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Behavioural and brain responses related to Internet search and memory

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Abstract

The ready availability of data via searches on the Internet has changed how many people seek and perhaps store and recall information, although the brain mechanisms underlying these processes are not well understood. This study investigated brain mechanisms underlying Internet-based vs. non-Internet-based searching. The results showed that Internet searching was associated with lower accuracy in recalling information as compared with traditional book searching. During functional magnetic resonance imaging, Internet searching was associated with less regional brain activation in the left ventral stream, the association area of the temporal-parietal-occipital cortices, and the middle frontal cortex. When comparing novel items with remembered trials, Internet-based searching was associated with higher brain activation in the right orbitofrontal cortex and lower brain activation in the right middle temporal gyrus when facing those novel trials. Brain activations in the middle temporal gyrus were inversely correlated with response times, and brain activations in the orbitofrontal cortex were positively correlated with self-reported search impulses. Taken together, the results suggest that, although Internet-based searching may have facilitated the information-acquisition process, this process may have been performed more hastily and be more prone to difficulties in recollection. In addition, people appear less confident in recalling information learned through Internet searching and that recent Internet searching may promote motivation to use the Internet.

Introduction

The availability and widespread use of Internet search engines has changed the ways in which individuals find information and may impact how they store and recall information. The ready availability of information on the Internet may decrease the value of needing to store and recall data. Sparrow *et al.* (2011) suggested that people may be becoming better at remembering where information is located than at recalling information; this has been termed the 'Google effect'. This Google effect resonates with a transactive theory of memory (Wegner, 1995) in which individuals may employ fewer resources relating to remembering shared information if they believe that someone or something has that information readily available.

Data suggest that utilizing search engines may influence brain activation patterns and behaviours. It has been suggested that members of the 'Google generation' (individuals born after 1993) may demonstrate weaker working memory and be less confident about their answers as compared with older individuals, even if they retrieve information and make responses more rapidly (Nicholas *et al.*, 2011). In a functional magnetic resonance imaging (fMRI) study involving middle-aged and older adults, Internet-searching behaviours were associated with specific patterns of brain responses in regions linked to executive functioning (Small *et al.*, 2009).

Given these data, questions are raised as to whether using search engines might change patterns of thinking, especially when facing new questions. If people are using Internet search engines as 'external memory drives' as suggested elsewhere (Sparrow *et al.*, 2011), they may show a diminished ability to remember knowledge learned through Internet-based searches. To explore this, we compared brain activations in recalling information learned through Internet-based and encyclopedia-based searches. We hypothesized that information learned through Internet-based searching might be less likely to be accurately recollected than that obtained through book-based searching, and that neural processes underlying the recollection of Internet-based vs. book-based information acquisition might differ with respect to the circuitry implicated in memory recall processes. Specifically, involvement of the ventral stream [involved in object identification and recognition (Mishkin & Ungerleider, 1982; Goodale *et al.*, 1991; Goodale & Milner, 1992)] and the dorsal stream (involved in recognizing where objects are in space) were hypothesized to be differentially involved. In addition, by analysing data relating to novel trials in Internet-based vs. encyclopedia-based

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searches, we hypothesized that people who use Internet-based searches to gather data might show less confidence about their abilities to remember the collected information. As studies have suggested that people using Internet-based searches appear better at remembering where information was stored than the information itself (Sparrow *et al.*, 2011), we hypothesized that Internet searching might relate to stronger impulses to use the Internet when faced with new questions, and that these impulses might relate to brain activations that might differ between the Internet-searching and encyclopedia-searching groups and might include regions that have been previously associated with drug cravings [e.g. the orbitofrontal cortex (OFC) (Chase *et al.*, 2011; Konova *et al.*, 2013)]. Given that the Internet-searching and encyclopedia-searching groups may differ in memory-related processing, we also hypothesized that between-group differences might exist during the presentation of novel stimuli in regions implicated in memory processing [e.g. middle temporal gyrus (MTG)], and that such activations might relate to response times (RTs) to the novel questions.

Materials and methods

Participant selection

The experiment conformed to The Code of Ethics of the World Medical Association (Declaration of Helsinki). The Human Investigations Committee of Zhejiang Normal University approved this research. The 50 participants were university students and were recruited through advertisements. Participants were randomly assigned into one of two groups: one using an Internet-based search engine and the other using an encyclopedia. The participants' ages ($t_{48} = 0.38$, $P = 0.66$) and gender composition ($t_{48} = 0.04$, $P = 0.93$) were balanced with no statistical differences observed between the Internet and encyclopedia groups. All participants provided written informed consent and underwent structured psychiatric interviews [using the the MINI-International Neuropsychiatric Interview (MINI)] (Lecrubier *et al.*, 1997) performed by an experienced psychiatrist. The MINI was designed to meet the need for a short but accurate structured psychiatric interview for multicentre clinical trials and epidemiology studies (Lecrubier *et al.*, 1997). All participants were free of psychiatric disorders (including depression, anxiety disorders, schizophrenia, and substance dependence disorders) as assessed by the MINI.

Task

Before fMRI, participants were asked to search and remember 60 items in order to make them accustomed to the acquisition method (Internet-based or encyclopedia-based). Participants were next asked to recall the 60 items during fMRI. During recollection, some new trials that they had not experienced previously would appear randomly, which were intended to elicit impulses to use the relevant search tools or recall information from their memory. Only 20 novel items were presented randomly, and none were presented in the first five trials. The current study focused on two issues: (i) the behavioural and brain response when participants recalled the information that they learned through Internet/encyclopedia searching; and (ii) the behavioural and brain responses when participants encountered novel search items.

