NeuroImage 57 (2011) 235–241

Contents lists available at ScienceDirect

NeuroImage

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

Neural correlates of binding features within- or cross-dimensions in visual conjunction search: An fMRI study

Ping Wei [a,b], Hermann J. Müller [c], Stefan Pollmann [d], Xiaolin Zhou [b,e,*]

[a] Beijing Key Laboratory of Learning and Cognition, Capital Normal University, Beijing 100048, China
[b] Center for Brain and Cognitive Sciences, and Department of Psychology, Peking University, Beijing 100871, China
[c] Department of Psychology, LMU Munich, D-80802 Munich, Germany
[d] Cognitive Neurology Research Group, Otto-von-Guericke-University Magdeburg, D-39016 Magdeburg, Germany
[e] Key Laboratory of Machine Perception (Ministry of Education), Peking University, Beijing 100871, China

ARTICLE INFO

Article history:
Received 8 December 2010
Revised 8 April 2011
Accepted 12 April 2011
Available online 22 April 2011

Keywords:
Visual search
Feature search
Conjunction search
Within-dimension conjunction
Cross-dimension conjunction
fMRI

ABSTRACT

The fMRI technique was used to investigate the functional neuroanatomy of binding features within- or cross-dimension during visual conjunction search. Participants were asked to perform feature search (FS; e.g., search for a vertical bar among tilted bars), within-dimension search (WS; e.g., search for an upright T among non-target oriented Ts and Ls), cross-dimension search (CS; e.g., search for an orange vertical bar among blue vertical bars and orange tilted bars), and complex search combining within- and cross-dimension features (WCS; e.g., search for an orange upright T among orange leftward Ts and blue Ls). Reaction times (RTs) taken to decide whether a target was present or absent were faster in the FS than in the WS, CS, and WCS conditions, but did not differ between the latter three conditions. Neuroimaging results revealed a set of posterior parietal regions, including frontal eye field and intraparietal sulcus, to be consistently activated in conjunction search (WS, CS, and WCS) relative to feature search, suggesting that these regions play a more prominent role in matching visual input against the target template in conjunction search. Furthermore, left occipital cortex was more activated in within-dimension conjunction search, and bilateral intraparietal sulcus was more activated in cross-dimension conjunction search. This suggests that features from the same dimension are 'bound' at a higher stage of the ventral pathway by conjoining the inputs from lower-level neurons, while combining features from these separate feature maps — a process assumed to require attentional resources, thus leading to slow, inefficient search. While exceptions to this account have been described soon after its inception, the general notion of a parallel, preattentive feature analysis stage and a subsequent attentive analysis of feature conjunctions has prevailed in more recent models such as Guided Search (Cave and Wolfe, 1990; Wolfe, 1994).

Recent studies using functi
(fMRI) have demonstrated that a
ing the posterior parietal cortex
frontal eye field (FEF) is involved
Ashbridge et al., 1999; Corbetta e
et al., 2000, 2002, 2003; Gitelma
Majerus et al., 2008; Müller-Plath
2003; Shulman et al., 2001;
Woodman and Luck, 2003; Wo
Woyciulevich and Kanwisher, 1999
question addressed in these st
substrates specifically related
feature search (Arguin et al., 199
2003; Friedman-Hill et al., 1995
2000, 2002; Leonards et al., 200
Kanwisher, 1999; Wilkinson et al
(with the exception of Wilkinson
was a combination of two feature
example, the target was a red ci
and shape) presented among c
circles. However, there are also c
features from the same dimen

* Corresponding author at: Department of Psychology, Peking University, Beijing 100871, China. Fax: + 86 10 6276 1081.
E-mail address: xz104@pku.edu.cn (X. Zhou).

1053-8119/$ – see front matter
doi:10.1016/j.neuroimage.2011.04.024

Humphreys, 1989); a well-known example is search for an upright T among differently oriented T's and L's (Duncan and Humphreys, 1989).

We reasoned that the neural substrates subserving search for cross-dimension conjunctions may be different from those for within-dimension conjunctions. Evidence in support of such a distinction comes from behavioral studies that demonstrated illusory conjunctions of color and form, but not of conjunctions within the form domain in normal observers (Cohen and Feintuch, 2002); intact binding of form features, but not color-form conjunctions in Balint's patients (Friedman-Hill et al., 1995; Humphreys, 2001; Humphreys et al., 2000); and a developmentally later onset of successful binding

