Neural Correlates of Realisation of Satisfaction in a Successful Search Process

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ABSTRACT

In a search process, searchers review documents to gather information relevant to their information need (IN). During this process, searchers may experience the satisfaction of their IN, indicating they have gathered adequate relevant information to answer their need. This complex concept of satisfaction is the ultimate goal of search systems. Most studies in Information Retrieval (IR) have been attempted to understand how searchers' needs are satisfied based on behavioural observation. However, the psychophysiological manifestation during the moment of satisfaction still remains unclear. Here, we use functional Magnetic Resonance (fMRI) to investigate which brain regions are involved during the moment of satisfaction. Twenty-six participants participated in the experiment, designed to represent a search process while being scanned. Our result shows the human brain regions involved during the moment of satisfaction. These findings provide an important step in unravelling the concept of satisfaction in a search process.

KEYWORDS

Satisfaction · fMRI · Information Need · Neural Correlates · Search Process.

INTRODUCTION

The satisfaction of an information need (IN) (referred to as satisfaction) is a fundamental concept in Information Retrieval (IR) (Al-Maskari & Sanderson, 2010). From the searcher's perspective, satisfaction can be seen to combine both the accuracy and the completeness of the task that a searcher performs (AlMaskari & Sanderson, 2010). Satisfaction can be explained by the concepts of information seeking and foraging in which a searcher usually needs to acquire new information in order to fulfil their IN(s) (Kuhlthau, 1991; Pirolli & Card, 1999). This could lead to stopping a search process when (i) searchers realise that their INs are satisfied (i.e. a successful search), (ii) the current solution is sufficient to meet the individual's objective (Prabha, Silipigni Connaway, Olszewski, & Jenkins, 2007) (i.e. a sufficient search), or (iii) searchers gave up their search unsatisfied (i.e. an unsuccessful search). In this paper, we aim to understand the underlying brain regions associated with satisfaction in successful search scenarios, and whether cognitive or emotional processes appear to be involved in this phenomenon.

In the field of psychology and cognitive science, satisfying IN(s) could be thought of as an adaptive behaviour (Desender, Boldt, & Yeung, 2018). A searcher can be thought to employ a decision process such as accumulating evidence in completing a task. The evidence accumulation models assume that in a sequential information search, the searchers will terminate their search when sufficient evidence has been accumulated to pass a decision threshold (Hausmann & L¨age, 2008). Thus, the realisation of satisfaction would lead to the stop of the search process. On the other hand, if the decision criterion is not met, then searchers would continue their information search and not show signs of satisfaction.

To understand the concept of satisfaction in a search process, several behavioural studies have been conducted based on observing human search behaviour and conducting surveys (Hassan, Shi, Craswell, & Ramsey, 2013; Hassan & White, 2013; Jiang, Hassan Awadallah, Shi, & White, 2015). However, such studies are limited in explaining what is happening to the internal states of searchers when their IN is being satisfied. Though recently a number of studies have begun to employ brain-imaging techniques such as fMRI and electroencephalography (EEG) to measure neural processing as a means to understand the internal states of searchers when performing search tasks (Moshfeghi, Pinto,

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Pollick, & Jose, 2013; Moshfeghi & Pollick, 2018; Moshfeghi, Triantafillou, & Pollick, 2016). These studies have focused on the brain regions involved in representing relevance and IN, and the neural basis of satisfaction remains unclear.

Therefore, in this paper, we aim to investigate the following research question **(RQ): "What are the brain regions corresponding to the realisation of satisfaction in a successful search process?"**. To answer this research question, we utilised an fMRI technique which provides us with the ability to capture the brain signals of participants while they engage in a search task. This technique has one remarkable advantage over other brain imaging techniques as it provides a superior spatial resolution of the brain signal, particularly in deep regions of the brain that are not readily accessible by other techniques. This is important as previous investigations of IN and satisfaction have revealed that deep brain regions such as the insula and cingulate cortex play an important role (Moshfeghi et al., 2016; Moshfeghi & Pollick, 2018). To use fMRI requires devising compatible paradigms, and we thus developed a novel task by using a puzzle idea where participants need to gather pieces of information by viewing piecewise, individual pieces of an image. This task demonstrates the possibility to simulate an information seeking process and was suitable for an fMRI study. Previous studies also show that using a puzzle as an experimental task could help in simulating an information seeking process (Kelly, 2009; Samimi & Ravana, 2014; Jansen, Bos, van der Vet, Huibers, & Hiemstra, 2010; Hills, Todd, & Goldstone, 2010; Dang Nguyen et al., 2019). This task helps us to examine brain activity during the times when participants were in a state of being satisfied in a successful search, and thus, the resulting brain imaging data enabled us to answer our research question.