Before scanning, participants were asked to find the answers to 60 questions and to remember the answers. One group was asked to find answers through an Internet search engine (Internet group) and the other group was asked to find answers through the use of a traditional printed encyclopedia (Encyclopedia group). Participants were asked to find the results and to remember all items within 40 min. This time duration was set based on a pilot study and was sufficient for subjects to perform the task. In order to avoid participants' recitation during the waiting period after the search–remember process, participants were asked to perform a 5-min distraction task (e.g. continuously subtract 4 from 99) and to complete a few questionnaires (taking about 5 min).

The participants were asked to find the answers to the questions and to remember them without taking notes in order to promote memory generation and recall processes. In the Encyclopedia group, questions were presented on printed, laminated pages. In the Internet group, the questions were shown on a computer screen in PDF format.

To avoid potential effects from participants' previous knowledge, the questions selected related to uncommon topics (e.g. the age of the first animal sent into space). In addition, participants were asked to identify questions to which they already knew the answers during learning. These items were excluded from further analysis (nine trials in all subjects). We doubled-checked the search results of all of these items before the experiment in both encyclopedia-related and Internet-related ways.

During fMRI, participants were asked to perform a recall and recognition task (Fig. 1). Stimuli were presented and behavioural data were collected using E-prime software (Psychology Software Tools, Inc.). Each scan consisted of 80 trials, 60 previously learned trials and 20 novel trials, and the latter are the focus of the present study. In each trial, a fixation was presented first for 500 ms, and then a recall period lasted for up to 4000 ms. In this period, one question was presented, and participants were asked to read and recall the items and to select 'remember' or 'forget' via button press. The stimulus turned black after the button press and the blackness lasted for (4000 – RT) ms. A black screen was presented for a duration of 500–2500 ms, with the duration jittered. A recognition question followed (the same question as in the recall stage) in which participants were asked to choose one answer from the options listed. This stage lasted for up to 2000 ms, awaiting a

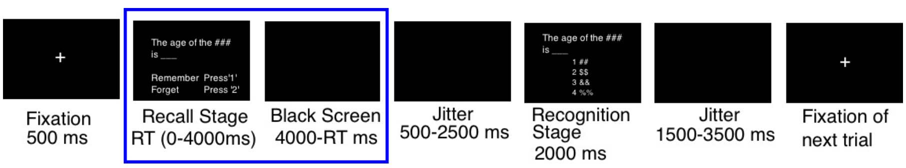

FIG. 1. The timeline of one trial in the fMRI task. In each trial, a fixation was presented first for 500 ms. A recall period followed, lasting for 4000 ms at most. During this period, one question was presented, and participants were asked to read and recall the items and select 'remember' or 'forget' with relevant key presses. The stimulus turned black after the key pressing and lasted for (4000 − RT) ms. A black screen, jittered from 500 to 2500 ms, was presented. The recognition stage (same question as during the recall stage) followed; at this point, participants were asked to choose one answer from the listed possibilities. This stage lasted for 2000 ms or until a button press, with the black screen following the button press to complete the 2000-ms duration. A jitter ranging from 1500 to 3500 ms followed. In this study, we focused on brain activations in the recall stage (the window in the blue frame) during presentation of novel stimuli.

button press, which was followed by a black screen with a jittered interval ranging from 1500 to 3500 ms (Fig. 1). We focused analyses on the recall stage in the current study.

Participants were told that they would be paid a guaranteed 50 Yuan (≈8 US$) for participation and, to encourage their motivation to respond accurately, were told that they would be rewarded with an additional 0–80 Yuan based on their task performance. Specifically, if they responded 'remember' in the 'recall' stage and chose the correct answer in the 'recognition' stage, they would gain an extra 1 Yuan for each trial. If they responded 'remember' in the 'recall' stage and chose the incorrect answer in the 'recognition' stage, they would lose 1 Yuan. The other responses were not rewarded or punished. These strategies were implemented to help to ensure that participants would perform the task in an honest and memory-based fashion. Only trials for which participants answered 'remember' in the recall stage and chose the right answer in the recognition stage were included in analyses. The following numbers of trials (mean ± SD) were evaluated per participant: (i) trials without clues: Internet group, 25 ± 1.92; Encyclopedia group, 30 ± 2.07 and (ii) trials with clues: Internet group, 17 ± 0.98; Encyclopedia group, 18 ± 0.83.

A short self-reported questionnaire was presented to participants after they finished their scan. The questionnaire focused on three aspects of their feelings about their answers, including estimated accuracy rates, strength of impulses to search the Internet when facing novel trials, and strength of impulses to search the encyclopedia when facing novel trials (Data S1).

Structural images were collected using a T1-weighted three-dimensional spoiled gradient-recalled sequence covering the whole brain (176 slices; repetition time, 1700 ms; echo time, 3.93 ms; slice thickness, 1.0 mm; skip, 0 mm; flip angle, 15°; inversion time, 1100 ms; field of view, 240 × 240 mm; in-plane resolution, 256 × 256). fMRI was performed on a 3T scanner (Trio, Siemens) with a gradient-echo EPI (echo planar scanning) T2-sensitive pulse sequence in 33 slices (interleaved sequence; thickness, 3 mm; time repeat (TR), 2000 ms; flip angle, 90°; field of view 220 × 220 mm; matrix 64 × 64). Stimuli were presented using a synchronous system (Invivo Company, www.invivocorp.com/) through a screen in the head coil, enabling participants to view the stimuli. The whole experiment lasted for 15 min.

