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Establishing visual category boundaries between objects: A PET study

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Abstract

Individuals with Alzheimer's disease (AD) often have problems in recognizing common objects. This visual agnosia may stem from difficulties in establishing appropriate visual boundaries between visually similar objects. In support of this hypothesis, Saumier, Arguin, Chertkow, and Renfrew (2001) showed that AD subjects have difficulties in establishing visual category boundaries between continuously graded shapes. In an attempt to investigate the neural basis of these impairments, the current study required a group of neurologically healthy elderly participants to categorically classify a series of ellipses varying in width while regional blood flow changes were measured using positron emission tomography (PET). Two categorization conditions were compared in order to isolate changes in cortical activity that dissociated the categorization of shapes situated either near or far from a category boundary that divided the width continuum. The participants produced a discontinuity in the probability and speed of categorizing the shapes at some point along the continuum, suggesting that the objects were classified into distinct categories. Moreover, a comparison of the PET scans obtained while the subjects were categorizing the shapes situated near vs. far form the category boundary revealed significant differences in cortical activity in the parietal and frontal brain areas. These findings suggest that both visuo-spatial and decision making mechanisms may be involved in establishing categorical distinctions between continuously graded stimuli. It is proposed that the functional role of the parietal and frontal cortical regions in establishing visual boundaries between categories of objects may be relevant for understanding object recognition impairments in AD.

Keywords: Vision; Neuroimaging; Form and shape perception; Object recognition; Classification (cognitive process)

1. Introduction

Earlier research has shown that Alzheimer's disease (AD) patients manifest object recognition impairments, which tend to be related to problems in categorizing visually similar objects (e.g., see Watmough & Chertkow, 2002, for review). These impairments may arise because the perceptual boundaries between object categories represented in their disrupted memory system are uncertain or fuzzy. Saumier, Arguin, Chertkow, and Renfrew (2001) tested this hypothesis by requiring a group of mild to moderate AD patients to categorize a series of eight computer-generated ellipses that varied along a continuum of width on the basis of two shape prototypes corresponding to the extremes of the shape continuum. All participants showed a discontinuity in the probability of categorizing the shapes, suggesting that the objects were classified into distinct categories. However, the magnitude of this categorical effect was significantly less pro-

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nounced in the AD patients than in the control group. These categorical perception problems are quite general and apply to stimuli that are devoid of semantic content. This provided evidence that semantic memory deficits in AD patients may arise from difficulties in establishing pre-semantic perceptual boundaries that would otherwise serve to support decisions as to whether an object is a member of a category or not.

Although visual categorization impairments in AD have been firmly established, the neural basis of these deficits remains to be elucidated. The current study addressed this issue by having a group of neurologically healthy elderly participants perform a visual categorization task involving ellipses while regional blood flow changes were measured using positron emission tomography (PET). Two categorization conditions were completed by the same subjects in order to isolate changes in cortical activity that dissociate the categorization of shapes situated either near or far from a category boundary that divided a stimulus continuum. It was hypothesized that categorizing shapes situated near the category boundary would impose greater processing resources on those cortical regions that are involved in establishing visual boundaries between categories of objects.

2. Methods

2.1. Participants

Eight English speaking non-demented (as assessed by standardized neuropsychological testing) healthy and independently living elderly subjects (4 men and 4 women) participated in the experiment. Mean age was 72.6 y.o. ($SD = 6.1$).

2.2. Stimuli

The stimuli were 10 black filled 2D computer-generated ellipses that varied in terms of width. The shapes were generated by constructing two ellipses corresponding to the end points of the width continuum, and by interpolating eight intermediate ellipses with a constant width difference between successive shapes. All ellipses were 5 cm in height. The respective widths of the thinnest and widest ellipses were 3.5 and 4.2 cm, and each neighboring pair of ellipses along the continuum differed by 0.3 cm.

2.3. Procedures

Perceptual categorization was tested on the basis of whether subjects classified ellipses that were distal (shapes 1, 2, 7, or 8) or proximal (shapes 3, 4, 5, or 6) to the midpoint of the shape continuum. The proximal or distal shapes were tested in two separate blocks of 32 trials. On each trial, a 500 ms fixation point (Geneva 24 point font) appeared in the center of the monitor, followed 500 ms later by three simultaneously presented shapes. An intermediate ellipse was presented in the center of the monitor, with each of the endpoint ellipses displayed 7 cm to the left and right of the intermediate ellipse. The stimuli remained in view for a duration of 3500 s. An inter-trial interval of 1 s elapsed before the next trial began. Within each block, the eight intermediate ellipses were shown in a random order and in equal numbers within each block. The endpoint ellipses were presented an equal number of times on the left- and right-hand side of the monitor for each intermediate ellipse.