The rest of the paper is organised as follows. First, we describe previous related work and background in Section 2. Section 3 provides a detailed methodological approach utilised in this experiment. Results are presented and analysed in Section 4. Lastly, Section 5 outlines the key conclusions.

RELATED WORK

Satisfaction and IR

Information Retrieval (IR) studies how to retrieve relevant information from a data collection in order to fulfil a particular IN. The satisfaction of an IN is similar to solving a jigsaw puzzle where a person needs to find all pieces of a puzzle and integrate them in order to solve the puzzle (Maggitti, Smith, & Katila, 2013; Nieuwenhuysen, 2006; Davies, 1989; Ellis, 1992; Frandsen, 1966). In the information seeking paradigm, the pieces of the puzzle can be considered as documents where searchers have to engage a search system in order to obtain relevant documents. During the search process, the searchers will integrate pieces of relevant documents to fulfil their IN. This is similar to solving a jigsaw puzzle where a player needs to integrate all pieces of the jigsaw to appreciate the full picture. The concept of a jigsaw has been used in several studies in IR, such as evaluating a retrieval system (Kelly, 2009; Samimi & Ravana, 2014; Jansen et al., 2010; Hills et al., 2010; Dang Nguyen et al., 2019)

Satisfaction can be linked to stopping behaviours in the information seeking process, where previous research has formalised the stopping criteria used to terminate a search (Kraft & Lee, 1979). The stopping rules used to terminate a search are fundamental aspects of information seeking behaviour and are thought to include both cognitive and decision-making processes. One way to conceptualise satisfaction is from the viewpoint of the decision process underlying satisfaction. This is typically achieved using the evidence accumulation model (Hausmann & L¨age, 2008), where a searcher has to accumulate evidence, and their decision will be made when the accumulated evidence has reached a decision threshold. In such a framework, satisfaction could also be inferred from a searcher's level of confidence.

The satisfaction of an IN also appears to play a crucial role in Information Seeking Behaviour, which is the field of studying the behaviour of searchers in seeking information to fulfil their need (Wilson, 2000, 1981, 1997). Information seeking models propose that during the early stages of search a searcher will usually feel a lack of information and express a need to engage a search system to gather pieces of relevant information to complete a task (Kuhlthau, 1991; Marchionini, 1997). At the final stage of search, after performing a number of iterations in gathering pieces of relevant information, the searchers usually express the satisfaction of their IN by stopping their search to complete the task (Kuhlthau, 1991; Marchionini, 1997). For example, at the final stage of the information search process model, a searcher will experience a sense of relief after gathering enough pieces of relevant information to solve a problem (1991). However, it is unclear whether the satisfaction process involves cognitive processes, affective processes, or both.

A number of IR studies have been conducted to understand the phenomenon of satisfaction by using implicit measures (e.g., dwell time and click-through) and explicit measures (e.g., self-reported judgments) (Al-Maskari & Sanderson, 2010; Fox, Karnawat, Mydland, Dumais, & White, 2005). For example, Fox et al. (2005) demonstrated an association between searcher satisfaction and implicit measures gathered from behavioural actions during a search task. As well, Hassan et al. (2013) utilised query-reformulation to construct a prediction model of searcher satisfaction based on query-reformulation. In addition, Hassan and White (2013) introduced personalised prediction models of searcher satisfaction that were constructed from searchers' search logs. Liu et al. (2015) suggested mouse movement as another possible implicit factor that should be included in predictive models. Jiang et al. (Jiang et al., 2015) argued that satisfaction could be expressed in different levels and proposed a model that predicted searcher satisfaction at multiple levels. Lastly, work from Mehrotra et al. (2017) applied deep sequential models and novel machine learning techniques to predict satisfaction.