The functional data were analysed using SPM8 (http://www.fil.ion.ucl.ac.uk/spm), and Neuroelf (http://neuroelf.net) as described previously (DeVito *et al.*, 2012; Krishnan-Sarin *et al.*, 2013). Images were slice-timed, reoriented, and realigned to the first volume, with T1-coregistered volumes used to correct for head movements. Images were then normalized to MNI space and spatially smoothed using a 6-mm FWHM Gaussian kernel. A general linear model was applied to identify blood oxygen level dependence activation in relation to separate event types. Six head-movement parameters derived from the realignment stage were included to exclude motion-related variances. The level of Internet-search using was included as a covariate during analyses (Data S1). Working memory was also measured as a covariate. A general linear model-based approach was used to identify voxels that were significantly activated for the event that was modelled.

In this study, we focused on group differences in brain responses to trials learned through different search tools and the novel trials. We first tested for voxels that showed higher or lower activity in the contrasts of different types of questions (questions without clues vs. questions with clues) in different groups. Second, we compared these two groups in the comparisons (Internet group vs. Encyclopedia group). Family-wise error thresholds were determined using AlphaSim. Significant clusters (family-wise error-corrected, $P < 0.001$) were thresholded at $P < 0.001$ (two-tailed, uncorrected) with an extent of at least 14 voxels, based on the unresliced voxel size (3*3*3). All steps were performed with pipeline software Neuroelf (Neuroelf.net). The smoothing kernel used during simulating false-positive (noise) maps using AlphaSim was 6 mm, estimated from the residual fields of the contrast maps being entered into the one-sample *t*-test. The formula used to compute the smoothness was that used in FSL (for more information, see http://www.fmrib.ox.ac.uk/analysis/techrep/tr00df1/tr00df1/node6.html).

Correlational analyses between behavioural performance and brain response

We selected the surviving clusters as regions of interest for further analysis. For each region of interest, a representative blood oxygen level dependence beta value was obtained by averaging the signal of all of the voxels within the region of interest. During the comparison between brain activities in recalling information gathered through Internet/Encyclopedia searching, we performed the correlations between brain activations in the surviving areas of the left ventral stream (mean value of clusters 1–4 in Table 1), the association area of the temporal-occipital-parietal lobes (mean value of clusters 8–10 in Table 1), the middle frontal lobe (mean value of clusters 11 and 12 in Table 1) and behavioural performances (RT, accuracy rates). In comparing brain activations with novel stimuli in different groups, we performed the correlations between brain activations in the MTG and RTs and between the OFC activation and self-reported responses.

Results

Behavioural performance

Behavioural performance in the 'search–remember' process

During the learning period, all participants finished the search–remember process in 40 min. However, the mean time for the process in the Encyclopedia group was longer than that in the Internet group (33.27 ± 2.24 vs. 25.42 ± 1.67 min; $t = 3.013$, $P = 0.003$).

Behavioural performance in the recall process

The RTs in the 40 trials without clues in the Internet and Encyclopedia groups were similar ($t = -1.44$, $P = 0.156$; Fig. 2a). However, the accuracy rate in the Internet group was lower than that in the Encyclopedia group ($t = -2.91$, $P = 0.005$; Fig. 2b).

Behavioural performance to novel stimuli

For the novel trials, the RT in the Internet group (mean ± SD: 2152.94 ± 424.36 ms) was longer than that in the Encyclopedia group (1838.57 ± 373.95 ms; $t_{48} = 2.757$, $P = 0.008$). In self-reported responses, the Internet group (5.68 ± 1.46) reported higher Internet-search impulses when facing novel items than did the Encyclopedia group (2.19 ± 1.17) ($t_{48} = 9.427$, $P = 0.000$). With respect to encyclopedia-search impulses, the Internet group (3.48 ± 1.36) showed similar responses as compared with the Encyclopedia group (2.88 ± 1.31; $t_{48} = 1.596$, $P = 0.117$). With respect to estimated accuracy rates, the Internet group showed numerically lower estimated accuracy rates than their real performance (−0.058 ± 0.054); the Encyclopedia group showed a close estimation of their real performance (0.008 ± 0.043).

TABLE 1. Regional brain activity changes in recall stage in Internet group minus Encyclopedia group

Cluster no.	x, y, z*	Peak intensity	Cluster size†	Region‡	Brodmann's area
Information learned through Internet search/encyclopedia					
1	−12, −84, −3	−4.794	170	L lingual gyrus	37
				L inferior occipital gyrus	19
2	−9, −99, 9	−4.289	25	L occipital lobe, cuneus	18
3	−21, −63, −6	−4.151	36	L lingual gyrus	37
4	−27, −66, −12	−4.856	165	L fusiform Gyrus	37
				L inferior occipital gyrus	19
5	48, −75, 12	−4.133	28	R middle occipital gyrus	18
6	30, −96, 6	−4.038	20	R middle occipital gyrus	18
7	39, −93, −12	−4.020	17	R inferior occipital gyrus	18
8	−51, −42, 9	−4.524	37	L MTG	22
				L superior temporal gyrus	39
9	−54, −66, 15	−3.934	26	L MTG	42
10	−45, −24, 21	−4.141	15	L superior temporal gyrus	40
11	57, −18, 21	−4.008	21	R frontal lobe, precentral gyrus	6
12	−48, −6, 9	−4.560	35	L frontal lobe, precentral gyrus	6,8
New strange trials					
1	63, −57, −6	−3.458	170	R MTG	21
2	21, 57, −3	3.384	93	R orbital frontal gyrus	10

