

Task demands modulate sustained and transient neural activity during visual-matching tasks

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Received 18 May 2004; revised 14 December 2004; accepted 17 December 2004
Available online 26 January 2005

The extent to which a task demands verbal or non-verbal processing may influence which neural regions underlie performance. In the present study, sustained and transient responses were examined using functional magnetic resonance imaging (fMRI) in conjunction with a mixed blocked/event-related design during three visual-matching tasks that varied in the extent to which they relied on verbal processing. In a name-matching task, subjects decided whether two letters had the same or a different name (e.g., A a); in a physical-matching task, subjects decided whether two letters were exactly the same or different (e.g., A A); in a non-letter-matching task, subjects decided whether two non-letters were exactly the same or different. Results revealed several regions in which sustained activity differed across the three tasks as well as several regions in which sustained activity did not differ. Most notably, regions in the right inferior frontal gyrus exhibited greater sustained activity during the name-matching task than during the physical or non-letter-matching tasks, indicating that sustained activity in this region is sensitive to the amount of verbal processing required by a particular task. Moreover, transient activity in the right inferior frontal regions, as well as others, exhibited the opposite pattern of results. In combination, results suggest that sustained and transient activities interact to produce the context-appropriate response during visual-matching tasks.

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Keywords: Task demands; Visual-matching tasks; Neural activity

Introduction

Consideration of the demands placed by particular tasks on processing systems within the brain is critical to understanding

how different regions underlie task performance in cognitive experiments. One type of demand examined widely in the literature is the extent to which a task relies on verbal information compared to non-verbal information (e.g., Blaxton, 1989; Klatzky and Atkinson, 1970; Richardson-Klavehn and Gardiner, 1998; Roediger et al., 1989). Functional neuroimaging studies indicate that regions in the right and left prefrontal cortex are differentially sensitive to changes along this dimension. In particular, regions within the left prefrontal cortex are activated to a greater extent during tasks that involve verbal processing than during tasks that involve non-verbal processing. This asymmetry has been observed in studies comparing semantic vs. perceptual encoding of words (Demb et al., 1995; Gabrieli et al., 1996), encoding of words vs. faces (Kelley et al., 1998; McDermott et al., 1999), and abstract textures (Wagner et al., 1998), and priming for real or familiar objects compared to non-sense, unfamiliar objects (van Turennout et al., 2000; Vuilleumier et al., 2002). In addition, studies comparing encoding of faces and words (Kelley et al., 1998; McDermott et al., 1999) and abstract textures and words (Wagner et al., 1998) have demonstrated greater right prefrontal activation than left during non-verbal encoding (faces, abstract textures) than during verbal encoding (words).

To date, studies examining the effects of verbal and non-verbal processing on activity within the prefrontal cortex have employed either blocked or event-related designs. These designs, while useful in many respects, are limited in that they do not allow sustained and transient components of neural activity to be measured independently (e.g., Chawla et al., 1999; Donaldson et al., 2001). Transient activity corresponds to the temporal profile of individual trials and is the signal measured in typical event-related designs. Sustained activity, in contrast, endures throughout the entire task period and is not related to the onset of individual trials. In blocked designs, these components of activity are confounded; in event-related designs, only the transient component is measured. Recent research indicates that sustained and transient components may be

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Available online on ScienceDirect (www.sciencedirect.com).

measured separately with fMRI using a “mixed blocked/event-related” design (Burgund et al., 2003; Donaldson et al., 2001; Otten et al., 2002; Velanova et al., 2003; Visscher et al., 2003; Wenger et al., 2004). In this design, blocks of a control period are separated by blocks of a task period, and events are presented in a temporally jittered (event-related) manner (see Fig. 1A).

Both sustained and transient components of neural activity may be relevant for the study of task demands in the prefrontal cortex. Indeed, in a recent mixed-design study, homologous regions in the right and left prefrontal cortex exhibited opposite patterns of sustained and transient activity during overt object naming (Burgund et al., 2003). Consistent with results from previous event-related studies of familiar object processing (Buckner et al., 1998; Koutstaal et al., 2001; van Turennout et al., 2000; Vuilleumier et al., 2002), transient activity in this study was greater in a region within the left inferior prefrontal gyrus (−47, 15, 16 in stereotactic space Talairach and Tournoux, 1988) than in a homologous region within the right inferior prefrontal gyrus (47, 19, 10). In contrast, sustained activity was greater in the right inferior prefrontal region than in the homologous left hemisphere region. Thus, regions in both left and right prefrontal cortex are involved in object naming; however, their effects are exerted through different (transient vs. sustained) mechanisms.

Clearly the overt object-naming task used in the Burgund et al. (2003) study required a high degree of verbal processing. Therefore, it is not surprising that transient activity was greater in the left than the right prefrontal region. Reasons for the involvement of the right prefrontal region in this task are not as clear however. One possibility is that sustained signals in the right prefrontal cortex are important for verbal processing, perhaps, as speculated by Burgund et al. (2003), for the inhibition of transient responses in right prefrontal regions (allowing left prefrontal regions to guide the majority of processing). Alternatively, it is possible that sustained signals in the right prefrontal cortex are involved in a wide range of tasks and are not specific to verbal processing per se. Indeed, sustained signals in right prefrontal regions could be greater during non-verbal than during verbal tasks, in line with previous evidence suggesting right prefrontal involvement in non-verbal processing (Kelley et al., 1998; McDermott et al., 1999; Wagner et al., 1998).

