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Brain bases of the automaticity via visual search task

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Abbreviation list

ACC (dACC): Anterior Cingulate Cortex (dorsal ACC)

aI: anterior insula

BA: Brodmann area

CON: cingulo-opercular network

d46: dorsal area 46

DAN: dorsal attention network

DLPFC: dorsolateral prefrontal cortex

DMN: default mode network

FEF: frontal eye fields

FG: fusiform gyrus

fMRI: functional Magnetic Resonance Imaging

FPN: frontoparietal network

GABAergic cells: gamma-aminobutyric acid cells

ICA: independent component analysis

iFC: intrinsic functional connectivity

IPL: inferior parietal lobule

IPS: intraparietal sulcus

IT: inferior temporal

LGN: lateral geniculate nucleus

LIP: lateral intraparietal area

LOC: lateral occipital complex

MT / MT+ / V5: middle temporal visual area or visual area 5

PET: Positron Emission Tomography

PFC: prefrontal cortex

PHC-1: parahippocampal visual field map 1

PHC-2: parahippocampal visual field map 2

PPC: posterior parietal cortex

ROI(s): region(s) of interest

rs-FC: resting state-Functional Connectivity

rs-fcMRI: resting state-Functional Connectivity Magnetic Resonance Imaging

SAN: salience network

SC: superior colliculus

SEF: supplementary eye fields

SMA: supplementary motor area

SPL: superior parietal lobule

TPJ: temporoparietal junction

V0-1: ventral occipital visual field map 1

V0-2: ventral occipital visual field map 2

V1: primary visual cortex

V2: secondary visual cortex

V3: visual area 3

V4 (hV4): visual area 4 / human visual area 4

v46: ventral area 46

V7: visual area 7

VAN: ventral attention network

VLPFC: ventrolateral prefrontal cortex

Justification

Among all the different goal-directed behaviors that humans perform on a daily basis, paying attention is the most basic. Attention is a basic process and the beginning of the rest of the cognitive processes, and it sustains them. Attention is constantly directed toward something or somewhere, either internal or external, as it is set toward a stimulus. Moving the attention focus and its maintenance to a specific location is mainly visually mediated. Most of the time, humans are visually seeking things: for instance, in the technological world we live in, who is not looking at his/her mobile device screen? Because visual attention is such a relevant process for human functioning, there is a need to fully understand how it operates at the behavioral and brain levels.

In terms of efficiency, paying attention is a consuming process. In order to release the resources designated to sustain the attention system, the brain has evolved to a more efficient attention system. Practicing a task repeatedly generally leads to the automation of the task performance. Automatic behaviors are mediated by brain changes, that is, when a task is automatized, changes in the attention system occur due to a reorganization of the cerebral resources. Because in normal life the majority of actions that involve visual attention processes are automatized, it is essential to completely understand how the behavioral changes contribute to the neuronal reorganization processes. In addition to exploring the neurobehavioral basis of attention processes, we ought to know how the healthy brain changes during the learning process and how it functions under automatic processing.

Some investigations have already been carried out to understand the neurobehavioral basis of the attention processes and the automation of behavioral actions. The use of visual search tasks has contributed to the establishment of the visual attention processing basis. Initially, behavioral studies used the visual search task to study the features of automaticity. The fact that the visual search task could be performed automatically, or without effort, led to the differentiation between controlled and automatic attention processing. That is, the different ways information is processed by a subject were differentiated based on the degree of control the subject had to exert. Beyond the classic approaches to the study of visual search, current research is evolving fast and focusing its efforts on understanding the brain basis for visual attention during experimental and real-word visual search tasks.

The use of neuroimaging techniques is crucial to understanding how the brain functions. Among others, the use of functional Magnetic Resonance Imaging (fMRI) in visual attention studies is widely extended, implementing either covert or overt visual search paradigms. Functional MRI provides a measure of the hemodynamic processes that occur in the human brain in a non-invasive context. The measure has good temporal resolution and excels in the spatial domain, thus becoming suitable for human studies that involve one or more explorations. Moreover, in our context, fMRI is accessible for basic research and applied fields of study, thus making it easier to compare the results obtained from different experiments in the long run.