R, right; L, left. *Peak MNI coordinates. †Number of voxels. We first identified clusters of contiguously significant voxels at an uncorrected threshold $P < 0.001$, as also used for display purposes in the figures. We then tested these clusters for cluster-level family-wise error correction $P < 0.001$ and the AlphaSim estimation indicated that clusters with 14 contiguous voxels would achieve an effective family-wise error threshold $P < 0.001$. Voxel size, 3*3*3. ‡The brain regions were referenced to the software Xjview (http://www.alivelearn.net/xjview8) and verified through comparisons with a brain atlas.

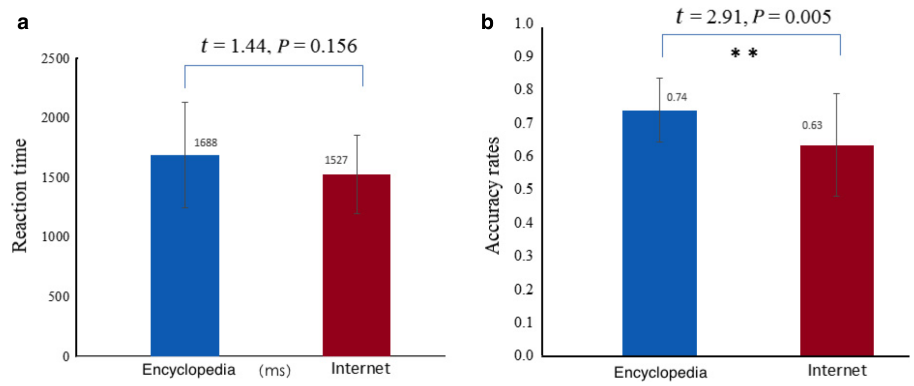

FIG. 2. Behavioural performance in different groups in trials without clues. (a) RTs by group. (b) Accuracy rates by group. $^{**}P < 0.01$.

Imaging results

Imaging results in recalling information learned through Internet searching

As compared with the Encyclopedia group, the Internet group showed less brain activation in the bilateral occipital gyrus, left superior/middle/inferior temporal gyrus, and bilateral middle frontal gryus (Table 1, Fig. 3a). The regions appeared to be located in three main brain areas: the ventral stream (from the occipital cortex to the MTG), the association area of the temporal-parietal-occipital cortices, and the middle frontal cortex (Fig. 3b and c). No brain areas along the dorsal stream were identified. No interactions were found with respect to group (Internet, Encyclopedia) or type (with clues, without clues).

Imaging results when exposed to novel information

As compared with the Encyclopedia group, the Internet group showed greater brain activation in the right OFC and lower brain activation in the right MTG (Table 1, Fig. 4). Beta values showed that the difference in the OFC was related to relatively increased brain activity in the Encyclopedia group; the difference in the MTG was related to relatively decreased activation in the Encyclopedia group.

Correlation results

In recalling information learned through Internet search, significant correlations were found between accuracy rates and brain activations in the association area of the temporal-occipital-partial cortices and the ventral stream. In addition, significant correlations were found between RTs and brain activations in the middle frontal areas and ventral stream (Fig. 5).

When exposed to novel information, brain activations in the MTG were negatively correlated with RTs ($r_{48} = -0.299$, $P = 0.037$). Brain activations in the OFC were positively correlated with self-reported impulses to search the Internet ($r_{48} = 0.297$, $P = 0.036$) but not for searching the Encyclopedia ($r_{48} = -0.013$, $P = 0.929$) (Fig. 6).

