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Dissociation between process-based and data-based limitations for conscious perception in the human brain

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ABSTRACT

Successful performance of a cognitive task depends upon both the quality of the sensory information and the processing resources available to perform that task. Thus, task performance can either be data-limited or process-limited (D. A. Norman and D. G. Bobrow, 1975). Using fMRI, we show that these conceptual distinctions are neurally dissociable: A parieto-frontal network involved in conscious perception is modulated by target interference manipulations that strain attentional processing, but not by equally difficult manipulations that limit the quality of target information. These results suggest that limitations imposed by processing capacity have distinct neural effects from those arising from the quality of sensory input, and provide empirical support for an influential neurobiological theory of consciousness (S. Dehaene, J.-P. Changeux, L. Naccache, J. Sackur, and C. Sergent, 2006).

Introduction

Any information processing system has limitations (Lloyd, 2000). In the context of human information processing, a distinction is made between two broad classes of limitations: those that result from the limited quality of information that is inputted into the system, i.e. data-based limits, and those that result from the limited processing capacities of that system, i.e. resource-based or process-based limits[1] (Norman and Bobrow, 1975).

The distinction between process-based and data-based limitations has long maintained a foothold in the behavioral and computational literature (Garner, 1970; Lavie and DeFockert, 2003), and implicitly forms the essence of an influential theory on the neural basis of conscious perception (Dehaene et al., 2006). According to this theory, failures of conscious perception of sensory events may take place either because the quality of the sensory information is too impoverished to yield a supra-threshold percept in the brain, or because the central brain mechanisms that support attentional processing of the sensory event are too overloaded to operate on that event, even if its sensory quality is above threshold for conscious perception. Consistent with a role for attentional processes in limiting awareness, activity of the parieto-frontal attention network generally co-varies with conscious perception (Beck et al., 2001; Dehaene et al., 2006; Marois et al., 2004a; Rees et al., 2002). However, it is still unknown whether this parieto-frontal activation is specific to conditions that are limited by attentional processing capacities, or whether it generalizes to conditions where data is limited as well. Indeed, there is as of yet no clear neurobiological evidence to support a dissociation between process-based and data-based limitations of human cognition because these two conditions have never been directly contrasted within a single experiment.

The process-based versus data-based limitation account predicts that only under conditions in which attentional processing is strained, i.e. when its computational load is increased, will the parieto-frontal network be modulated. That is, when processing load of a given task increases, a larger amount of processing resource should be allocated or a processing device should be deployed for a longer period of time in order to meet the task demands, thereby increasing activation of brain regions implicated in capacity-limited processes. By contrast, manipulations limiting the quality of sensory input to the system would have a minimal impact on the network's processing capacity. The impoverishment of input data to be handled by the system does not impose any additional processing demand on the system. Hence, data-based limits should not modulate activation in the parieto-frontal network.

Here we tested this prediction using a variant of the attentional blink (AB) paradigm, which reveals a profound deficit in the conscious perception of targets embedded in a rapid serial visual presentation (RSVP) stream of distractor items when these targets are presented

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[1] The term 'resources' is used to denote flexible, energetic forms of commodities necessary for processing (Kok, 1997). However, in the distinction between resource-limit and data-limit, resource-limit may not only imply limitations originating from finite amount of flexible *resource*, but also limits from scarcity or temporary unavailability of processing *devices*. Hence, we favor the term 'process-based limit' in this article as it clearly conveys that what is ultimately limited is the system's ability to process information, in contrast to limitations in the amount or quality of data to be processed (data-based limit).

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within a few hundred milliseconds of each other (Chun and Potter, 1995; Raymond et al., 1992). The AB is well suited to investigate the neural dissociation of process-based and data-based limitations because this paradigm allows these two limitations to be independently manipulated. Growing evidence shows that experimental factors taxing attentional processes interact with the AB (Dux et al., 2008, 2009), whereas degrading the quality of sensory input does not (Jannati et al., 2012; McLaughlin et al., 2001). Even though the exact cause of the AB is still under debate (for a review, see Dux and Marois, 2009), it is well-established that the AB reveals behavioral deficits primarily produced by increased processing load.

Processing can be strained by increasing distractor interference, as such a manipulation disrupts the attentional deployment for target selection (Chun and Potter, 1995; Di Lollo et al., 2005; Serences et al., 2005; Simons, 2000). The effects of limiting data input, in contrast, can be revealed by manipulating the duration of target presentation (Garner, 1970; Lavie and DeFockert, 2003; Norman and Bobrow, 1975). We hypothesize that the parieto-frontal network will be modulated by the distractor interference manipulation, but not by the stimulus duration manipulation.

Materials and methods

Experiment 1

Participants

Fifteen adults (aged 20–35; 5 males) participated in exchange for monetary compensation. The Vanderbilt Institutional Review Board approved the experimental protocol and written informed consent was obtained from each participant. One participant's data was excluded from the analysis due to failure to follow the task instructions and another because of excessive head motion (>10 mm).

Behavioral paradigm

The targets were randomly chosen among eight letters (B, N, Z, T, F, H, K, or L) in each trial. The distractors consisted of digits, excluding 0 and 1. All characters (white courier font on a black background) subtended $0.6° \times 1°$ of visual angle. Each trial's RSVP stream contained 11 frames (three target letters and eight digit distractors), with the first target presented anywhere between the third and the sixth frame. Similar to Kawahara et al.'s (2006) experimental design, three targets were presented in each trial of all conditions to reveal the transient effect of distractor presentation on attentional target selection (see Results) and to equate the number of targets to detect and respond to across conditions.