search trials with 2 null trials were intermixed. A search trial lasted 2500 ms. At the start of a search trial, a white fixation cross, subtending 0.20° in visual angle, appeared at the center of the black screen for 400 ms, followed by a black screen for 100 ms. Then the fixation sign was presented again for another 500 ms, making the cross appear to flash briefly. This was to warn participants about the upcoming search display, which was presented for 500 ms. The search display consisted of a central fixation marker surrounded by 8 bar stimuli (each measuring 0.8° × 0.2°) or 8 T-shape stimuli (each subtending 0.8° × 0.8°). The stimuli were placed at 8 (randomly selected) positions on a virtual, cross-shaped grid, with a maximum eccentricity of 3° of visual angle (see Fig. 1 for block sequence and sample display). At the end of this 1500 ms, the fixation cross was presented for 1000 ms. For null trials, only the fixation sign was presented throughout the trial for 2500 ms. The 6 search and 2 null trials in each block were randomly ordered. After each trial, an additional presentation of the fixation sign, with the duration of either 0 ms (for one trial), 250 ms (two trials), 500 ms (two trials), 750 ms (two trials), or 1000 ms (one trial), was added for jittering between trials. Effectively, participants saw 6 search trials in each block, with variable intervals between trials. Participants were asked to search for the target and respond as quickly and accurately as possible upon the presentation of the search display. They were instructed to maintain eye fixation on the fixation cross in the display center throughout the whole experiment (see also Nobre et al., 2003; Soto et al., 2007). Before scanning, the observers were familiarized with the task and performed several practice blocks in which they were explicitly told to maintain fixation during the task.

Da a ac i i io

A 3T Siemens Trio system with a standard head coil at the MRI Center for Brain Research in Beijing Normal University was used to obtain T2*-weighted echo-planar images (EPI) with blood oxygenation level-dependent (BOLD) contrast (matrix size: 64 × 64, pixel size: 3.4 × 3.4 mm). Twenty-four transversal slices of 4 mm thickness, oriented parallel to the anterior and posterior commissures, were acquired sequentially in ascending order with a 1 mm gap (TR = 1.5 s,

are shown in Table 2 and Fig. 3. As compared to the FS condition, the WS, CS, and WCS conditions activated similar brain areas in frontal and parietal lobes.

In order to determine the neural substrates of binding features from the same dimension, we performed a conjunction analysis (Friston et al., 2005; Price and Friston, 1997) between contrasts of WCS vs. CS and WS vs. FS. If this within-dimension search requires specific neural substrates for accomplishing the task, it should be consistently activated whenever there is a need to bind two features from the same dimension, that is, the horizontally and the vertically oriented bar. Based on a conservative conjunction null hypothesis (Friston et al., 2005; Nichols et al., 2005) implemented in SPM 5, we set the threshold of $p<0.001$, uncorrected, in combination with an extent threshold of 20 voxels (see also, for example, Kim et al., 2011; Weissman et al., 2002). Results revealed activations in the left fusiform gyrus (see Table 3 and Fig. 4).

The same logic was applied to the conjunction analysis of WCS vs. WS and CS vs. FS, which revealed the neural substrates involved in binding features from different dimensions, that is, color with orientation in the CS condition or color with T-shape in the WCS condition. This contrast revealed activations in bilateral superior parietal cortex and bilateral IPTO (junction of intraparietal and transverse occipital sulcus; uncorrected $p<.001$ in combination with an extent threshold of 20 voxels; see also Table 3 and Fig. 4).

By asking participants to perform four types of visual search, we

search) conditions, while RTs in the latter three conditions did not differ statistically from each other. Neuroimaging results found a set of fronto-parietal regions, including frontal eye fields and intraparietal sulci, were consistently activated in conjunction search (WS, CS, and

9etCS,653.7(in2206[(nd1-03.3)-2964)-419.3iven717(gS,653.4(a64413.1nd1395.from1395.m)-295.f)0(7(n663.5)0(aom1391(fer1317.give)-n2(3S,653n2

Gitelman, D.R., Parrish, T.B., Friston, K.J., Mesulam, M.M., 2002. Functional anatomy of visual search: regional segregations within the frontal eye fields and effective connectivity of the superior colliculus. Neuroimage 15, 970–982.
Goodale, M.A., Milner, A.D., 1992. Separate visual pathways for perception and action. Trends Neurosci. 15, 20–25.
Gottlieb, J., 2007. From thought to action: the parietal cortex as a bridge between perception, action, and cognition. Neuron 53, 9–16.
Humphreys, G.W., 2001. A multi-stage account of binding in vision: neuropsychological evidence. Vis. Cogn. 8, 381–410.
Humphreys, G.W., Müller, H.J., 1993. Search via recursive rejection (SERR): a connectionist model of visual search. Cogn. Psychol. 25, 43–110.
Humphreys, G.W., Cinel, C., Wolfe, J., Olson, A., Klempen, N., 2000. Fractionating the binding process: neuropsychological evidence distinguishing binding of form from binding of surface features. Vision Res. 40, 1569–1596.
Humphreys, G.W., Hodsoll, J., Riddoch, M.J., 2009. Fractionating the binding process: neuropsychological evidence from reversed search efficiencies. J. Exp. Psychol. Hum. Percept. Perform. 35, 627–647.
Kaptein, N.A., Theeuwes, J., Van der Heijden, A.H.C., 1994. Search for a conjunctively defined target can be selectively limited to a color-defined subset of elements. J. Exp. Psychol. Hum. Percept. Perform. 21 (5), 1053–1069.