsychologia

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

Representation of visual symbols in the visual word processing network

Taim Muayqil [a,b,1], Jodie Davies-Thompson [a,1], Jason J.S. Barton [a,*]

[a] Department of Medicine (Neurology), Department of Ophthalmology and Visual Sciences, University of British Columbia, Canada
[b] Department of Medicine (Neurology), King Saud University, Riyadh, Saudi Arabia

ARTICLE INFO

Article history:
Received 29 July 2014
Received in revised form
13 January 2015
Accepted 30 January 2015
Available online 31 January 2015

Keywords:
FMRI
Neuroimaging
Visual word form area
Object recognition

ABSTRACT

Background: Previous studies have shown that word processing involves a predominantly left-sided occipitotemporal network. Words are a form of symbolic representation, in that they are arbitrary perceptual stimuli that represent other objects, actions or concepts. Lesions of parts of the visual word processing network can cause alexia, which can be associated with difficulty processing other types of symbols such as musical notation or road signs.
Objective: We investigated whether components of the visual word processing network were also activated by other types of symbols.
Method: In 16 music-literate subjects, we defined the visual word network using fMRI and examined responses to four symbolic categories: visual words, musical notation, instructive symbols (e.g. traffic signs), and flags and logos. For each category we compared responses not only to scrambled stimuli, but also to similar stimuli that lacked symbolic meaning.
Results: The left visual word form area and a homologous right fusiform region responded similarly to all four categories, but equally to both symbolic and non-symbolic equivalents. Greater response to symbolic than non-symbolic stimuli occurred only in the left inferior frontal and middle temporal gyri, but only for words, and in the case of the left inferior frontal gyri, also for musical notation. A whole-brain analysis comparing symbolic versus non-symbolic stimuli revealed a distributed network of inferior temporooccipital and parietal regions that differed for different symbols.
Conclusion: The fusiform gyri are involved in processing the form of many symbolic stimuli, but not specifically for stimuli with symbolic content. Selectivity for stimuli with symbolic content only emerges in the visual word network at the level of the middle temporal and inferior frontal gyri, but is specific for words and musical notation.

1. Introduction

Neuroimaging studies have shown that perception of visual words is correlated with activation of a network of cortical regions, with a left hemisphere dominance (Barton et al., 2010; Reinke et al., 2008). This includes the middle temporal gyrus, inferior frontal gyrus, and in particular a region in the mid portion of the fusiform gyrus that has been named the 'visual word form area' (Cohen et al., 2000a, 2002b; McCandliss et al., 2003). Damage to the latter or its connections may be responsible for at least some cases of acquired alexia without agraphia, also known as pure alexia (Epelbaum et al., 2008; Gaillard et al., 2006; Leff et al., 2006; Pflugshaupt et al., 2009; Sheldon et al., 2012).

As reading is an acquired visual expertise for an arbitrary set of stimuli specific to the culture and language to which the individual is exposed, the stimulus selectivity of this word processing network must develop through experience. Greater degrees of literacy are associated with greater responses to words in the visual word form area, and a decline in responses to other objects like faces (Dehaene et al., 2010). The 'recycling hypothesis' proposes that visual word perception exploits the competency of ventral occipitotemporal regions at analyzing line segments and junctions that make important contributions to processing of object contours (Dehaene and Cohen, 2011; Szwed et al., 2011). The dominance of left hemispheric regions may evolve through efficiency constraints that favour local intra-hemispheric connectivity between visual word processing regions and other language areas, which in most subjects are located in the left hemisphere (Plaut and Behrmann, 2011).

* Correspondence to: Neuro-ophthalmology Section K, VGH Eye Care Centre, 2550 Willow Street, Vancouver, BC, Canada V5Z 3N9. Fax: +1 604 875 4302.
E-mail addresses: tmuayqil@gmail.com (T. Muayqil), jodie.davies@unitn.it (J. Davies-Thompson), jasonbarton@shaw.ca (J.J.S. Barton).

[1] Authors (TM & JDT) are both first-authors and equally contributed to the manuscript.

http://dx.doi.org/10.1016/j.neuropsychologia.2015.01.045
0028-3932/

Along with other studies showing that the left fusiform gyrus retains significant responsivity to stimuli other than words (Flowers et al., 2004; Price and Devlin, 2003; Starrfelt and Gerlach, 2007), these points suggest that the selectivity of regions of the visual word processing network for visual words over other types of objects is partial rather than absolute. Furthermore, one can also ask whether this partial selectivity is limited to visual words alone or favours certain other types of stimuli as well, a question that is prompted by several neuropsychological observations. A number of reports note that patients with pure alexia can also have difficulty with perception of written numbers, musical notation and other objects such as map symbols, road signs, and flags (Beversdorf and Heilman, 1998; Horikoshi et al., 1997; Kawamura et al., 2000; Starrfelt and Behrmann, 2011). Hence it may be that the expertise of this left visual cortical network may be not for words alone but also for certain other object classes.