Knowing how attention works is a relevant matter not only for basic psychology, but also for applied disciplines like neuropsychology and neurorehabilitation. For instance, advances in the general attention systems should be valuable for clinical neuropsychology, such as the application of assessment and intervention programs based on the scientific study of human behavior in relationship to normal and abnormal functioning of the central nervous system (American Psychological Association, 2010). Therefore, knowledge about the cerebral basis of attention functioning is essential to properly apply neurorehabilitation programs. Multiple neurological, psychological and social factors mediate in accomplishing these objectives, but neuroplasticity processes seem to be fundamental and be responsible for behavioral changes. That is, understanding how the healthy brain changes due to learning, training and automation, makes it possible to develop better neuropsychological theories and better neurorehabilitation programs that, in the long run, may be implemented. In summary, there is a need to perform cross-sectional studies to understand the brain functioning during task performance. However, we also need longitudinal data to explore how the brain changes due to cognitive training.

Previous studies developed in our research group, Neuropsychology and Functional Neuroimaging of Jaume I University, have been focused on the study of the brain changes related to training in a task and the effects of practicing a skill. For instance, by using Resting State Functional Connectivity (rs-FC) it was demonstrated that by studying the brain changes it is possible to predict the learning of foreign sounds (Ventura-Campos, et al., 2013); and the study of the morphological and functional brain changes made it possible to differentiate the motor and auditory brain characteristics in musicians compared to non-musicians (Palomar-García, Zatorre, Ventura-Campos, Bueichekú and Ávila, 2016). The present study is the first of a series of studies developed

in our research group that focus on the study of the neural basis of the visual search task and the development of automatic processing as a result of cognitive training on the visual search task. It is a promising project, covering different cognitive domains such visual attention, working memory and multitasking.

The main objective of this thesis is to contribute more empirical data to the development of neurobehavioral and automaticity visual attention theories through the use of visual search tasks. To accomplish this, different fMRI visual search paradigms and analysis techniques are used, and the results are interpreted according to current neurocomputational theories.

Chapter 1. General introduction

1. The concept of attention

William James (1890) understood the concept of attention as the core node of human behavior and cognitive operations. Although “everyone knows what attention is” (James, 1890), the truth is that attention is such a wide cognitive domain that there is still no unitary definition. Over the years, psychologists have elaborated successive taxonomies to attain a sense of order and synthesis of what attention is. Is attention sustained or transient? Is it serial or parallel? Is it top-down or bottom-up? Is it exogenous or endogenous?

In a recent taxonomy, the concept of attention was organized according to its focus (or target) instead of its properties. Thus, external attention refers to the processing of sensory information, whereas internal attention is associated with the modulation of internally generated information (Chun, Golomb and Turk-Browne, 2011). However, attention is still widely understood as the tripartite *orienting, selection and maintenance system*, but in an evolved version that includes its mechanisms (Posner and Petersen, 1990; Eimer 2014). It should be emphasized that, since the formulation of classical psychological theories, and as cognitive neuroscience continues to progress, continuous efforts are being made to unify the definition of what attention is (Treisman and Gelade, 1980; Deco and Rolls, 2005; Buschman and Kastner, 2015).

Although attention includes all the sensory domains, visual attention has been the most widely studied (Buschman and Kastner, 2015). Current visual attention theoretical models are numerous, most of them focused on the selection process, and they have been classified in terms of covert or overt attention (Eckstein, 2011). Along with visuo-spatial tasks, the visual search task is one of the most commonly used psychological paradigms to study visual attention (Nakayama and Martini, 2011; Buschman and Kastner, 2015). Visual attention was originally studied with covert visual search tasks (Estes and Taylor, 1964; Shiffrin and Gardner, 1972; Shiffrin and Schneider, 1984) that lead to the development of the Feature Integration Theory (Treisman, Skaane and Gelade 1977; Treisman and Gelade, 1980). After the Feature Integration Theory, several theories and models were formulated, inheriting some of its essential features but extending or further

developing others; for instance, the Guided Search Model (Wolfe, 1989), the Biased Competition Model (Desimone and Duncan, 1995) or the three attentional system proposed by Posner and colleagues (Posner and Boies, 1971; Posner and Petersen, 1990) among many others.