These alternatives could not be distinguished in the Burgund et al. (2003) study, in which only the object-naming task was

examined. Therefore, in the present study, we compared sustained activity during three visual-matching tasks that varied in their requirements for verbal processing. In a name-matching task, subjects decided whether two letters had the same or a different name (e.g., A a). This task requires a high degree of verbal processing because a name for each letter must be generated in order to make the comparison. In a physical-matching task, subjects decided whether two letters were exactly the same or different (e.g., A A). In contrast to the name-matching task, this task does not require verbal information. In fact, verbal information, such as the letters’ names, must be ignored in order to perform the task. Nonetheless, because the stimuli are letters, some verbal processing may occur in this task. Therefore, the third task was a non-letter-matching task in which subjects decided whether two unfamiliar letter-like forms (see Fig. 1B) were exactly the same or different. Like the physical-matching task, this task requires matching of stimuli on the basis of non-verbal rather than verbal information. Unlike the physical-matching task however, stimuli in the non-letter-matching task are unfamiliar and do not have verbal information associated with them.

Comparisons of sustained activity during these three tasks allow us to test the following specific predictions. If sustained signals in the right prefrontal cortex are important for verbal processing per se, activity in this region should be greater during the name-matching task than the physical- or non-letter-matching tasks. In contrast, if sustained signals in the right prefrontal cortex are involved in a wide range of tasks and are not specific to verbal processing per se, they should be observed during all three tasks. Finally, if sustained signals in right prefrontal regions are greater during non-verbal than during verbal tasks, activity should be greater during the physical- and non-letter-matching tasks than the name-matching task.

Method

Subjects

Eighteen volunteers (9 male; mean age 24 ± 4 ; range 18–32 years) from the Washington University community participated for payment. Subjects were screened using a detailed questionnaire to insure that they had no history of neurological or psychiatric problems or drug abuse. In addition, all subjects were right-handed and had normal or corrected-to-normal vision. Informed consent was obtained from each subject in accordance with the guidelines and approval of the Washington University Human Studies Committee.

Materials

Stimuli were pairs of letters during the name- and physical-matching tasks and pairs of unfamiliar letter-like forms during the non-letter-matching task. Letters were taken from the entire Roman alphabet, excluding the letters ‘m’ and ‘h’, which were used for practice; thus 24 different letters were used during the letter-matching tasks. Unfamiliar non-letters were modeled after Gibson et al. (1962) and were similar to real letters in terms of size, number of lines (curved and straight; vertical and horizontal), and number of enclosed spaces (see Fig. 1B). Twelve prototypes plus a three-line variation of each prototype (Gibson et al., 1962) were used in the present study; thus, non-letter pairs were created from a set of

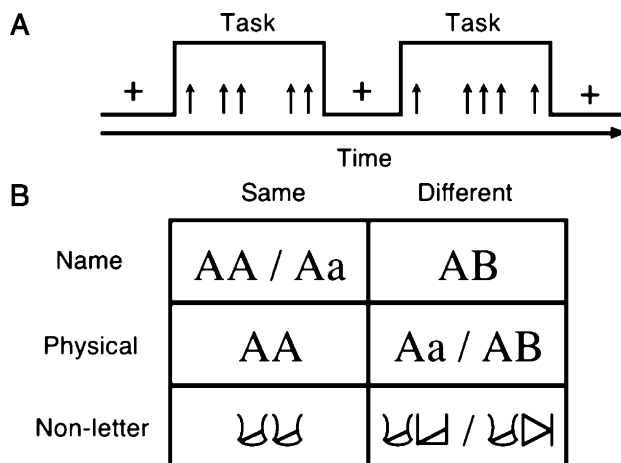


Fig. 1. Schematic of the mixed blocked/event-related design (A) and examples of letter and non-letter pairs used in the three tasks (B).

24 letter-like forms (two versions of each of 12 prototypes). Letters were presented in 36 point, Times font. All stimuli were presented centrally, in white against a black background, and subtended approximately 0.5° of widest (horizontal or vertical) visual angle individually. Pairs of letters (and non-letters) subtended approximately 2° in the horizontal dimension.

Ninety-six pairs of letters (or non-letters) were presented during each matching task. Half of the pairs were “same” and half were “different”, according to the particular task instruction (see Behavioral paradigm). In the name-matching task, half of the “same” pairs (24 trials) were composed of the same letters in the same lettercase (e.g., A A), and half were composed of the same letters in a different lettercase (e.g., A a). The “different” pairs were composed of different letters in the same lettercase (e.g., A B). In the physical-matching task, “same” pairs were composed of the same letters in the same lettercase (e.g., A A). For “different” pairs, half of the trials (24) were composed of the same letters in a different lettercase (e.g., A a), and half were composed of different letters in the same lettercase (e.g., A B). Finally, in the non-letter-matching task, “same” pairs were composed of the same version of a prototype. For “different” pairs, half of the trials (24) were composed of different versions of the same prototype, and half were composed of two different prototypes (see Fig. 1B).