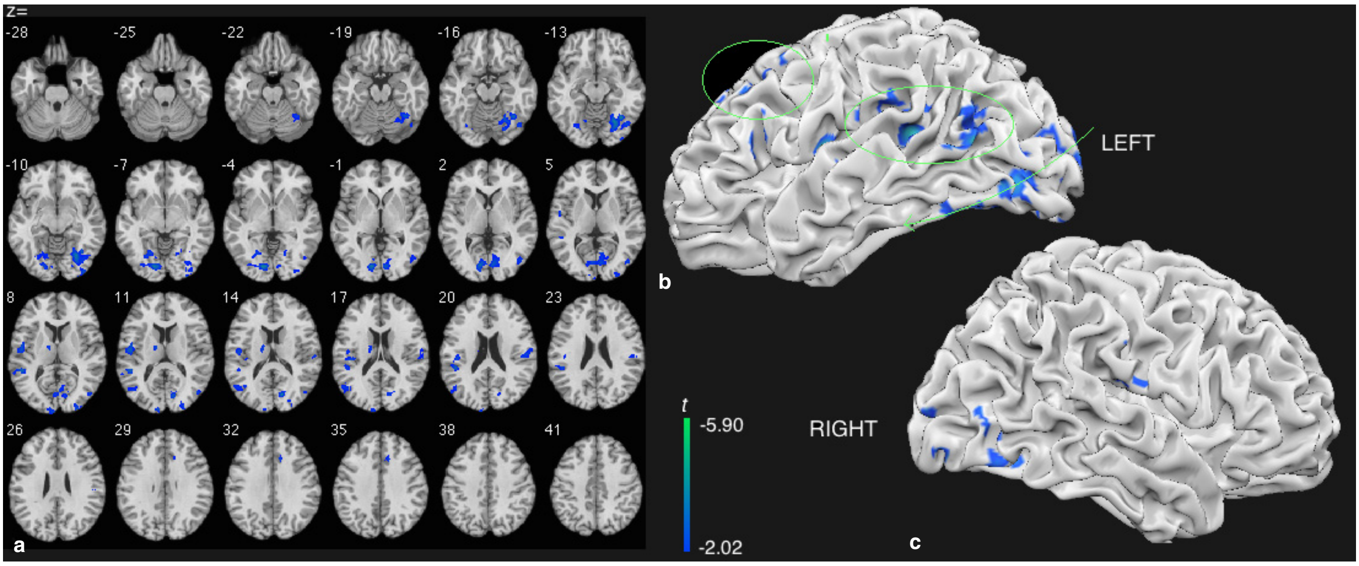

FIG. 3. Brain areas showing different activations when comparing the Internet group with the Encyclopedia group. (a) Brain activations in transverse view. (b) Brain activations in left hemisphere in rendered view. (c) Brain activations in right hemisphere in rendered view.

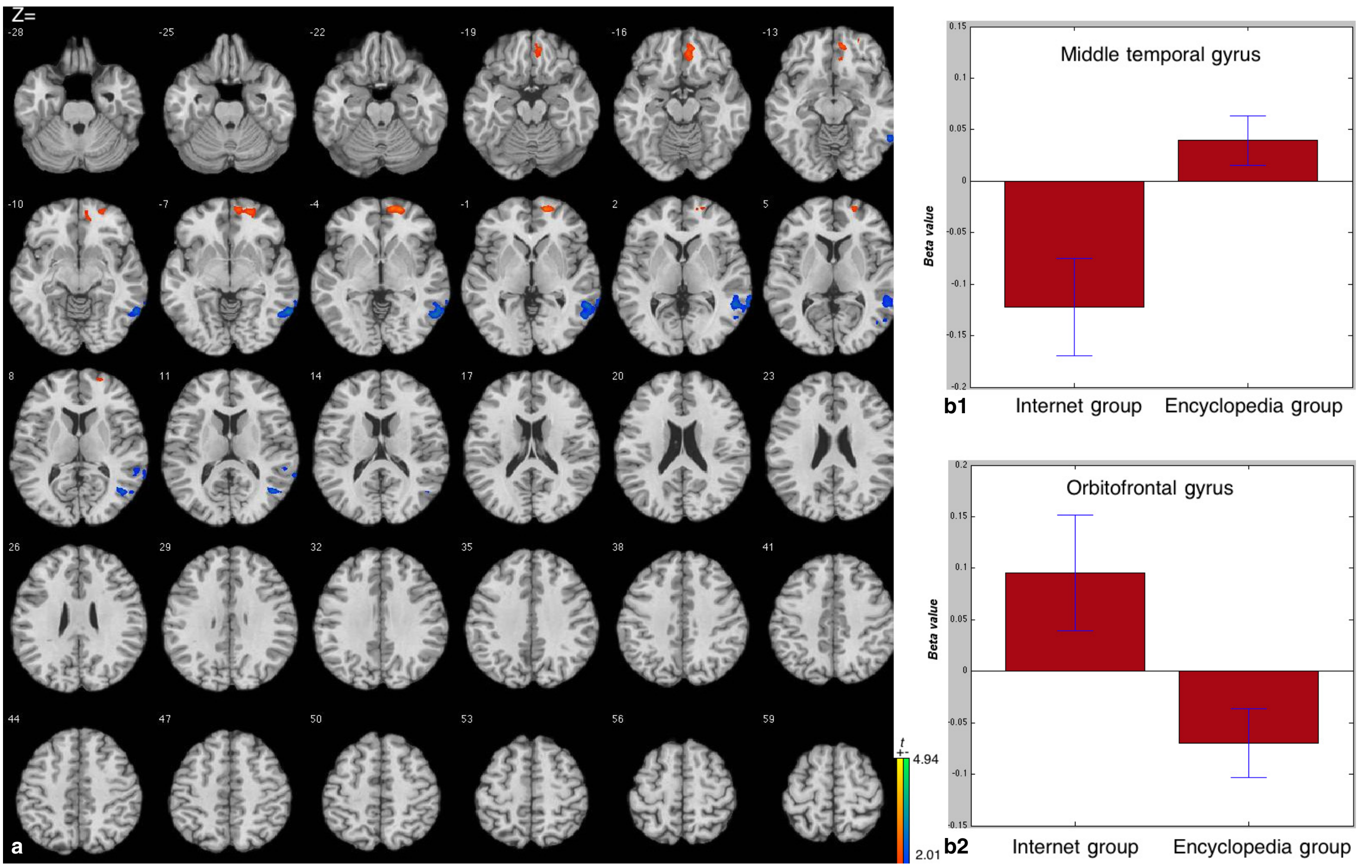

FIG. 4. Brain areas showing different activations to novel trials when comparing the Internet group with the Encyclopedia group. (a) Brain areas showing different activations when comparing the Internet group with the Encyclopedia group with respect to responses to the 20 novel trials. Right side of the brain is on the right. (b1 and b2) Beta figures of MTG and OFC in different groups.