Despite the popularity of covert search, tasks that allow eye movements have been increasingly incorporated into the visual attention panorama. The use of these tasks came from the need to overcome covert search limitations, such as controlling for stimuli eccentricity or density, and even the absence of control of participants' involuntary eye movement (Eckstein, 2011). Thus, first the Saliency Model (Itti, Koch and Niebur, 1998; Itti and Koch, 2001), then the Priority Map Model (i.e., Serences and Yantis, 2006), and now neurocomputational models (e.g., Deco and Rolls, 2005) have all been formulated to explain the bottom-up guiding of attention, the interaction between bottom-up inputs and top-down influences, and the feedforward relations within the attentional system.

Far from being exhaustive, this introduction aims to review the main visual attention theories and models, focusing on those that are more relevant to our experimental framework. Along with this review, a brief synopsis of the main brain areas and networks involved in visual attention and visual search tasks is provided and current findings on the development of automaticity and brain plasticity are presented.

1.1. The visual search task and the theories of visual attention information processing

Around the 1980, a group of theoretical models stemming from attention and perception psychological fields of study were formulated in order to explain the main characteristics of conscious and automatic processing of information (e.g., Spelke, Hirst and Neisser, 1976; Shiffrin and Schneider, 1977; Logan, 1979; Shiffrin and Dumais, 1981). These models were developed based on the experimental evidence found in classic psychological experiments, such as visual search or categorization tasks, and in the development of automaticity on language and memory tasks (Spelke, Hirst and Neisser, 1976; Shiffrin and Schneider, 1977; Logan, 1979; Shiffrin and Dumais, 1981).

The main contribution of the visual search tasks to the information processing field of study was not only to provide evidence to differentiate controlled processing from automatic detection, but also, to establish the conditions and methods through which automatic detection could be achieved. One of the most popular theories was the one developed by Shiffrin and colleagues by the end of the 1970's: the Controlled and Automatic Human Information Processing Theory (Schneider and Shiffrin, 1977; Shiffrin and Schneider 1977). This theory converged attention and memory processes to explain the mechanisms and conditions under which humans are able to complete different attention tasks, thus explaining how humans are able to process contextual information.

1.2. The Controlled and Automatic Human Information Processing Theory

The Controlled and Automatic Human Information Processing Theory (Schneider and Shiffrin, 1977; Shiffrin and Schneider 1977) inherits from Atkinson and Shiffrin's Human Memory Theory some important characteristics about the different ways the human mind processes information. The Human Memory Theory had already established that some actions happened to occur under controlled processes, whereas others were simply inherent to humans (Atkinson and Shiffrin, 1968). The theory, which focused on the functioning of the memory system and the features of its different modules, also included a differentiation between the transient features of the human processing information from the *atemporal structures* of the memory system. Controlled processes were understood as the actions that occurred under the subject's active and conscious control of information. As the tasks' features changed, so did the control processes. On the other hand, the different memory modules, such as the sensory register and the short-term and the long-term modules, remained invariable, as did the way the information traveled from one to another (Atkinson and Shiffrin, 1968).

Although the Human Information Processing Theory starts from this position, the processing of information is understood in terms of different systems that rely more or less on the active control of the attention processes (Schneider and Shiffrin, 1977; Shiffrin and Schneider 1977). The main distinction between these two theories is that some actions

occur under automatic processing, whereas others are controlled by the subject of the action. Thus, the novelty was the introduction of automatic processing into the schema. Memory was still a component of the theory, but it was referred to the place where information was saved, and it was linked to the limits of attention in processing information at the same time.

The Human Information Processing Theory (Shiffrin and Schneider, 1977) is an attention selection model where attention is understood as limited. Thus, the selection of information is mandatory in order to process whichever internal or external input is presented. That is, in this theory, the perceived sensorial information or the remembered episodes need to be selected, in order to avoid overloading the attention system and be processed. Memory is understood as a set of nodes that are developed through learning and that are permanent, associated and interrelated.

Figure 1. View of information processing model in consistent mapping paradigm. An explanation of the feature encoding processes for a single frame with two characters and two masks is offered. In this case, numbers are distractors and letters are targets, thus, detection is automatic from the visual character and/or the category code level. Attention is immediately attracted by the input number. Extracted from Shiffrin and Schneider (1977, p. 163).