Neuroscience and IR

Recent years have seen IR's field take an increasing interest in neuroscience (Gwizdka & Mostafa, 2016; Gwizdka, Mostafa, Moshfeghi, Bergman, & Pollick, 2013). This interest has focused on gaining an understanding of how the different components of IR emerge from measurable activity in the brain. These studies have employed a wide range of brain imaging techniques to probe brain activity related to brain states involved in processing relevance and IN. Two imaging techniques that are frequently used in these studies are functional magnetic resonance imaging fMRI and EEG, with the choice between techniques often guided by the appropriateness of the technique to the question at hand.

A collection of fMRI studies by Moshfeghi and colleagues (Moshfeghi et al., 2013, 2016; Moshfeghi & Pollick, 2019, 2018; Moshfeghi, Triantafillou, & Pollick, 2019) has focused on using fMRI to understand the brain regions activated during relevance judgment and IN. Results from one study (Moshfeghi et al., 2013) revealed the brain regions that are activated during the relevance judgment process. Another study (Moshfeghi et al., 2016) indicated that IN was reflected by brain processes associated with the switching between internal and external information sources. Relevant to the current research was a study examining how transitions between stages of search related to activity changes in large-scale brain networks (Moshfeghi & Pollick, 2018). While this study included satisfaction as one of the stages it did not focus on satisfaction on its own.

Apart from the use of fMRI, other studies have applied different brain measurement techniques to investigate the concept of IR, especially relevance. For example, EEG has been applied in several studies to investigate the concept of relevance to text information (Gwizdka, Hosseini, Cole, & Wang, 2017; Eugster et al., 2014; Allegretti et al., 2015; Pinkosova, McGeown, & Moshfeghi, 2020). The related technique of Magnetoencephalography (MEG) has also been used to study the relevance of visual information (Kauppi et al., 2015). However, to understand the neural mechanisms of the satisfaction of IN it is important to investigate the activity of the entire brain. As stated in the Introduction, fMRI has the advantage over EEG and MEG in terms of spatial resolution and the ability to measure these deep brain structures. That is why it was used in the current study.

METHODOLOGY

Design

This study used a within-subject design. Participants were first given a caption and then presented with separate tiles of an image with the task of determining whether the caption matches the image. The independent variables were the realisation of satisfaction in a search process (SAT) and the validation of the response (VAL). The dependent variable was the brain activity revealed by the fMRI Blood Oxygen Level Dependent (BOLD) signal.

Participants

Twenty-six participants participated in this study (16 females; aged: 20-43 years, mean age: 25 years). All participants were typically developed and at least 18 years old. The recruited participants were right-handed, had a normal or corrected-to-normal vision. Six participants had head motion exceeding 3mm or 3 degrees and were excluded from the analysis. Two participants did not correctly follow the instructions, and one participant demonstrated poor performance (less than 50 per cent of captions self-reported correct). These three participants were also excluded, leaving seventeen participants entering into the final analysis. All participants were scanned using the fMRI scanner at the Centre for Cognitive Neuroimaging, University of Glasgow.

Stimuli Generation and Validation

Stimuli Generation

We developed a stimuli dataset by carefully selecting images from the Microsoft Common Objects in Context dataset (Lin et al., 2014), which provides a large set of images and a list of captions for each image. In order to obtain images that could be divided into tiles that could be sequentially presented to simulate a search task, we used the following criteria for selecting images from Microsoft COCO: a) an image had to be non-iconic and display everyday scenes. b) an image had to contain at least two objects and could not be easily matched to a caption by one small portion of the image. c) the caption for an image was effortless to understand and described more than one object appearing in the image. With this criteria, 100 images were selected. All images in this subset were converted into grey-scale images, and each grey-scale image was divided into nine tiles by constructing a 3x3 matrix.

Behavioural Study 1: Image Stimuli Selection

We conducted the first behavioural study in order to help distil a final set of images that on average were sufficiently difficult to engage participants to view multiple tiles before answering. A total of twenty-five healthy participants were recruited from the university environment for the study. For every participant, the procedure involved first being presented with a caption that described an image in the data set. Next, participants viewed, in random order and one at a time, the nine tiles that comprised the image. When participants were satisfied with the information extracted from the collection of tiles viewed, they were asked to press a button to indicate that they were satisfied that the caption matches the image. Results showed a distribution of difficulty for the 100 images and in choosing final stimuli we avoided the extremes of this distribution to focus on images that were of moderate difficulty and primarily around the mean of 4-5 tiles to recognise that the caption matched the image. From this study we were able to choose 50 potential images.