Three conditions (Continuous, Discontinuous, and Continuous-hard) were presented in each fMRI run (Fig. 1). In the *Continuous* condition, the three target letters were presented successively. This condition served to establish a reference pattern of behavioral performance and brain activation to which the two other conditions could be compared to assess their effectiveness in impairing performance and in modulating brain activity. In the *Discontinuous* condition, one of the eight digit distractors was inserted between the first and second targets. The stimulus presentation rate was constant across the Continuous and Discontinuous conditions for each individual participant, but it was adjusted (80–130 ms stimulus duration, 0 ms ISI) between participants, based on task performance in pilot testing, to yield about 80% correct performance. Finally, in a third condition (*Continuous-hard*), visual stimulation was identical to that of the Continuous condition, except that the duration of each target frame (90–160 ms for T1, 50–90 ms for T2, and 70–130 ms for T3) was adjusted independently after each fMRI run to match performance with the Discontinuous condition. Based upon behavioral pilot testing, in the first run, T1 duration for the Continuous-hard condition was lengthened by 16.7 ms (monitor refresh rate) and T2 duration was shortened by 33.3 ms, compared to the other conditions.

The RSVP was followed by the visual presentation of target response panels. The response panel for T1 appeared 2 s after the onset of the RSVP and listed the eight potential target letters in a row at fixation, with the letters colored red over a black background. Above the letter row the sentence 'First Target?' was also presented in red. Each letter was assigned to a distinct manual button press, mapped in a spatially congruent manner onto all the fingers except the thumbs. The T1 response panel remained visible for 2 s, followed by a 1-sec presentation for each of the T2 (green colored letters) and T3 (blue colored letters) response panels. The T1 panel was presented for a longer time because pilot testing showed that T1 RTs (mean = 1077 ms) were longer than T2 (283 ms) and T3 RTs (394 ms). This is probably because participants retrieved all three targets at the onset of the T1 response panel. Upon the onsets of the T2 and T3 response panels, the participants would then just have to select and execute the appropriate responses based upon already retrieved target identities.

Each trial lasted a total of 6 s, with trials separated by a blank interval of variable duration that followed an exponential distribution (23 trials × 4 s, 10 trials × 6 s, 4 trials × 8 s, 2 trials × 10 s, and 1 trial × 12 s) to facilitate deconvolution analysis of the BOLD response. Each participant completed six such fMRI runs, each consisting of 20 Discontinuous trials, 10 Continuous trials, and 10 Continuous-hard trials. Thus, the number of trials in which a digit distractor followed T1 (Discontinuous) was the same as the number of trials in which another target followed T1 (Continuous and Continuous-hard). The presentation order of these three trial types was randomly intermixed, thereby ensuring that any activation differences between conditions were not due to preparatory or expectation effects.

fMRI methods

Anatomical 2D and 3D high-resolution T1-weighted images were acquired with conventional parameters on a 3T Philips scanner at the Vanderbilt University Institute of Imaging Sciences. Thirty-three 3.5 mm axial slices (0.5 mm skip; 3.75 × 3.75 mm in-plane) were taken parallel to the AC–PC line (TR, 2000 ms; TE, 35 ms; FA, 79°; FOV, 240 mm). The functional scan included 238 brain volumes. Imaging data were analyzed using Brain Voyager QX 1.10. Data preprocessing included 3D motion correction, slice scan time correction, linear trend removal, and spatial smoothing with an 8-mm (FWHM) Gaussian kernel. All functional data of each participant were aligned to the first functional run, and co-registered to that individual's anatomical T1-weighted image. Functional and anatomical data were transformed into standardized Talairach space.

To create statistical parametric maps (SPMs) of BOLD activation, regressors were defined for each trial type and convolved with a double gamma function (SPM2, http://www.fil.ion.ucl.ac.uk/spm). Two group random-effects contrast analyses were performed to isolate brain regions preferentially activated by the Discontinuous condition. The first used a balanced contrast, with regression coefficients of 2 for the Discontinuous condition and −1 for each of the Continuous and the Continuous-hard conditions. A voxel-wise statistical threshold of $p<.005$ was corrected for multiple comparisons using a cluster filter of five contiguous voxels (as determined via simulation using the Brain Voyager cluster threshold plug-in), yielding a map-wise error rate of $p<0.05$ (Forman et al., 1995). The second SPM was constructed using a conjunction of two contrasts (Nichols et al., 2005), (Discontinuous-Continuous) and (Discontinuous-Continuous-hard), using a voxel-wise statistical threshold of $p<.05$ with a cluster threshold of 11 contiguous voxels. Given that this conjunction contrast analysis is fairly conservative (Friston et al., 2005), we adopted a slightly more lenient threshold for the SPM to decrease the probability of Type II errors. For both SPMs, regions of interest (ROI) were defined as all contiguous supra-threshold voxels of distinct activation foci.

For ROI analysis, event-related timecourses of the BOLD signal for each participant and condition were estimated using a deconvolution analysis (using the eight volumes immediately following trial onsets).