The theory defended that the operation of the memory and the information processing (attention) systems were interconnected, and their functioning was straightforward. Knowledge about something typically remains passive and inactive in the majority of the memory nodes. These nodes constitute the long-term store or long-term memory. When

a small portion of information is retrieved from memory, some of these long-term store nodes become active, thus creating the short-term store. The mechanisms that make it possible to activate some memory nodes are control or automatic processing. These mechanisms are external to memory and operate under different circumstances. Controlled processing is needed during rehearsal and the coding and search for information. It manipulates the information that goes in and out of the short-term store. However, every time a bit of information leaves the short-term store, it is lost because this store is transient and temporal. On the other hand, automatic processing is engaged when a learned response has to be given. It directly connects with the long-term store, where sequences to already known inputs are stored. Only the stimuli that have been learned over the time are able to drive the attention system automatically, without the active control of the subject.

In terms of information processing, a process is controlled, and not automatic, when the subject has to consciously and actively attend to every step of a task for the purpose to resolve it (e.g., novel visual search task). Controlled processing of information is understood as a temporary sequence of nodes that operates using short-term memory storage (Schneider and Shiffrin, 1977). Controlled processes were classified into *accessible* control processes or *veiled* control processes. The accessible ones were all those processes that could be established and modified by instruction. The veiled processes were contrary to the accessible ones because they were difficult to modify through instruction and occurred so quickly that they were difficult to perceive through introspection (Shiffrin and Schneider, 1977). Both types of control processes shared some characteristics regarding the need for active attention and their general functioning. The theory assumed that, as the capacity of the short-term store was limited, the number of operations that the attention system could perform under controlled processing were also limited. The model defended that only one sequence was handled at a time, or perhaps, two serial sequences could be processed but one after the other and slowly (Shiffrin and Schneider, 1977). Control processes were depicted as easily learned and not requiring extensive training. In addition, control processes can be used to generate permanent learning because they control the flow of information between short- and long-term stores. Learning general information and/or automatic processing development occur when control processes reach asymptotic performance, which in general, happens very quickly under consistent context settings (Shiffrin and Schneider, 1977).

On the other hand, automatic processing was understood as a sequence of nodes that automatically responded to a specific stimulus, whether internal or external. Its main feature was that it did not require the active control of the subject to operate. Contrary to controlled processing, automatic processing operates with information stored in the long-term storage; thus, it is not limited by the capacity limitations of the short-term store (Schneider and Shiffrin, 1977). The information on the long-term store was defined as not being transient and being available for its use in different automatic sequences. Due to this feature, automatic processing could occur in parallel and the sequences could be completely independent from each other. Automatic processing in its essence involves capturing the focus of attention in such a way that the presence of other stimuli cannot interfere (Shiffrin and Schneider, 1977).

In this model, the development of automatic processing is understood as an associative learning. When different information nodes are active in the short-term store at the same time, and control processes are demanding the activation of these nodes in response to a stimulus, an association between the stimulus and the active nodes is created. Each time this stimulus appears and the control processes focus the attention on these nodes, an increase in their association will occur. The consistency in this association is what makes the development of the automatic processing possible. Moreover, automatic sequences can be *actional* when internal or overt responses were produced after the presentation of a stimulus, and *informational* when actions did not occur (Shiffrin and Schneider, 1977). It depends on the task features where controlled or automatic processing is engaged. Both can occur simultaneously, sometimes automatic processing occurs first (e.g., when processing sensory inputs), and normally, during the processing of complex tasks, control processes precede and initiate automatic processes (Shiffrin and Schneider, 1977).

To support the theory with empirical evidence, Schneider and Shiffrin (1977) carried out a series of experiments that were able to capture the essence of the model, which posits that selective attention, short-term search, detection and recognition depend on two possible information processing mechanisms: automatic processing and controlled processing. Variations of the visual search paradigm were used to collect the evidence to support the theory. A visual search task was chosen because it is able to capture the different attention effects depending on the manipulation of the tasks characteristics. Basically, what was modified through the experiments was: the frame size, the memory

set and the mapping. The frame size was defined as the number of elements (alphanumeric characters) in each frame, which varied from 1 to 4. The memory set consisted of the elements that the subject had to memorize before each search frame was presented, thus, the memory sets were the targets, and the characters not presented in the memory set, but in the frame, were the distractors. Finally, the mapping was the most important variable and determined whether the characters presented in the memory set and the frame varied or not throughout the experiment. If they varied, the paradigm was called varied mapping, and control processes were engaged throughout the experiment. In turn, if they did not vary, paradigm was called consistent mapping and it allowed the development of automaticity after at least 600 trials of practice (Shiffrin and Schneider, 1977; Schneider and Shiffrin, 1977).