Behavioural Study 2: Image Tile Sequence Generation

We conducted a second behavioural study in order to generate appropriate sequences for the presentation of the tiles for each image. Three assessors separately rated relevance using a 3-point scale (0-not relevant, 1-somewhat relevant, and 2-very relevant) for each of the nine tiles of an image. Calculating Fleiss' kappa for each image provided us images that had their component tiles consistently perceived.

We generated a pre-determined sequence for each image by sorting the tiles from the least relevant tile to the most relevant tile. We will use this sequence of tiles in the experimental task in order to simulate an information seeking scenario. At this early stage, participants will typically generate an ill-defined IN, which could identify the first couple of documents as irrelevant (Liu et al., 2018; White & Roth, 2009). So, the participants need to go through a series of documents to be able to complete the task. From this second study, we were able to select a set of images with a calibrated and fixed sequence of tile presentation for the main fMRI experiment.

Stimuli

A total of 24 images were chosen for the experiment. The majority of these images were of moderate difficulty. However, in order to encourage participants to pay attention to all trials, two trials were designed so that the image was inconsistent with the caption, forcing participants to view all tiles. Moreover, to break the pattern that early tiles were of limited relevance two trials were designed such that the first tile fully informed that the image matched the caption. These trials encouraged participants to pay attention to the task, and they also provided results that gave insight into whether participants were following instructions.

Procedure

This section describes the flow of the study, from start to finish. Ethical permission was obtained from the College of Science and Engineering, University of Glasgow. A pilot study was conducted before running the actual experiment in order to confirm that the experimental procedure worked as expected. Participants were instructed of the duration of the experiment, which included approximately 50 minutes to perform all functional brain imaging tasks examining search processes, and approximately 10 minutes to obtain an anatomical scan of brain structure. Participants were informed that they could leave at any point during the experiment and would still receive payment (the payment rate was £6/hr.). They were then asked to sign a consent form. Before beginning, the experiment participants underwent a safety check to guarantee that they did not possess any metal items inside or outside of their body, or had any contraindications for scanning, such as certain tattoo inks. They were then provided with gear (similar to a training suit) to wear for the duration of the experiment to avoid potential interference with the fMRI signal from any metal objects in their clothes.

Before starting the experiment, all participants were asked to complete an entry questionnaire, which assessed the participants' background related to demographics and online search experience. Following this, they performed the main task, as shown in Figure 1 where each participant encountered the experimental conditions related to information search while being scanned. Before starting to engage with the main task, participants were given a corresponding set of example trials in order to familiarise themselves with the procedure. At the completion of the study an exit questionnaire was given to assess participants' experience of the experiment.