Discussion

This study investigated behavioural and brain responses to information learned through Internet searching and to novel items during fMRI in groups of individuals who had recently used the Internet or an encyclopedia to search for answers to questions. Our findings largely supported our hypotheses.

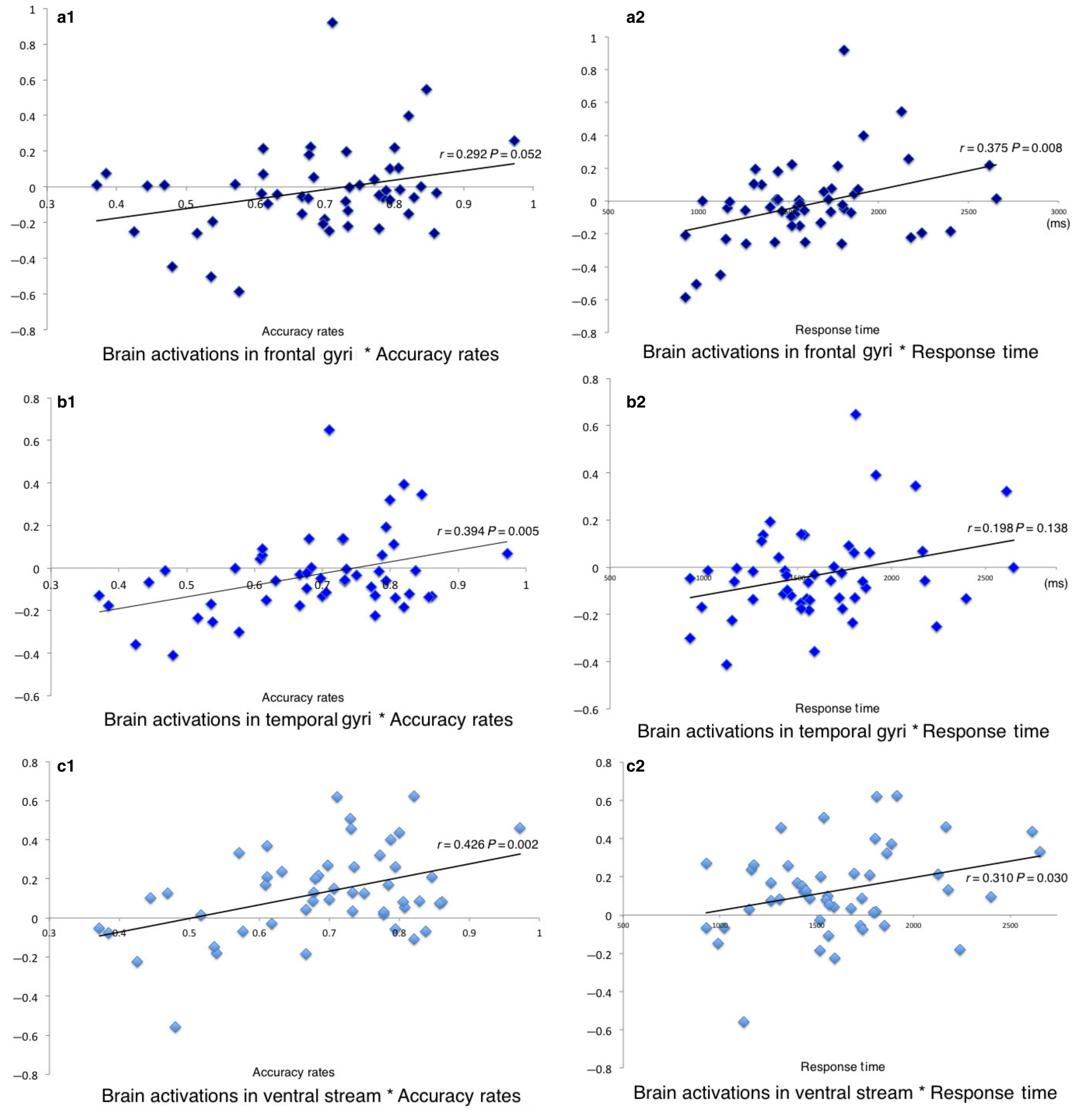

FIG. 5. Correlations between behavioural performance and brain activations in relevant brain regions. (a1, b1 and c1) Correlations between accuracy rates and brain activations in different regions. (a2, b2 and c2) Correlations between responsible time and brain activations in different regions.

Recollection of information learned through Internet searching

The Internet group took less time than the Encyclopedia group to finish a 'search–remember' process. However, they showed lower accuracy rates in recalling information than did the Encyclopedia group. These results suggest that the search engine facilitated the information acquisition process, with participants needing less time to finish the search–remember process; however, after 10–20 min, they showed less ability to recall the information that they were instructed to remember. In other words, participants may obtain information more rapidly using Internet-based search processes, but they also may not recall the information as well.