Behavioral paradigm

All subjects completed two successive runs of each of the three matching tasks, administered in different counterbalanced orders, for a total of six functional runs. As depicted in Fig. 1A, each run was composed of alternating blocks of control and task. During the control blocks, a cross hair (+) was displayed continuously. This cross hair turned red for 2.5 s at the beginning and end of each task block in order to cue subjects to the beginning and end of the task. During each task, 24 letter (or non-letter) pairs were presented for 500 ms each in a temporally jittered manner such that 0, 1, or 2 control frames followed each stimulus frame. The cross hair preceded each presentation and remained on the screen between stimulus frames.

During the name-matching task, subjects were instructed to respond “same” when letters within the pair had the same name (e.g., A a) and “different” when letters within the pair had different names (e.g., A B). During the physical-matching task, subjects were instructed to respond “same” when letters within the pair were exactly the same (e.g., A A) and “different” when they were not (e.g., A a). Similarly, during the non-letter-matching task, subjects were instructed to respond “same” when non-letters within the pair were exactly the same and “different” when they were not. Subjects pushed the right (or left) button on a button wand with the index finger of their right (or left) hand to indicate a “same” response, and the left (or right) button with the index finger of their left (or right) hand to indicate a “different” response. The hand (left vs. right) used to indicate a “same” response was counterbalanced across subjects.

Each run lasted approximately 6 min, separated by a 3-min break. Before each new task, subjects engaged in 12 practice trials to ensure that they understood the instructions.

Data acquisition

MRI data were acquired on a Siemens 1.5-T Vision scanner (Erlangen, Germany) using the standard circularly polarized head

coil. A pillow and a thermoplastic face mask were used to minimize head movement. Headphones dampened scanner noise and enabled communication with subjects. Stimulus presentation and response measurement were controlled by a Macintosh computer and the PsyScope software package and button box (Cohen et al., 1993) with a connected button wand that was compatible with MRI. Stimuli were projected onto a screen at the head of the bore that was viewable in a mirror attached to the coil.

Anatomical images were acquired first using a sagittal MP-RAGE three-dimensional T1-weighted sequence (Mugler and Brookeman, 1990) with a voxel size of $1 \times 1 \times 1.25$ mm (TR = 9.7 ms; TE = 4 ms; flip angle = 12° ; TI = 300 ms; and TD = 0 ms). At the beginning of each session, the main field was shimmed to a tolerance of <0.1 ppm. Functional images were acquired using an asymmetric spin-echo, echo-planar sequence sensitive to blood oxygenation level-dependent (BOLD) contrast (T2*; TR = 2.5 s, T2* evolution time = 50 ms, flip angle = 90° , voxel size = 3.75×3.75 mm in-plane resolution). During each functional run, 134 sets of 16 contiguous 8-mm thick axial images were acquired parallel to the anterior–posterior commissure plane.

Image analysis

Data from each subject were preprocessed to remove noise and artifacts, including correction for movement within and across runs using a rigid-body rotation and translation algorithm (Friston et al., 1994; Snyder, 1996). Image slices were temporally realigned (using sinc interpolation) to the midpoint of the first slice, accounting for differences in the acquisition time for each individual slice. Data were then resampled into 2-mm isotropic voxels and warped into a standardized atlas space (Talairach and Tournoux, 1988).

Preprocessed data were analyzed using the general linear model (GLM; Friston et al., 1994; Josephs et al., 1997; Miezin et al., 2000; Worsley and Friston, 1995; Zarahn et al., 1997), and estimates of the magnitude of effects were derived from the model. Sustained effects were modeled in the GLM as a square wave that started 7 time points (17.5 s) after the cue at the beginning of the task block and ended at the cue at the end of the task block.¹ No shape was assumed for transient effects. Instead, these effects were modeled in the GLM by the 7 time points (i.e., image acquisitions) immediately following each stimulus onset. In addition, factors were coded to account for the cues at the beginning and end of each block and for the within-run linear trend (linear drift and a

¹ The sustained signal was coded to begin 17.5 s after the task began to ensure that any transient response to the cue that appeared at the beginning of each task block was not misattributed to the sustained signal measurement. Unlike the transient signals for the task conditions, which were estimated based on many individual events (~96 for each of the three task conditions per subject), the cue signals were estimated based on just a few events (12 for each of two [beginning and ending] cue types), which is not enough to reliably separate the transient signal from other overlapping signals. By delaying the beginning of the sustained signal until after the response to the beginning cue was likely to have returned to baseline (17.5 s after the presentation of the cue), the potential misattribution of the cue response to the sustained response was avoided. By estimating the sustained signal in this manner, we can be confident that the measurement is not contaminated by a response to the cue.

constant term). All effects were modeled simultaneously in the GLM for each subject.