Figure 2. Classic visual search task paradigm, in single-frame variation. In varied mapping conditions, the memory set stimuli (*J, D*) and the target frame stimuli change in every trial. In consistent mapping conditions, roles between targets (*4, 7, 8, 1*) and distractors are kept constant throughout the experiment. Extracted from Schneider and Shiffrin (1977, p. 18).

Results lead to the formulation of a common framework to explain the flow of the processing during detection or search in attention tasks. Briefly, when a visual stimulus is presented, automatic processing starts coding its different features (e.g., contrast, color, position, angle). Automatic processes occur in parallel for each visual input presented in the scene. The different processed features become active in the long-term store and are transferred to the short-term store. Some of them will engage the activation of other nodes or generate actions, whereas others will return to their inactive state in long-term store. The ones that remain active in the short-term store produce consequent processes. These

processes could be an automatic detection when a sequence of actions just follows the presentation of that specific stimulus, or the engagement of controlled processes to direct the focus of the attention during the search for the appropriate information and, in turn, the production of a suitable response (Shiffrin and Schneider, 1977).

1.3. The Feature Integration Theory

Models of covert attention started as a method to study visual perception that eventually would have to be based on attentional processes, as perception and attention were not easily separable. Treisman et al., (1977) formulated a hypothesis where focused attention makes it possible to identify the different objects of the visual scenes, but the features have to come first in perception. This idea, which would later become popularized as the Feature Integration Theory of attention, proposed that the different characteristics of the objects were automatically codified in early visual stages, but what was responsible for the final identification of the objects was the ability to focus the attention on each of them by serially processing all the physical features (Treisman et al., 1977).

The central aspects of the theory were devoted to offering an explanation of how attention was needed in order to perceive objects as identities (i.e., conjunctions). In general, the theory assumed that objects in visual scenes were identifiable due to the parallel visual-attention mechanisms that processed the different features of these objects. In the early stages of the visual processing, the physical characteristics of the objects, such as color, orientation, shape, spatial frequency, brightness or direction of movement, are coded, engaging parallel and divided attention mechanisms (Treisman and Gelade, 1980). This process was defined as occurring pre-attentively or without the subject's active control of the attention. The fact that focal attention is held to process the different features of an object at the same spatial location and temporal interval made it possible to recompose the object's identity afterwards, with no possible confound between objects features (Treisman, 1977).

There were some limitations in object identification. For example, the identification of a specific object could only occur under two conditions: when the objects varied in one feature (e.g., color or shape), or when the objects varied in more than one feature and no error in their description could occur (e.g., color, shape and orientation). The first type of identification processes were thought to occur under parallel processing because only one feature had to be clarified. The second, when more than one feature has to be verified, were related to serial processing (Treisman, 1977). On the other hand, object identification was not possible without guided attention. Authors offered a plausible explanation for what they called the illusory conjunctions or wrong object identifications. These could happen in the occasions when the focus of attention was wide, instead of narrow, and oriented toward the whole visual scene. At those moments, the perceived visual elements were not restricted by contextual information and/or prior, stored knowledge (i.e., top-down processing) and because the attention was divided, confusion could occur and random conjunctions could be formed (Treisman and Gelade, 1980).

The manner in which the processing system operated to identify the objects was related to the need to narrow the focus of attention. This narrowing went from the general and parallel processing of the different objects' features, to the strict processing of one compound made up of a group of features in the same location and time as a unique object (Treisman, 1977; Treisman and Gelade, 1980). It was depicted that, when searching for specific multidimensional objects or objects with more than one distinct feature, a three-stage serial process begun. First, this process checked for a match between any object and one of the target features. Then it searched for that feature in other candidate objects. Finally, if the features were found in the successive steps, re-evaluation of the selected objects occurred, and the target was finally found, but if all the objects were evaluated and none of them presented the features, the search ended. In conclusion, it was proposed that the process narrowed the focus of attention over on a specific object at each time, and that it was a repetitive and terminating mechanism (Treisman, 1977).