During fMRI, the Internet group showed less brain activation along the ventral stream. The identified brain regions included the occipital gyrus, inferior temporal gyrus, and fusiform area in the left hemisphere. The ventral stream has been described as the 'what' stream; it travels from V1 in the occipital cortex to the temporal

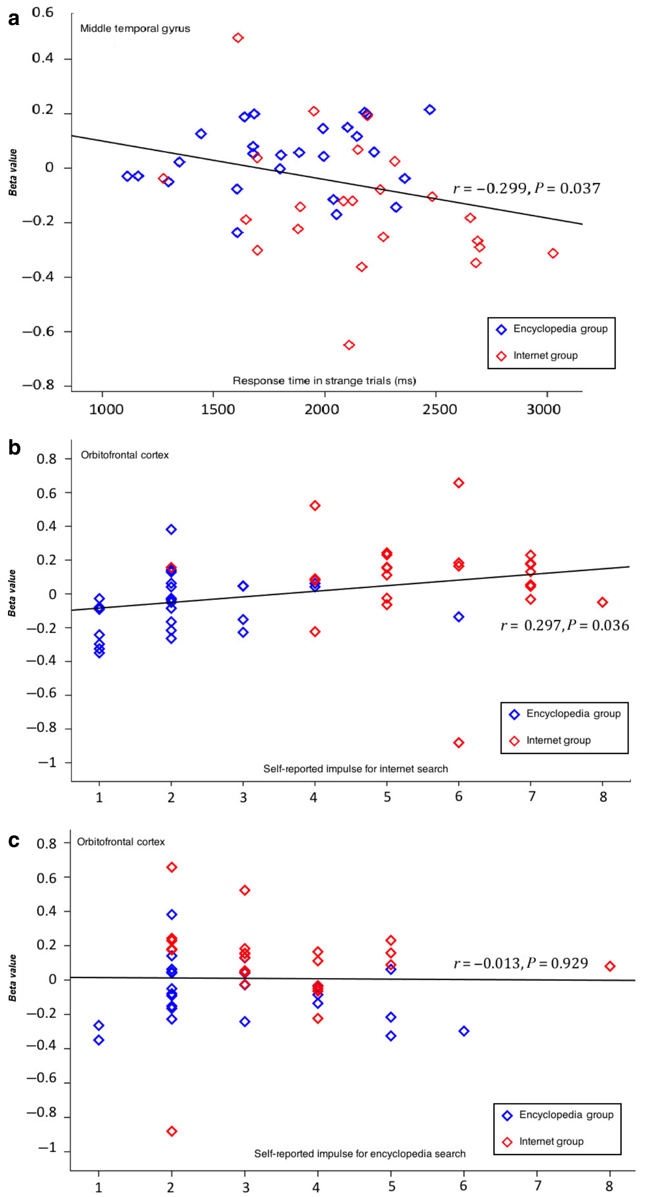

FIG. 6. Correlations between brain activations and behavioural and self-reported responses. (a) Correlation between RT to novel stimuli and brain activations in the MTG. (b) Correlation between self-reported impulses for Internet searching and brain activations in the OFC. (c) Correlation between self-reported impulses for Encyclopedia searching and brain activations in the OFC.

cortex and is involved in object identification and recognition (Mishkin & Ungerleider, 1982; Goodale *et al.*, 1991; Goodale & Milner, 1992). Areas in the ventral stream are influenced by extra-retinal factors including attention, working memory, and stimulus salience (Goodale & Milner, 1992). The positive correlation between activations in the ventral stream and accuracy rates suggests that accuracy in the recall stage was linked to recruitment of this region. In this study, the Internet group showed less brain activation in the ventral stream than did the Encyclopedia group, suggesting that the Internet group may have been less able to recruit the 'what'-processing stream during information recollection. This result is in line with the conclusion of Sparrow *et al.* (2011) that people who use Internet search engines are better at remembering where information is stored than at remembering the information itself. However, inconsistent with our hypothesis, no brain areas were identified in the dorsal stream (also termed the 'where' stream), which is proposed to be involved in recognizing where objects are in space. It is possible that the 'where' information in the Internet is more abstract (i.e. less a 'location' given its virtual nature than a spatial position in the real world); however, this interpretation is speculative and warrants further investigation.

The Internet group (as compared with the Encyclopedia group) also showed less brain activation in the association area of the temporal-parietal-occipital cortex, including several brain regions in the left MTG. The association areas integrate information from different sensory areas and relate the information to past experiences. The medial temporal lobes have been implicated in encoding declarative long-term memory, with declarative memory referring to all memories that are consciously available (Simons & Spiers, 2003; Barense *et al.*, 2005; Axmacher *et al.*, 2008; Jeneson & Squire, 2012; Cohen & Stackman, 2015). Amnesiac patients with damage to the medial temporal lobe as compared with healthy control subjects have been found to perform more poorly on explicit learning tests (Meulemans & Van der Linden, 2003). To examine if the temporal lobe activations were related to memory processing in the current study, we performed a correlation analysis between accuracy rates and identified brain activations. The identified positive correlation suggests that the more that this region was engaged, the higher the accuracy rates that were achieved. In this study, the Internet group showed lower activation in the temporal gyrus during recollection, and this might suggest that they were less able to recruit this region when recalling information. This finding and interpretation are consistent with the observed behavioural performance in which the Internet group showed lower accuracy rates during recollection.