Regions exhibiting sustained activity were identified based on two voxel-wise analyses. A one-way ANOVA in which task type (name vs. physical vs. non-letter) was the independent variable was performed to identify regions exhibiting different sustained activity across the three tasks; a one-way *t* test assessing the magnitude of the response across all task blocks was performed to identify regions exhibiting sustained activity that did not vary across the tasks. Each of these statistical images was smoothed with a 4-mm radius hard sphere kernel and masked by an additional image reflecting voxels in which the percent change in bold signal from baseline was $|0.1|$ or greater during either of the three matching tasks. A peak (local extremum) search algorithm was then used to identify the coordinates (Talairach and Tournoux, 1988) of activation peaks ($P < 0.005$, uncorrected) in the masked images. Peaks separated by less than 10 mm in each image were consolidated by coordinate averaging, and spheres (10-mm radius) were centered on each peak. Finally, spherical regions were masked to exclude voxels that did not meet a statistical threshold of $P < 0.01$ (uncorrected).

Region-based analyses were performed on each of the regions identified in the voxel-wise analyses. Sustained activity was examined in a one-way, repeated-measures ANOVA in which task type (name vs. physical vs. non-letter) was the independent variable and in a one-way *t* test assessing the magnitude of the response across all tasks. Transient activity was examined in each region by a two-way, repeated-measures ANOVA in which time (at

seven time points) and task type (name vs. physical vs. non-letter) were the independent variables.

Behavioral analysis

Response times and error rates were each analyzed in a one-way, repeated-measures ANOVA with task type (name-matching vs. physical-matching vs. non-letter-matching) as the independent variable.

Results

Effect of task

Two regions within the right inferior prefrontal gyrus emerged from the voxel-wise ANOVA assessing the effect of task (see Fig. 2). Critically, these regions were centered on coordinates in stereotactic space (43, 16, 13 [Fig. 2A] and 40, -9, 12 [Fig. 2B]; Talairach and Tournoux, 1988) that were close to the coordinates of the right inferior prefrontal gyrus region found in the object naming study (47, 19, 10; Burgund et al., 2003). In the anterior region (43, 16, 13), percent signal change was greater during the name-matching task (0.29) than during the physical (0.06) or the non-letter (0.09)-matching tasks, both P s < 0.005 , for the simple-effect contrasts. Moreover, signal change in the physical- and non-letter-matching tasks did not differ, $P > 0.61$, for the simple-effect contrast. Similarly, in the posterior region (40, -9, 12), percent signal change was greater during the name-matching

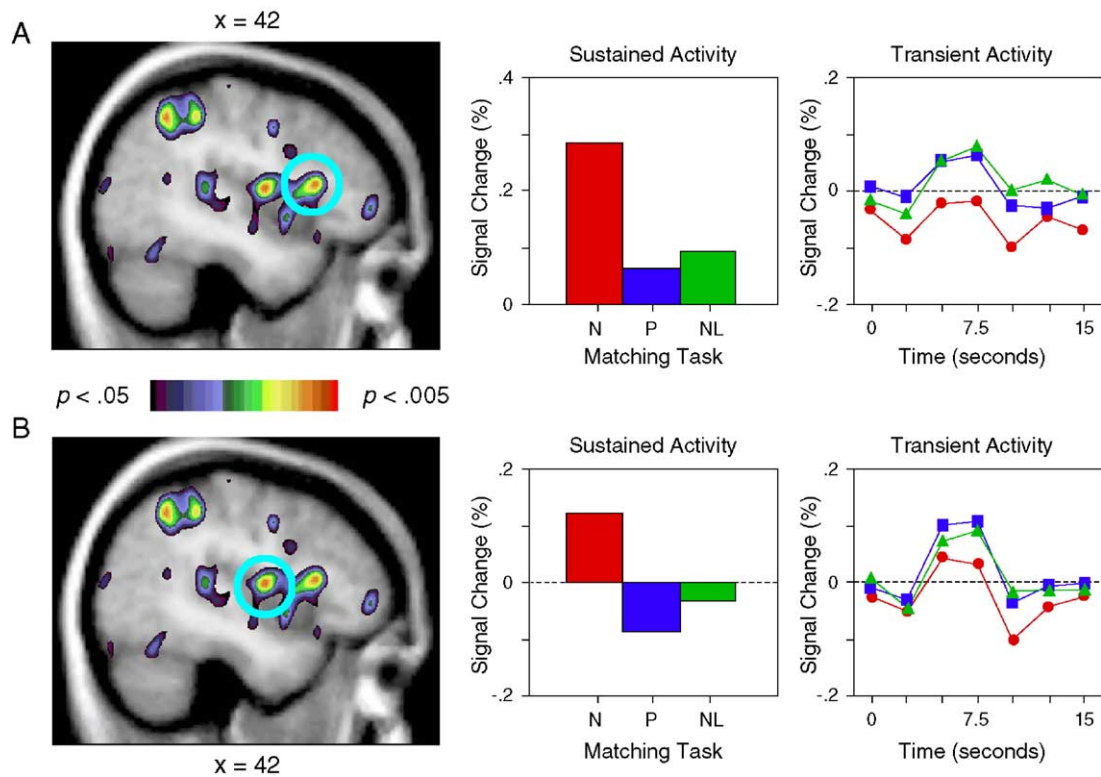


Fig. 2. Regions within the right inferior frontal gyrus defined based on the voxel-wise ANOVA assessing task type (A [43, 16, 13] and B [40, -9, 12]). Sustained activity during the three tasks is shown in the middle column. Transient activity is shown in the right column (red circles = name matching; blue squares = physical matching; green triangles = non-letter matching).

task (0.13) than during the physical (−0.09)- or the non-letter (−0.03)-matching tasks, both P s < 0.005, for the simple-effect contrasts, and signal change in the physical- and non-letter-matching tasks did not differ, $P > 0.26$, for the simple-effect contrast.