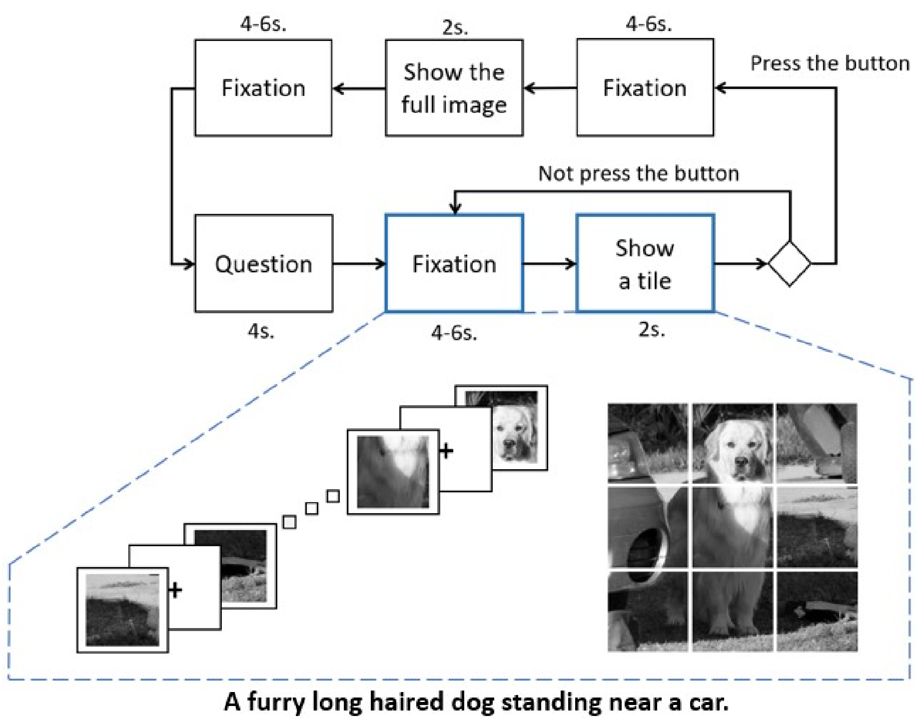

Figure 1. Flowchart of the main task.

Task

Our goal was to design a task that could represent an information search paradigm as well as be compatible with fMRI scanning protocols. The approach would provide a window on the neural and cognitive processes active during an information seeking task. From this approach, we were able to extract and analyse the moment of satisfaction of the participants. For the experimental task, we designed a task that was closely similar to a puzzle game to simulate the information seeking behaviour in the experimental environment (Figure 2). In the task, participants encounter an image puzzle task, where they have to identify whether a caption matches an image. In the task, the image was divided into nine pieces. The participants viewed only one piece of the image at a time. Relating to a web search, each piece of the image could be thought of as a document in a web search that might satisfy an IN of a searcher. A piece of the image could contain relevant/irrelevant information to what the searcher is looking for.

This experimental design is an imitation of the information search paradigm in the information seeking process, where a searcher has to gather pieces of information to fulfil their IN. Each piece of an image in this experiment can be thought of as a relevant/irrelevant piece of information in the search process. The searcher will terminate their search when they realise that they have extracted enough relevant information for determining that the caption matches the image. It should be noted that while the search scenario provided by the current procedure is not entirely congruent with the experience of everyday searches on the internet, it does allow us control over factors such as search history and the granularity of information provided at the moment of satisfaction. These issues of search history and information granularity are important to consider when doing brain imaging studies with fMRI, where not controlling such factors leads to experimental confounds that tremendously complicate the interpretation of brain data.

The task was divided into two phases, as illustrated in Figure 1. The first was a revelation phase where participants were presented a caption and then viewed individual tile pieces of the image presented sequentially until they determined that the image matched the caption. This revelation phase was meant to simulate an information seeking process, where the caption would represent a topic to search, and the individual image tiles would represent documents with differing levels of relevance that are evaluated as part of the search. The second part was a validation phase where participants were shown the entire image so that they could confirm that their response was correct.

In order to encourage participants to pay attention to all trials, two catch trials were designed so that the image was inconsistent with the caption, forcing participants to view all tiles. Two additional trials were added so that the first tile was fully informative that the image matched the caption (breaking the pattern that early tiles were of limited relevance). Participates, who failed to identify these trials were excluded from the analysis.