One intriguing possibility is suggested by the fact that visual words, numbers, map symbols, musical notation and road signs are all types of visual symbols. That is, as stimuli they have an added semantic element, of signifying and communicating concepts or objects other than themselves. Musical notation is a unique category because it has an orthography that resembles written language. Flags and logos are symbols that represent entities, which also convey semantic meaning but lack a phonemic component, yet previous studies have suggested that logos can induce activity in the fusiform gyri (Bruce et al., 2014). There has been less study of instructive symbols such as traffic signs or other symbols used to indicate forms of action or behaviours, rather than representing entities in the manner flags and logos do. The neuropsychological reports in alexia raise the intriguing question as to whether the visual word processing network is involved in these other aspects of visual symbolic communication. This issue is further highlighted by several fMRI studies of the perception of musical notation, symbols, and logos that show activation of similar fusiform, middle temporal, and frontal regions (Bruce et al., 2014; Nakada et al., 1998; Reinke et al., 2008; Wong and Gauthier, 2010). Furthermore, a study of training with an unfamiliar language suggested that fusiform activity may be enhanced not just by visual familiarity but also by the semantic aspect of linking arbitrary meanings to the trained stimuli (Xue et al., 2006).

The goal of our study was to investigate the potential involvement of the visual word processing network in the perception of other types of visual symbols. We examined four classes of symbolic stimuli: visual words, musical notation, instructive symbols that indicate actions, and flags or logos that represent a national or corporate entity. For clarity, we focused upon emblematic symbols, for which the relation between the symbol's shape and the concept, item or event it signifies is arbitrary, in contrast to iconic symbols, which have a form that captures the defining physical aspects of the class of objects to which they refer (Shin et al., 2008). For each of the four classes we created an equivalent set of stimuli that did not have any symbolic content. Our hypothesis was that, if the word processing network is involved more generally in symbolic communication, then significant differences between the activity seen with symbolic versus non-symbolic stimuli would be found for some or all of these four classes.

2. Methods

2.1. Participants

16 healthy right-handed participants (11 males; mean age: 27.3 years, range: 21–39 years) with no history of neurological dysfunction, and visual acuity of 20/20, took part in the study. All participants spoke English as a first language and did not know spoken or written Korean. Subjects who considered themselves literate in music were recruited via an online participation pool at the University of British Columbia. Music literacy was confirmed by an independent paper task in which subjects were presented with a music bar consisting of four to six notes, and, on a cartoon drawing of a piano, were instructed to write the order of notes the music would play. Only subjects who could correctly identify and locate 90% or more of the musical notes were included in the study. The protocol was approved by the institutional review boards of the University of British Columbia and Vancouver General Hospital, and written informed consent was obtained for all subjects in accordance with The Code of Ethics of the World Medical Association, Declaration of Helsinki.

2.2. Stimuli

Fig. 1 shows the four stimulus categories participants viewed: (i) *visual words*, (ii) *musical notation*, (iii) *instructive symbols* (e.g. traffic signs), and (iv) *flags and logos. Visual words* were 4–6 letters long and were chosen to have minimal imageability, to minimize generation of visual imagery (average: 303; range: 233–338). Word criteria were obtained from the MRC Psycholinguistic Database (http://websites.psychology.uwa.edu.au/school/MRCDatabase/uwa_mrc.htm). *Musical notation* were notes displayed on a staff that contained a common recognizable tune of three to five notes (e.g. Jingle Bells, London Bridge). *Instructive symbols* included symbols denoting actions, consisting mostly of traffic signs, and a limited number of device-operating symbols (e.g. play, rewind) or symbols indicating a warning or function (e.g. hazard sign, recycle). The latter were included to increase the variety of symbols, so that these were not confined to traffic situations. *Flags and logos* consisted of well-known country flags (e.g. United States, United Kingdom) and logos of popular brands (e.g. Pepsi, Nike). No text or depictions of living beings (animals or faces) were included in these non-word categories. Twelve individuals not involved in the study were shown various flags, logos and instructive symbols, and the most frequently recognized images were chosen for the experiment.

For each of the four symbolic categories, there was a non-symbolic equivalent that lacked a communicated meaning (Fig. 1). For *visual words*, Korean text was used as an equivalent. For *musical notation*, parallel vertical lines were used instead of horizontal lines as substitutes for staffs, and miscellaneous shapes used to represent pseudo-notes. For *instructive*, and *flags and logos*, similar stimuli were created in Adobe Photoshop CS (www.adobe.com) and used as non-symbolic equivalents.

As images across the different categories naturally vary in size, stimuli were either sized at a fixed height of 300 pixels (*instructive symbols*, *flags and logos, and their pseudo-equivalents*) or a fixed width of 600 pixels (*visual words*, *musical notation, and their pseudo equivalents*), and mounted on a white background to produce a final image of about 600×300 pixels.

Finally, symbolic images and non-symbolic images had corresponding unidentifiable scrambled equivalents. Scrambled images were created using a Telegraphics add-on for Adobe Photoshop CS (http://www.telegraphics.com.au/sw/info/scramble.html) that randomizes pixel clusters across an image (cluster size: 8×8 pixels). This method was chosen over Fourier-transform scrambling as Fourier-transform images can often contain areas within the image resembling shapes. This resulted in a total of 16 stimulus groups: 4 conditions (*symbolic, non-symbolic, scrambled symbolic, scrambled non-symbolic*), for each of the 4 categories (*visual words, musical notation, instructive symbols*, and *flags and logos*).