Analyses of the transient activity in these regions revealed an opposite effect of task. In the anterior region (43, 16, 13), the peak of the transient signal was decreased during the name-matching task (−0.02) relative to the physical (0.06)- and non-letter (0.07)-matching tasks, $P < 0.0001$, for the main effect of task. Similarly, in the posterior region (40, −9, 12), the peak of the transient signal was decreased during the name-matching task (0.04) relative to the physical (0.11)- and non-letter (0.09)-matching tasks, $P < 0.005$, for the main effect of task.

In addition to the right inferior frontal regions, several other regions also emerged from the voxel-wise ANOVA assessing the effect of task. Regions in the right middle frontal gyrus, left temporal lobe, and putamen exhibited effects that were similar to those in the right inferior frontal regions—greater sustained activity during the name-matching task than during the physical- or the non-letter-matching tasks (see top of Table 1). Other regions exhibited different effects of task (see Fig. 3). Regions in the cuneus (Fig. 3A) and lingual gyrus exhibited less sustained activity during the non-letter-matching task than during the name- or the physical-matching tasks (see middle of Table 1). This difference was due to large decreases in activity during the non-letter-matching task in both regions. In addition, regions in the middle frontal gyrus (Fig. 3B), the medial frontal gyrus, and inferior parietal lobules exhibited less sustained activity during the physical-matching task than the name- or the non-letter-matching tasks (see bottom of Table 1).

Like regions within the right inferior frontal gyrus, transient responses in most of these other regions exhibited the opposite pattern from sustained responses. For example, transient responses in the cuneus were greater during the physical and non-letter-matching tasks than during the name-matching task,

and responses in the middle frontal gyrus were more negative in the name and non-letter-matching tasks than in the physical-matching task.

No effect of task

Several regions exhibiting sustained activity that did not differ across the three tasks were defined based on the voxel-wise t test assessing the magnitude of the response across all tasks (see Table 2). Regions in the medial and superior frontal gyri, left precentral gyrus, and bilateral middle temporal gyrus exhibited significant increases in sustained activity across the three tasks (see Fig. 4A). Regions in the inferior medial frontal and cingulate gyri and the left caudate exhibited significant decreases in sustained activity across the three tasks (see Fig. 4B). Critically, none of these regions exhibited an effect of task in the region-based ANOVA; therefore, sustained activity was essentially equivalent across the three tasks in these regions.

A few of these regions, such as the one in the middle temporal gyrus shown in Fig. 4A, exhibited the opposite pattern of results in the transient responses. However, many regions, such as the inferior medial frontal gyrus shown in Fig. 4B, exhibited transient responses that were in the same direction as the sustained responses.

Behavioral

Results from the analyses of response times and error rates during the three matching tasks are listed in Table 3. Both analyses revealed main effects of task type, $F_{rt}(2, 34) = 31.82$, $P < 0.0001$, for the response times, and $F_{err}(2, 34) = 14.73$, $P < 0.0001$, for the error rates. Simple effect contrasts revealed longer responses times and a greater percentage of errors during the non-letter-matching task than during both the name-matching task, $F_{rt}(2, 34) = 47.61$, $P < 0.0001$, $F_{err}(2, 34) = 10.37$, $P < 0.0005$, and the physical-matching task, $F_{rt}(2, 34) = 47.83$, $P < 0.0001$, $F_{err}(2, 34) = 23.98$, $P < 0.0001$. Moreover, response times and error rates during the

Table 1
Regions exhibiting an effect of task

Region	BA	x	y	z	Peak Z	Voxels	Sustained		Transient	
							t test	Task	Time	Task
Name > physical = non-letter										
R Inferior frontal	45	43	16	13	2.58	62	**	**	***	***
R Inferior frontal	44	40	−9	12	2.93	112	−	***	***	**
R Putamen	−	19	−3	12	2.74	112	−	***	***	***
R Middle frontal	9	22	37	34	2.65	80	*	***	*	***
L Superior temporal	22	−61	−51	14	3.19	107	−	***	***	**
L Middle temporal	20	−59	−31	−13	2.69	86	−	***	**	−
Non-letter < name = physical										
L Cuneus	19	−3	−75	33	3.09	152	−	***	***	**
R Lingual	19	17	−50	1	2.70	69	−	***	***	*
Physical < name = non-letter										
R Middle frontal	8	29	24	39	2.98	101	−	***	*	***
L Middle frontal	8	−27	20	41	2.86	93	−	***	***	***
R Medial frontal	9	2	28	42	2.95	119	**	**	**	***
R Inferior parietal	40	43	−55	45	2.58	64	*	**	−	**
R Inferior parietal	40	47	−39	45	2.84	132	−	***	***	*
L Inferior parietal	40	−54	−33	49	2.79	92	−	***	***	*

Approximate Brodmann area (BA) and peak locations (x , y , z in mm) in the Talairach and Tournoux (1988) atlas with associated significance (peak Z) and number of voxels. Sustained and transient columns display statistics from regions-based analyses. *, **, and *** indicate significance levels for the tested effects at $P < 0.05$, $P < 0.005$, and $P < 0.0005$, respectively.