Evidence in favor of this hypothesis came from visual search, texture segregation identification, and spatial localization tasks. Visual search tasks made it possible to explore the set-size effect in feature versus conjunction searches and, through different experiments, gave enough support to distinguish the parallel and pre-attentive processes that occur during individual feature perceptions from the later object identification processes (Treisman and Gelade, 1980). However, the Feature Integration Theory offered

little explanation about how grouping processes were actually visually processed. Soon after the Feature Integration Theory, some other spotlight theories emerged to better explain how attention moved through space and processed visual objects (Eriksen and Eriksen, 1974; Posner, 1980; Posner and Petersen, 1990), whereas other alternative theories emerged to defeat it and proposed that attention was centered on object rather than on space (Cave and Franzel, 1981; Prinzmetal, 1981; Duncan and Humphreys, 1989; Wolfe). As experimental evidence related to the attention selection processes has progressively been accumulated, visual attention theories consider the codification of both object and space properties plausible, and that the focus of attention is sustained in one location while scanning the whole visual scene (Driver, 2001; Buschman and Kastner, 2015).

1.4. The Attention System of the Human Brain

Among the different accounts of the human attention system that emerged after Feature Integration Theory, one of the most influential was the one offered by Posner and colleagues (Posner and Boies, 1971; Posner, 1980; Posner, Inhoff, Friedrich and Cohen, 1987; Posner and Petersen, 1990) because it made an effort to distinguish the different attention processes and then, to link them to the brain functioning.

In the early formulation, three components of attention were depicted: selectivity, alertness and a capacity module (Posner and Boies, 1971). Selectivity was referred to as the ability to extract the relevant information from the general context. Alertness was a process that made it possible to maintain the attention in order to perform vigilance tasks through increasing the general brain cortical activation. Finally, the theory stated that attention was limited in its capacity. The development of Posner's theory of attention evolved over the years until the presentation of the Attention System of the Human Brain model (Posner and Petersen, 1990), where an outline of the brain structure that supported the attention system was offered.

In the original framework, three main concepts were postulated. The first one, affirmed that the attention system was anatomically distinct from the other information

processing systems, like the sensory system, the decision making system, and the action production system. Second, attention was related to the joint functioning of a broad network of brain areas. Finally, each of the areas pertaining to the attention brain network supported a different attention function (alerting, orienting or executive control) (Posner and Petersen, 1990).

1.4.1. Alerting

The alerting network was referred as an important function; specifically, it was “the ability to prepare and sustain alertness to process high-order priority signals” (Posner and Petersen, 1990). It was related to a particular sustained state, which was defined as adequate to focus the attention during vigilance tasks and to perform cognitive tasks from the beginning to the end. Alertness was conceived as a state that did not directly affect the information process per se – whatever sensory or memory inputs were being processed -, but rather the speed at which the attention could react to the stimulus.

Early on, case reports of neglect patients, along with neurophysiological and neuroimaging data collected during the performance of vigilance tasks signaled a relationship between the alerting system and the right cerebral hemisphere (Heilman, Watson and Valenstein, 1985; Wilkins, Shallice and McCarthy, 1987). Metabolic increases in the prefrontal cortex and decreases in the anterior cingulate cortex, which was linked to target detection, were found during the performance of a sustained attention task (Cohen, Semple, Gross, Holcomb, Dowling et al., 1988). This evidence supported the idea that different cerebral structures supported the different attentional processes. At the neurotransmission level, the norepinephrine system was associated with the changes in the alert state (Aston-Jones, Foote and Bloom, 1984). The norepinephrine system was thought to propagate from locus coeruleus to frontal areas and then backwards to posterior visual processing related areas such as the posterior parietal cortex (PPC), the pulvinar nucleus of the thalamus, and the superior colliculus (SC). Therefore, anatomically, the alerting system was linked to posterior areas of the right hemisphere and, functionally, it was an attention subsystem that assisted the orienting process such that visual information could be rapidly selected.

The current conception of the alerting system brain substrates still supports the involvement of the norepinephrine system (Petersen and Posner, 2012). Moreover, pharmacological studies have been able to differentiate that norepinephrine drugs affect the alerting system and that acetylcholine drugs affect the orienting system (Marrocco and Davidson, 1998; Beane and Marrocco, 2004). Behavioral and neuroimaging studies focused on differentiating the three attention systems have found that their efficiency is uncorrelated, and, that three separate anatomical networks support them (Fan, McCandliss, Sommer, Raz and Posner, 2002; Fan, McCandliss, Fosella, Flombaum and Posner, 2005). Therefore, as originally thought, functions carried out by the different systems remain independent, although they are possible interrelated during the processing of real-world situations (Petersen and Posner, 2012).