The other identified brain areas included regions of the medial frontal gyrus, precentral gyrus, and superior frontal gyrus. These frontal brain regions contribute to executive functioning, information processing, error awareness and other processes including aspects of working memory, especially free recall (Rushworth *et al.*, 2004; Talati & Hirsch, 2005; Turriziani *et al.*, 2008). Non-verbal working memory has been related to function of the left middle frontal gyrus (Turriziani *et al.*, 2008). In young adults, frontal activation is largely lateralized to the left hemisphere for verbal working memory and to the right for non-verbal working memory (Reuter-Lorenz *et al.*, 2000). In older adults, both verbal and non-verbal memory tasks tend to induce bilateral activation patterns in frontal regions (Reuter-Lorenz *et al.*, 2000). Studies involving multiple patient groups also show that working memory performance is associated with medial frontal cortical function (Amici *et al.*, 2007; Luerding *et al.*, 2008). In the current study, RTs were positively associated with increased medial frontal cortical activations, raising the possibility that shorter RTs may relate to more efficient functioning of the medial frontal cortex. Thus, the lower brain activation in middle frontal brain regions in the Internet group raises the possibility of more efficient processing in this group, whereas the association between activation of this region and accuracy suggests a trade-off between rapid responding and accuracy.

Processing novel information

The Internet group showed lower brain activation in the MTG in the right hemisphere compared with the Encyclopedia group. As described, the MTG has been implicated in encoding declarative long-term memory (Simons & Spiers, 2003; Barense *et al.*, 2005; Axmacher *et al.*, 2008; Jeneson & Squire, 2012; Cohen & Stackman, 2015). The lower MTG activation in the Internet-searching group suggests that they may be engaging this brain region to a lesser degree when encountering novel items. To examine if the MTG activations were related to memory processing in this study, we investigated relationships between brain activations in the MTG and RTs relating to these novel trials. The identified negative correlation between these two factors suggests that the more that this region was engaged, the shorter the RT. In this study, the Internet group showed less brain activation in the MTG and longer RTs in recalling, consistent with the notion that the Internet group may engage less cognitive processing during recollection-related processes. In self-reported 'estimated accuracy rates' about their answers, the Internet group reported lower accuracy than their real performance, which suggests that they may be less confident about their answers, as has been previously suggested (Nicholas *et al.*, 2011). The longer RTs in the Internet group suggest that they may need more time to process and determine whether or not the novel items have been encountered previously. In summary, the current results suggest that people using Internet-search processes to obtain information seem to show less confidence about recalling/determining whether material is novel or has been previously presented, and they show less MTG activation in relation to this processing.

The Internet group also showed greater brain activation in the OFC than did the Encyclopedia group. The OFC contributes importantly to executive control, emotion regulation, impulse inhibition, drug craving in addictions and other processes (Chase *et al.*, 2011; Burguiere *et al.*, 2013; Konova *et al.*, 2013; Rudebeck *et al.*, 2013; Takahashi *et al.*, 2013). The OFC facilitates successful goal-oriented behaviours by inhibiting the influence of emotional information in variable contexts (Bari & Robbins, 2013; Moorman & Aston-Jones, 2014). To examine if the identified OFC activations related to impulses, we performed a correlation analysis between brain activations in the OFC and self-reported search impulses to use the Internet or encyclopedia when encountering the novel items. The positive correlation between OFC activation and self-reported impulses to search the Internet search suggests that OFC activation may link to Internet-use motivations as it does in drug craving in addictions, although this possibility is speculative and warrants further examination. The Internet group reported stronger impulses to search the Internet when encountering novel stimuli than did the Encyclopedia group, which is in line with the notion that recent Internet use may relate to urges to use the Internet. OFC activation was not related to self-reported impulses to search for information using the encyclopedia. The behavioural and imaging results raise the possibility that recent Internet searching promoted motivations to use the Internet and that this may lead to a preference for or reliance on search tools when facing new situations. This result and interpretation resonate with previous suggestions that people may use Internet search engines as 'external memory drives' in a manner that may diminish the importance of using brain-based memories as an informational resource (Sparrow *et al.*, 2011).

This study has several limitations. First, in order to create the oddball 'strange items', we asked participants to search and remember 60 trials before fMRI. As such, the searching process may have affected their performance. Second, the current study focused on declarative memory; future studies should investigate different types of learning and memory processes. Third, although the focus on the 'recall' stage is linked to our hypotheses, other phases of working memory may also relate differentially to Internet and traditional forms of learning. Although studies have found that encoding and decoding memory processes show overlaps with respect to regional brain activations related to these processes, the brain activations involved in recollection processes may differ from those involved in other working memory processes. Future studies should use fMRI tasks that parse different stages of memory processes (e.g. see Panwar *et al.*, 2014) to investigate different types of learning.

Conclusions

The results extend our knowledge on relationships between brain activations and behaviours relating to memory processing linked to Internet-based or book-based searches. Internet searching facilitated information acquisition; however, Internet searching was associated with lower accuracy in recalling information. The identification of specific brain regions linked to these processes raises questions regarding the potential impact of the Internet on learning processes. The findings may also have implications for a broader range of activities (e.g. gaming, gambling) in which people engage using the Internet, and future studies should investigate the possible role of Internet-based learning in recreational and problematic engagement in such behaviours. The findings from brain activations to novel stimuli indicate that people appear less confident about recalling information learned through Internet-based as compared with encyclopedia-based searches, and recent Internet searching appears to promote motivations to use the Internet. Future studies should examine the extent to which these tendencies may relate to learning and memory processes and a possible reliance on search engines when encountering novel problems or situations.

Supporting Information

Additional supporting information can be found in the online version of this article:
Data S1. Self-reported questionnaire after scan.

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Abbreviations

fMRI, functional magnetic resonance imaging; MTG, middle temporal gyrus; OFC, orbitofrontal cortex; RT, response time.

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