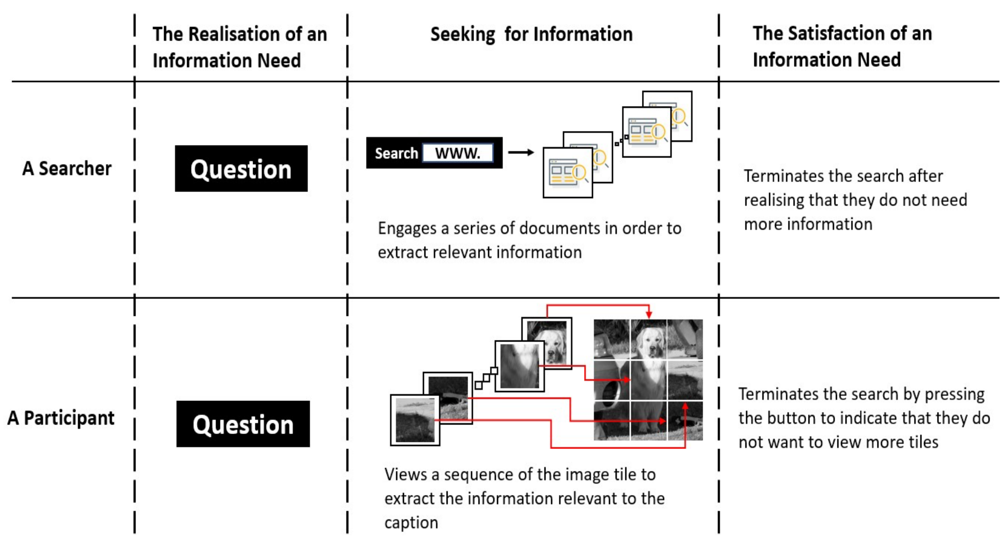

Figure 2. Illustration of the similarity between the web search paradigm and the image puzzle task used in this study and they were asked to press the button again if the response they had provided in the revelation phase was correct.

Revelation Phase

In this phase, for each of the 24 experimental trials, the participants were first presented with a caption followed by a sequence of tiles described in Section 3.3. The task was to decide whether or not the caption was appropriate to the image shown as a sequence of tiles. While image tiles were being presented to participants, they were asked to press a button (the response hand was counterbalanced) as soon as they noticed that the caption matched to the image (i.e., realised they satisfied their task).

Validation Phase

Once participants responded in the Revelation phase, the Validation phase began. In this phase, the image as a whole was shown to participants, and they were asked to press a button again if their response provided in the Revelation phase was correct.

The design of pressing the button at the moment of satisfaction realisation and validation is important for data analysis. We chose to contrast brain activity at these two periods since both include a button press and general recognition processes. In this way the brain activity associated with the realisation of satisfaction can be isolated.

Apparatus

The images were presented using Presentation software version 21.1 and projected using an LCD projector onto a translucent screen while participants watched them in an angled mirror in the scanner.

Image Acquisition

Imaging was performed using a 3T Siemens TIM Trio MRI scanning at the Centre for Cognitive Neuroimaging, University of Glasgow. Functional volumes were acquired using a T2*-weighted gradient echo, echo-planar imaging sequence (68 interleaved slices, TR: 2000ms, TE: 30ms, voxel size: 3 x 3 x 3 mm, FOV: 210mm, matrix size: 70 x 70). Also, a high-resolution anatomical volume was acquired at the end of the scanning using a T1-weighted sequence (192 slices, TR: 1900ms, TE: 2.52ms, voxel size: 1 x 1 x 1 mm, FOV: 210mm, matrix size: 256 x 256).

Data Analysis

We first analysed the behavioural logs resulting from 17 participants who passed the exclusion criteria in the procedure above. On average, the participants responded 17 (SD 2.7) of a possible 20 times that they were correct in matching the caption to the image. These trials were subsequently used in the fMRI analysis since they constitute successful search processes.

fMRI Preprocessing

The fMRI data were analysed using Brain Voyager 20. A standard pipeline of pre-processing of the data was performed for each participant (Goebel, 2017). This involved slice scan time correction using trilinear interpolation based on information about the TR and the order of slice scanning. Three-dimensional motion correction was performed to detect and correct for small head movements by spatial alignment of all the volumes of a participant to the first volume by rigid-body transformations. In addition, linear trends in the data were removed, and high pass filtering with a cutoff of 0.0025 Hz performed to reduce artefact from low-frequency physiological noise. The functional data were then co-registered with the anatomic data and spatially normalised into the Montreal Neurological Institute (MNI) space. Finally, the functional data of each individual underwent spatial smoothing using a Gaussian kernel of 6mm to facilitate the analysis of group data.

General Linear Model (GLM) Analysis

Analysis began with first-level modelling of the data of individual participants at the moment of satisfaction and the moment of validation using multiple linear regression of the BOLD-response time course in every voxel. Only trials that participants self-reported as correct were used in the analysis. Predictor time courses were adjusted by convolution with a hemodynamic response function. Group data were tested with a second level analysis using a random-effects analysis of variance using search epoch as a within-participants factor. A contrast was performed between brain activity at the moment of satisfaction and the moment of validation. To address the issue of multiple statistical comparisons across all voxels, activations are reported using False Discovery Rate (FDR) at a threshold of q < 0.05 (Benjamini & Hochberg, 1995). Using FDR, we control for the number of false positive voxels among the subset of voxels labelled as significant. The coordinates were converted into the Talairach space using the MNI to Talairach mapping (Lacadie, Fulbright, Arora, Constable, & Papademetris, 2008), and these Talairach coordinates were used to identify brain regions and Brodmann areas using Talairach Client version 2.4.3.