1.4.2. Orienting

The orienting network was mainly studied in reference to the visual world. The orienting concept barely changed from its original proposal to the days when the Attention System of the Human Brain was presented (Posner, 1980; Posner and Petersen, 1990). Orienting was referred to “the aligning of the attention with a source of sensory input or an internal semantic structured stored in memory” (Posner, 1980). Orienting could be overt, when visually seeing a stimulus, or covert, when priority was given to the specific location of a stimulus (Posner and Petersen, 1990).

Anatomically, the orienting system was thought to be supported by the posterior parietal lobe, the lateral pulvinar nucleus of the thalamus and the SC in monkeys, and in humans by the parietal cortex (Mountcastle, 1978; Wurtz, Goldberg and Robinson, 1980; Petersen, Robinson, and Morris, 1987; Posner and Petersen, 1990). By that time, lesion studies made it possible to elucidate the particular functions that, each of these areas supported in relation to orienting. Disengagement of the attentional focus on contralateral stimuli was related to lesions located in the PPC. Slower shifts of attention and re-evaluating already attended space locations were linked to damage in the SC. Finally, lesions in the pulvinar nucleus led to difficulties in the engagement of cued stimulus locations and appeared to affect it contralaterally (Posner and Cohen 1984; Posner, Walker, Friedrich and Rafal 1984; Petersen et al., 1987; Posner 1988). It was generally understood that covert visual attention involved these three areas in a serial manner. The

orienting system would make possible to move the focus of attention from one spatial location to another by, first, disengaging it from its current location, a function performed by the parietal cortex. Next, the SC would be responsible for moving the focus of attention. Finally, the pulvinar nucleus of the thalamus would re-engage the focus to a new target location (Posner and Petersen, 1990).

A recent revision of the original framework links the orienting system's anatomical bases to the dorsal and ventral account of the attention system (Corbetta and Shulman, 2002; Petersen and Posner, 2012). It also considers the evidence coming from research at the neurotransmission level and the progress made in neurophysiological studies with single-unit cell recordings. The latter brings attention theories together, as single-unit studies in ventral stream areas have found that focusing attention on a specific target stimulus reduces the chances that other stimuli will attract the attention (Petersen and Posner, 2012), thus, supporting the Biased Competition Model which is essentially based in the idea that neurons compete to attract attention to one location (Harter and Aine, 1984; Duncan and Humphreys, 1989; Bundesen, 1990; Desimone and Duncan, 1995).

On the one hand, the dorsal system is located in posterior parietal areas [intraparietal sulcus (IPS) and superior parietal lobule (SPL)] and in frontal eye fields (FEF) (Corbetta and Shulman, 2002). Briefly, it is related to the shifts in attention that are mediated by top-down sources or some prior knowledge about the location of the target (Corbetta and Shulman, 2002). However, there is mixed evidence about whether covert and overt attention shifts are supported by the same areas (Corbetta, Akbudak, Conturo, Snyder, Ollinger, et al., 1988; Petersen and Posner 2012). On the other hand, the ventral system includes the temporoparietal junction (TPJ), which includes portions of the inferior parietal lobule (IPL) and the superior temporal gyrus, and the ventrolateral prefrontal cortex (VLPFC), comprising inferior and middle frontal gyri (Corbetta and Shulman, 2002). The ventral system, contrary to the dorsal system, is responsible for the shifts in attention driven by the sensory stimuli (Corbetta and Shulman, 2002).

A double dissociation has been found in relation to the neurotransmitters involved in the alerting and orienting systems. As explained above, the alerting system is sustained by the norepinephrine system (Marrocco and Davidson, 1998; Beane and Marrocco, 2004). It is believed that the orienting system is supported by the cholinergic system, as acetylcholine antagonists affect the normal functioning of orienting (Davidson and

Marrocco, 2000). However, dopaminergic agonists do not affect orienting, and cholinergic agonists do not affect alerting. Thus, actual experimental evidence defends a double dissociation between these two orienting systems, separating them functionally and anatomically (Marrocco and Davidson, 1998; Beane and Marrocco, 2004; Posner, 2012, Petersen and Posner, 2012).