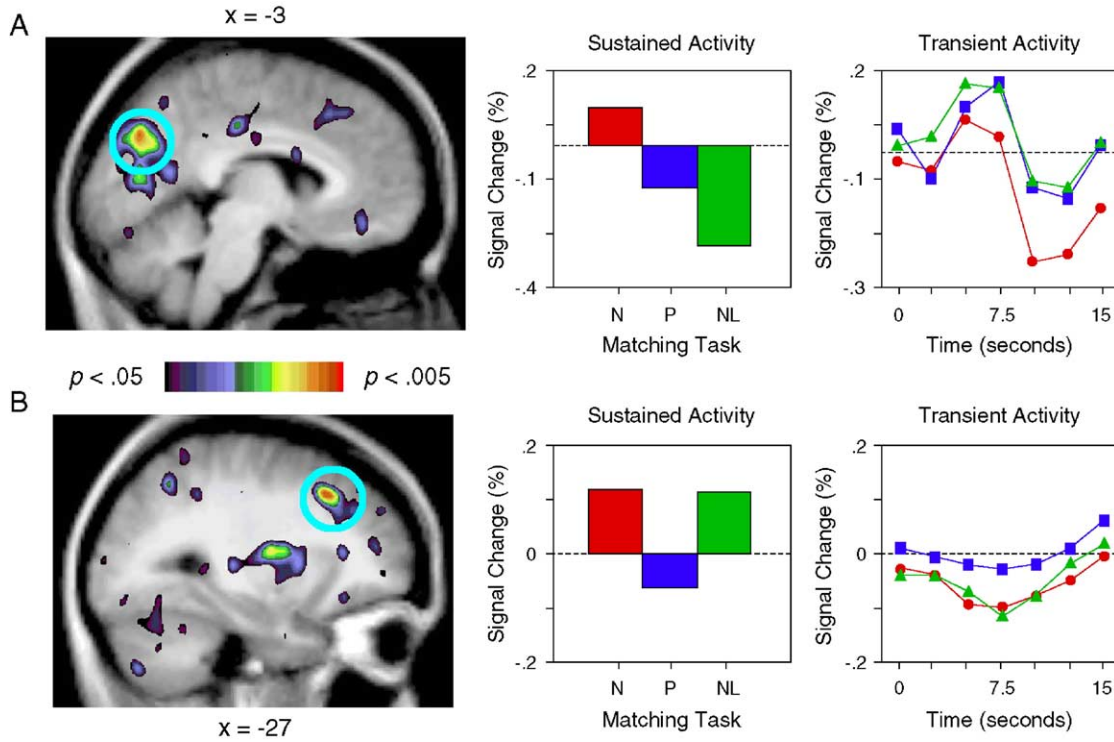


Fig. 3. Regions within the cuneus (A [−3, −75, 33]) and left middle frontal gyrus (B [−27, 20, 41]) defined based on the voxel-wise ANOVA assessing task type. Sustained and transient activity is displayed for each region using the same conventions as Fig. 2.

name and physical-matching tasks did not differ, $F_{\text{N}}(2, 34) < 1$, $F_{\text{err}}(2, 34) = 2.81$, $P > 0.07$.

Discussion

In the present research, we examined sustained and transient neural activity using fMRI during three visual-matching tasks that varied in the amount of verbal processing required. The name-matching task, in which subjects matched letters according to their

name (e.g., A a), required a high degree of verbal processing, whereas the physical-matching task, in which subjects matched letters according to their physical identity (e.g., A A), and the non-letter-matching task, in which subjects matched unfamiliar, letter-like forms according to their physical identity, required little or no verbal processing. Results revealed several regions that exhibited differences in sustained activity across the three tasks. Most notably, two regions within the right inferior prefrontal gyrus exhibited increased sustained activity during the name-matching task, but not during the physical- or non-letter-matching tasks,

Table 2
Regions exhibiting no effect of task

Region	BA	x	y	z	Peak Z	Voxels	Sustained		Transient	
							t test	Task	Time	Task
Overall increase										
L Medial frontal	6	−3	4	50	3.27	214	***	−	***	−
L Superior frontal	8	−8	37	44	2.89	68	***	−	***	−
L Precentral	4	−44	−16	42	2.91	65	***	−	***	*
L Middle temporal	21	−60	−37	1	2.95	64	***	−	**	−
R Middle temporal	21	57	−37	−1	2.92	110	***	−	*	−
R Middle temporal	21	46	−34	−4	2.88	81	***	−	***	−
R Middle temporal	21	58	−27	−6	3.14	189	***	−	***	−
Overall decrease										
R Inf. medial frontal	10	7	59	2	−3.10	133	***	−	−	−
R Inf. medial frontal	10	11	49	3	−2.82	82	**	−	***	−
L Inf. medial frontal	10	−3	48	4	−2.83	83	***	−	***	−
R Inf. cingulate	24	11	39	0	−3.48	163	***	−	***	−
L Caudate	−	−15	21	4	−2.83	65	***	−	***	−

Approximate Brodmann area (BA) and peak locations (x, y, z in mm) in the Talairach and Tournoux (1988) atlas with associated significance (peak Z) and number of voxels. Sustained and transient columns display statistics from regions-based analyses. *, **, and *** indicate significance levels for the tested effects at $P < 0.05$, $P < 0.005$, and $P < 0.0005$, respectively.