RESULTS AND DISCUSSION

Our analysis contrasted, for each trial, brain activity during the realisation of satisfaction to the validation of their response. We hypothesised this contrast would reveal brain regions involved in cognition, decision making and affect. It is notable that this contrast also controls for motor activity associated with the button press, as in both Satisfaction and Validation phases the participant is making a button press. Thus, we expect this contrast to primarily reveal high-level cognitive processes associated with the moment of satisfaction.

The results, based on seventeen participants, showed that 4 of 5 clusters had higher activation during the moment of satisfaction (shown in Figure 3 and Table 1). This included the right insula and superior frontal gyrus as well as the left anterior cingulate and posterior cingulate cortex. These regions were more active when participants indicated satisfaction than when they validated their response (Satisfaction > Validation). The frontal and cingulate regions found have been associated with the processing of higher cognitive functions such as memory retrieval process and decision-making (Bein, Reggev, & Maril, 2014). The right insula activity was found in the anterior region of the insula, and the right insula has been shown to play a role in affective processing (Uddin, Nomi, H´ebert-Seropian, Ghaziri, & Boucher, 2017). It has also been implicated in the salience network, which is involved in the identification of stimulus properties of behavioural relevance (Uddin, 2015). As such, the results of the contrast of Satisfaction versus Validation reveal a multilayered response suggesting processing in both cognitive and affective domains.

There was only one cluster located in the ventral region of the right posterior cingulate, which had higher activation when participants validated their answer (Validation > Satisfaction). This general region can be associated with the default mode network, which is involved in various cognitive functions (Buckner, Andrews-Hanna, & Schacter, 2008), including confidence judgment, integrating memory, and information processing (Chua, Schacter, Rand-Giovannetti, & Sperling, 2006). The right ventral posterior cingulate has also been associated with scene processing (Chrastil, Tobyne, Nauer, Chang, & Stern, 2018). Greater activity for scene processing is consistent with behavioural activity during the Validation judgment because, at this time, the participant sees the scene depicted by all nine tiles together shown as a coherent image of a scene as opposed to separate fragments.

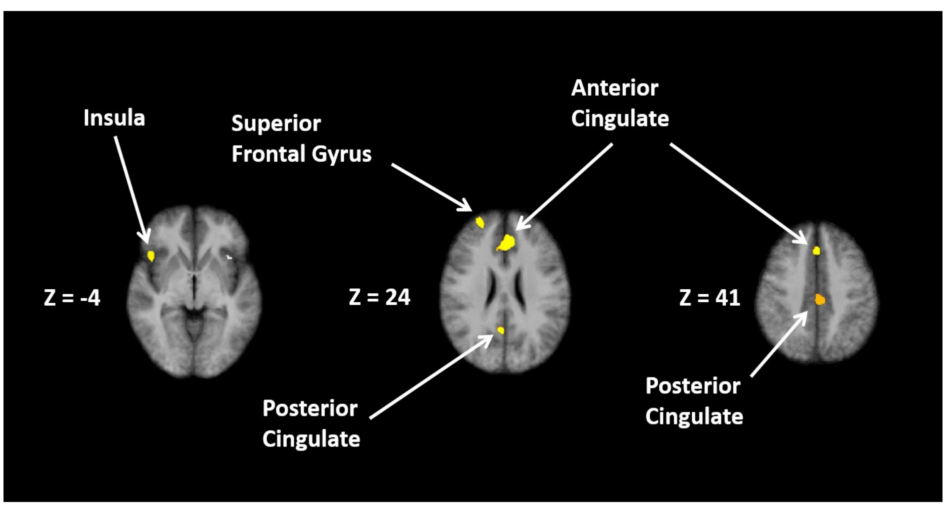

Figure 3. The five activation clusters from the contrast of brain activity at the moment of satisfaction to the moment when a Validation judgment was given. Results are projected onto the average anatomical structure for three transverse sections. Note that the brains are in a radiological format where the left side of the brain is on the right side of the image.