The Proximal and Distal categorization conditions were randomly ordered across subjects. For each condition, subjects were asked to respond as quickly as possible and no feedback was provided regarding the accuracy of their responses.

3. PET

PET scans were obtained from an ECAT EXAT HR + (CTI/SIEMENS) tomograph in a 3D acquisition mode. Transverse and axial resolution of scanning was 4.5–5.8 and 4.9–8.8 mm, respectively. Using the bolus $H_2{}^{15}O$ (10 mCi) methodology (Raichle, Martin, Herscovitch, Mintum, & Markman, 1983), a 60 s scan measuring normalized cerebral blood flow (CBF) was obtained from the beginning of each categorization task. The sum of the PET images across all frames were calculated for each scan. Automatic PET-to-PET registration was used in order to correct for between-scan head movement prior to matching the MRI and PET data sets. This method uses the first summed PET scan for a particular subject as the registration target for each subsequent summed PET scan. Each subject's summed PET image, which encompassed the entire cerebrum and 3/4 of the cerebellum, was realigned and transformed into standard Tailarach space, and then co-registered with a pre-experimentally acquired MRI scan of that individual. The subtraction analysis involved calculating a t value at each voxel by dividing the mean CBF difference by its standard deviation pooled across all brain voxels. Significant increases in CBF were detected on the basis of a 3D Gaussian random field theory (Worsely, Evans, Marrett, & Neelin, 1992), which corrects for multiple comparisons across brain volume.

During scanning, the subject's head was immobilized with a customized head holder device (vac-Lock,k MED-TECH). The visual stimuli were presented on a monitor positioned above the subjects at a viewing distance of approximately 75 cm. One scan was performed for each subject in each condition (i.e., proximal and distal).

4. Results

4.1. Behavioral data

The critical behavioral observations are the proportions in which each intermediate ellipse was classified as more similar to one or the other reference ellipse. Since the proportions of classification for the thin and wide endpoint ellipses are complementary, the data were analyzed in terms of the trials on which each stimulus was classified as thin. As can be seen in Fig. 1A, subjects show a discontinuity in the proportions of classification