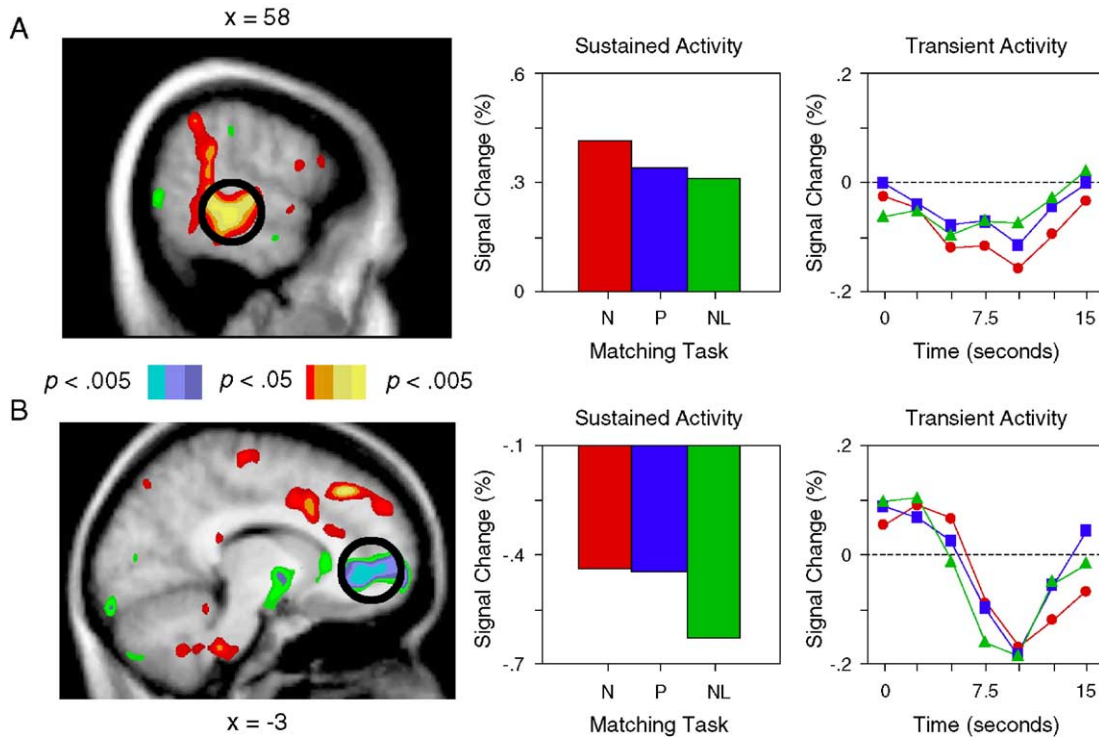


Fig. 4. Regions within the right middle temporal gyrus (A [58, -27, -6]) and the inferior medial frontal gyrus (B [-3, 48, 4]) defined based on the voxel-wise t test assessing the magnitude of sustained activity across all tasks. Sustained and transient activity is displayed for each region using the same conventions as Figs. 2 and 3.

suggesting that these regions play an important role in verbal processing. Furthermore, the majority of regions showing differences in sustained activity across the three tasks, including those in the right inferior prefrontal gyrus, exhibited the opposite pattern of transient activity. That is, as sustained activity during one of the tasks increased, transient activity during that task decreased, and vice versa. In combination, these results suggest that sustained and transient activities interact to produce the context-appropriate response during visual-matching tasks.

The role of the right inferior prefrontal gyrus in verbal processing

Previous neuroimaging studies have observed greater activity in regions within the right inferior prefrontal cortex during non-verbal processing tasks than during verbal processing tasks (Kelley et al., 1998; McDermott et al., 1999; Wagner et al., 1998). Critically, these studies employed blocked designs in which sustained and transient responses were confounded. In the present study, in which sustained and transient responses were separated using a mixed blocked/event-related design, greater transient activity was observed during non-verbal processing tasks (the physical and

non-letter-matching tasks) compared to verbal processing tasks (the name-matching task), in regions within the right inferior prefrontal cortex. In contrast, greater sustained activity was observed during the verbal processing task compared to the non-verbal processing tasks. These findings suggest that previous studies employing blocked designs may have been more sensitive to differences in transient activity than to differences in sustained activity, and thus, highlight the importance of separating sustained and transient responses using a mixed blocked/event-related design.