Condition	Brain Area	Hemi-sphere	MNI Coordinates				Effect size		Number of Voxels mm^3
			X	Y	Z	BA	F(1,21)	p-value	
Sat > Val	Insula	Right	45.0	20.0	-5.0	13	40.59	0.000009	311
	Superior Frontal Gyrus	Right	27.0	56.0	25.0	10	40.37	0.000010	732
	Anterior Cingulate	Left	0.0	35.0	19.0	32	56.01	0.000001	3964
	Posterior Cingulate	Left	-6.0	-25.0	40.0	31	50.30	0.000003	530
Sat < Val	Posterior Cingulate	Right	6.0	-55.0	16.0	23	115.78	<0.000001	1531

Table 1: For the contrast of Satisfaction (Sat) vs Validation (Val), including their anatomic label, Hemisphere (Hem), location (MNI coordinates), Brodmann Area (BA), effect size as indicated by F statistic and p-value, and volume for the different brain regions, as provided by the Number of voxels.

CONCLUSION AND FUTURE WORK

Using the brain imaging technique of fMRI, this study investigated brain activity of the realisation of satisfaction of an IN in a successful search process. We designed an experimental task that involved participants being presented with an image caption and then being sequentially presented with segments of this image until they were satisfied that the caption matched the presented segments. A total of 26 participants were scanned, and after six participants were removed for excessive head movement and three participants removed based on behavioural performance, data from a total of seventeen participants were analysed. Results of the contrast of Satisfaction to Validation addressed our RQ to reveal five brain regions. Four regions showed greater activation during Satisfaction, and one region showed greater activation during the Validation phase.

The four regions associated with Satisfaction are consistent with the involvement of both cognitive and affective processes at the moment of satisfaction. One of these regions, the superior frontal gyrus, has previously been reported in studies of relevance (Moshfeghi et al., 2013) and IN (Moshfeghi et al., 2016), suggesting a general-purpose role in cognitive processing during search processes. However, this activity in the superior frontal gyrus appears to be found in the right hemisphere for image-based tasks and the left hemisphere for text-based tasks. While such a difference is consistent with what is known about the hemispheric specialisation of language and visual processing, more research is needed to understand the significance of this distinction for search. Evidence for affective processing during search processes, as suggested by brain activity in the insula, has been previously discussed (Moshfeghi & Pollick, 2018), where greater activity was found in the right insula for the realisation of IN as compared to query formulation. This finding of both cognitive and emotional brain regions associated with satisfaction is consistent with suggestions that it is appropriate to think of emotions as within the domain of cognitive control (Inzlicht et al., 2015; LeDoux & Brown, 2017; Pessoa, 2013). Within the context of this framework, we can propose that the inherent complexity of understanding satisfaction arises from the actions of inter-related neural systems for emotion and cognitive control.

There are many avenues for future research. Examination of the brain regions related to satisfaction holds promise to disentangle the cognitive and affective aspects of search. In particular, returning to the psychological perspectives of accumulation, one could potentially examine the time-course of brain activities building up to the moment of satisfaction. Finally, the systematic application of tools employing reverse inference (Yarkoni, Poldrack, Nichols, Van Essen, & Wager, 2011) might provide greater insight into how the current results fit into the broader domain of cognitive neuroimaging research and how brain activity relates to psychological functions. Finally, our findings are an important step towards unravelling the nature of satisfaction of an IN and, in turn, designing search systems that can better satisfy a searcher's IN.

There are limitations of the current research. For example, although the experimental task of extracting information from tiles of visual images is similar to a standard search at the conceptual level of accumulating information until satisfaction, there are practical differences between this and a standard search task. For example, in a standard search task we might expect to issue queries and receive documents that guide the formulation of additional queries. Although our results do not further inform an understanding of these aspects of standard search, given our focus on the cognitive processes involved at the moment of satisfaction we believe that the current results provide an important starting point to guide future studies that provide more realistic scenarios in which to understand the neural mechanisms of search satisfaction.

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