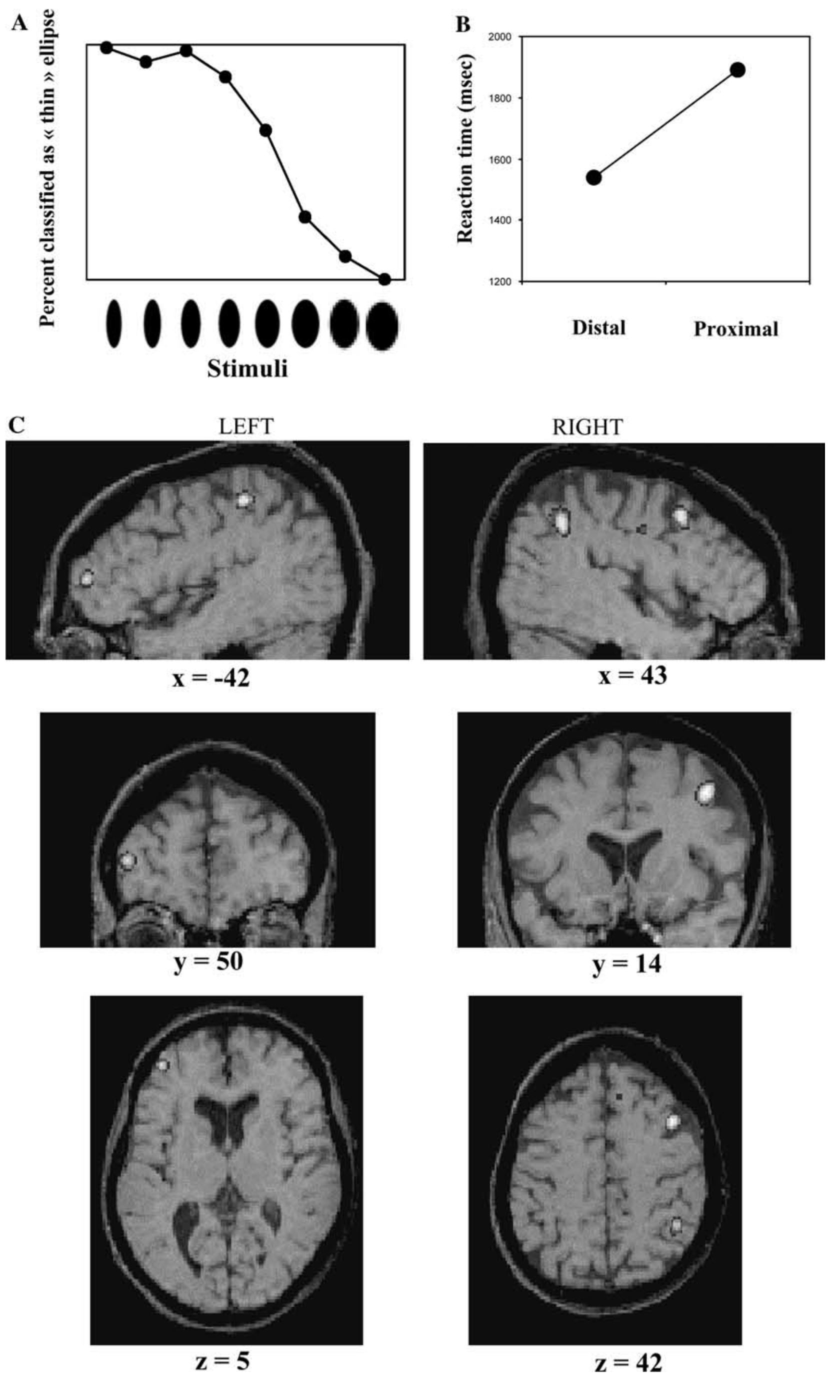

Fig. 1. (A) Classification results. The data are represented in terms of the percentages with which each intermediate shape in the continuum was judged as more similar to the thin ellipse. (B) Average reaction times for categorizing shapes that are proximal or distal to the midpoint of the shape continuum. (C) Cortical regions demonstrating changes in rCBF as a result of subtracting the proximal and distal categorization conditions. The *t*-statistical map has been superimposed onto, sagital, horizontal, and coronal slices of one subject's MRI scan transformed into Tailarach space. Appropriate Tailarach coordinates are provided below each slice.

as a function of the shape continuum and that this discontinuity occurs near the midpoint of the shape continuum. The subject's reaction times (Fig. 1B) are also significantly slower for classifying shapes situated near the category boundary than those located further away from the boundary, $t(7) = 3.0$, $p < .05$.

4.2. PET data

For each subject, the effect of establishing a category boundary on regional brain activation was determined by subtracting the scan conducted while the subject was categorizing shapes near the category boundary from the scan conducted while the subject categorized shapes distal from the category boundary. The subtraction, averaged over subjects, yielded statistically significant peaks of activation in the frontal and parietal lobe areas (see Fig. 1). Within the frontal region, significant differences in CBF were observed in the right frontal lobe region (x, y, z Tailarach coordinates: 44, −7, 33; $t = 3.6$), as well as the right (42, 13, 40; $t = 4.2$) and left (−41, 49, 6; $t = 3.99$) middle frontal gyrus. In addition, significant differences in activation were obtained in the parietal region, including two adjacent areas of the right superior parietal lobe (46, −50, 36; $t = 4.4$; 48, −30, 39; $t = 3.6$), and in the left Angular gyrus (−43, −37, 50; $t = 4.2$).

5. Discussion

The present study required a group of subjects to categorize a series of ellipses that varied in width on the basis of two reference ellipses corresponding to the extremes of the width continuum. One important finding is that the participants produced a discontinuity in the likelihood and speed of classifying the shapes as more similar to one of the reference ellipses at some point along the shape continuum. This implies that the shapes tended to be classified into distinct categories of 'thin' or 'wide' shapes, with a well-defined boundary separating those two categories at a particular point along the shape continuum. These findings are unlikely due to mechanisms responsible for accessing shape representations in memory since subjects performed the perceptual categorization task on-line while viewing the reference shapes. These results concur with those of Saumier et al. (2001).

The present study goes further by using PET imaging in order to examine changes in brain activity associated with visual categorization of the shapes situated near vs. far from the category boundary. Although the sample of subjects scanned was small, a comparison of the PET scans obtained during the two categorization conditions revealed significant differences in cortical activity in several brain regions situated in the parietal and frontal areas. The location of the activations in the parietal region is interpreted as reflecting visuo-spatial processes when comparing the intermediate and reference shapes for categorization. Activations within the frontal lobe area, however, suggest that decision making mechanisms may be involved in establishing categorical distinctions between continuously graded stimuli. It is suggested that the categorical perception impairments previously observed in AD individuals by Saumier et al. (2001) may reflect the disruption of these neural mechanisms. The functional role of the parietal and frontal neural regions in establishing visual boundaries between categories of objects may thus be relevant for understanding object recognition impairments in AD.

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