The role of sustained activity in right inferior prefrontal regions during verbal compared to non-verbal processing tasks has not been examined directly in previous studies. However, results from the present study are in line with results from a study examining sustained and transient activity during an object-naming task (Burgund et al., 2003). In the object-naming study, increased sustained activity paired with no transient activity was observed in a region within the right inferior prefrontal gyrus that was very close (within ~10 mm) to the anterior region observed in the present study (47, 19, 10 compared to 43, 16, 13 in stereotactic space [Talairach and Tournoux, 1988]). In the present study, this pattern of results was observed during the name-matching task, but not during the physical or non-letter-matching tasks. In combination, results from these studies provide strong support for the role of sustained activity in right inferior prefrontal cortex during verbal processing. Despite differences between the name-matching task in the present study and the object-naming task used by Burgund et al. (2003), such as stimulus type (letter vs. picture), behavioral response (button press vs. overt verbal response), and task (matching vs. naming), similar effects were observed. Indeed, the only common element between the two tasks is that both require

Table 3
Responses times and error rates during visual matching

Task	Response time (ms)	Error rate (%)
Name matching	1037 ± 296	3.4 ± 8.3
Physical matching	1038 ± 292	0.9 ± 1.5
Non-letter matching	1078 ± 208	8.2 ± 2.4

Mean response times and error rates during the three tasks. ± indicates standard deviations from the mean.

processing of a stimulus' name. Moreover, processing of name information is the task requirement that distinguished the name-matching task from the physical- and non-letter-matching tasks in the present study. Thus, regions within the right inferior prefrontal gyrus exhibit increased sustained activity and decreased transient activity during tasks that require processing of name information.

Interaction between sustained and transient signals

An opposite pattern of sustained and transient activity was observed in many of the regions exhibiting a difference in sustained activity across the three tasks. For example, regions in the right putamen, right middle frontal gyrus, and left middle and superior temporal gyri exhibited similar patterns of sustained and transient activity as regions within the right inferior frontal gyrus—increased sustained activity during the name-matching task paired with decreased transient activity, and little or decreased sustained activity during the physical- and non-letter-matching tasks paired with increased transient activity. Other regions that were sensitive to other differences between the three tasks also exhibited opposite patterns of sustained and transient activity. For example, in the cuneus (see Fig. 3A), relative decreases in sustained activity were associated with relative increases in transient activity during the non-letter-matching task. In the left middle frontal gyrus (see Fig. 3B), increased sustained activity was paired with decreased transient activity in the name- and non-letter-matching tasks. Thus, increased sustained activity seems to be associated with decreased transient activity, and vice versa, in many regions throughout the cortex, providing further support for the hypothesis that sustained and transient responses interact to produce the correct, context-appropriate response during visual-matching tasks.²

In addition to regions showing differences in sustained activity across the three tasks, several regions exhibited equivalent activity across the three tasks, suggesting that these regions may control aspects of processing that are common across the three tasks, such as pressing a button or making a sameness judgment. Some of the regions exhibiting equivalent sustained activity across tasks exhibited the opposite pattern of transient activity, but many did not. The inconsistent relationship between sustained and transient responses in these regions suggests that the interaction between sustained and transient activity is not the same in all regions. For example, increased sustained activity in the right middle temporal gyrus was paired with decreased transient activity (see Fig. 4A), suggesting that sustained and transient activity may interact in a manner similar to that observed in regions exhibiting differences between tasks. However, in the inferior medial frontal gyrus, decreased sustained

activity was paired with decreased transient activity (see Fig. 4B). Thus, the opposite pattern of sustained and transient activity that was observed in many regions was not obligatory, suggesting that task-specific processing may be controlled through multiple mechanisms.

Conclusions

The present mixed blocked/event-related design study demonstrates the role of sustained activity in the right inferior prefrontal cortex during a relatively verbal task (name matching) compared to less verbal tasks (physical and non-letter matching). In addition, the opposite pattern of sustained and transient activity that was observed in many regions, including the right inferior prefrontal, suggests that sustained and transient activities interact to produce the context-appropriate response during visual-matching tasks. Interactions between sustained and transient activity in right inferior prefrontal regions, as well as others, may be the mechanism through which appropriate neural processing pathways are selected and controlled.

Acknowledgments

B.L.S. is a scholar of the Child Health Research Center of Excellence in Developmental Biology at Washington University School of Medicine (HD01487). Other support for this research was provided by the McDonnell Center for Higher Brain Function, and by the National Institute of Health, NS32979, NS51733, NS55582, and LM06858. In addition, we thank David Balota for helpful discussions that lead to this work, and Francis Miezin, Abraham Snyder, and Chaiyapoj Netsiri for invaluable technical assistance.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at [doi:10.1016/j.neuroimage.2004.12.039](https://doi.org/10.1016/j.neuroimage.2004.12.039).

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² It was suggested by an anonymous reviewer of this article that the opposing patterns of sustained and transient activity observed in many of the regions may be spurious. That is, opposing patterns in the signals may have emerged from a lack of fit in the models from which the signals were estimated. To examine this possibility, we created datasets based on the parameters from the present experiment using a computer simulation (Bay Zero; Buckner et al., 1998; Burock et al., 1998; Kelly et al., 2002; see also, Burgund et al., 2002; Visscher et al., 2003). Results from these simulations indicate that sustained and transient signals were estimated accurately in the present experiment; thus opposing patterns of sustained and transient activity observed in many of the regions were not spurious. Details of the simulations are described in the online Supplement associated with this article.

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