1.4.3. Executive

Originally, the executive network was presented through the explanation of how and what occurs when the detection of a target was made (Posner and Petersen, 1990). The theory defended that target detection produced interference in the attention process flow, capturing the majority of the resources and thus slowing the detection of other possible targets (Posner, 1978). In fact, at that time, it had already been observed that the monitoring of different visual locations was disturbed only when a target was detected (Duncan, 1980).

The executive network was associated with the neural activity of midline frontal areas, especially the anterior cingulate cortex (ACC), which increased its activation during target detection tasks (Posner, Petersen, Fox and Raichle, 1988). The fact that detection of one target slowed the attention system, made the authors consider the limited capacity of the system and the concept of focal attention, linking executive network to spotlight theories that explained how the focus of attention sequentially moved and stayed engaged in different space locations (Tresiman and Gelade, 1980). At that time, the theory was focused on the anatomical connections between the ACC and other cortical areas like the posterior parietal and dorsolateral prefrontal areas (Goldman-Rakic, 1988, Posner and Petersen, 1990). Authors considered the possibility that midline structures acted like a top-down filter that controlled the information that was to be sent to these other cortical areas (Posner and Petersen, 1990).

Currently, the conception of the executive network's brain support has evolved considerably, with the apparent involvement of two neural networks (Dosenbach et al., 2006; Dosenbach et al., 2007; Petersen and Posner, 2012). According to the dual-network architecture of top-down control, these two networks separately co-exist and are

responsible for the top-down control of the information flow, but they have different functions within the top-down influence (Dosenbach et al., 2008).

One is the frontoparietal network (FPN), which includes the dorsolateral prefrontal cortex (DLPFC), dorsal frontal cortex, middle cingulate cortex, and IPL along with the IPS and precuneus. The other is the cingulo-opercular network (CON), which consists of the anterior prefrontal cortex, anterior insular (aI) / frontal opercular cortex and dACC / medial superior frontal cortex (Dosenbach et al., 2008). Whereas the FPN is associated with the initiation and adjustment of control during task execution, the CON seems to be responsible for task set maintenance (Dosenbach et al., 2006; Dosenbach et al., 2007; Petersen and Posner, 2012). According to recent functional connectivity brain studies that embrace different data analysis approaches (Dosenbach et al., 2007; Seeley et al., 2007; Dosenbach et al., 2008; Power et al., 2011), the whole evolved version of the Attention System of the Human Brains seems to be a plausible account of the way the different attention processes (alerting, orienting and executive control) take place, and which brain areas and networks support these functions.

1.5. The Priority Map Model

The priority map model is a visual attention computational theory that attempts to explain the neural basis of focal visual attention from a plausible neural architecture approach. The first formulation of the Priority Map Model goes back to Koch and Ullman's (1985) conception of the "saliency map". Saliency maps were conceived as two dimensional representations of the visual scene in the brain that allowed the visual attention system to encode all the saliency values of the visual stimuli. It was a bottom-up conception of the operation of the visual attention system that included several attention mechanisms (Koch and Ullman, 1985). Some of these mechanisms are commonly found in saliency theories of attention, such as the pre-attentive processing of visual features, the competition for saliency, or the integration into topographical maps with salient locations (Itti and Koch, 2001). The way sensory information is combined and the way its saliency is extracted from the map to guide the selective attention process is what differentiates the different models focused on bottom-up processes (it is also what

makes all of them different from the top-down models) (Wolfe, 1994; Milanese, Gil and Pun, 1995; Tsotsos et al., 1995; Itti et al., 1998; Itti and Koch 2000).

Early saliency map models were based on classic models of visual attention (Treisman and Gelade, 1980). Today, they have evolved into more complex computational models with different theories about how selective attention works, and most of them include both bottom-up and top-down mechanisms to account for the control of attention (Itti and Koch, 2001; Serences and Yantis, 2006, 2007; Bisley and Goldberg, 2010). In fact, the most evolved conception of the saliency maps by Itti and colleagues (Itti and Koch, 2001) changes the conception of saliency maps to comprehend that, although much of the model emphasizes the interplay between attention and scene processing, both top-down attentional bias and training also influence visual perception. More recent works also adopt the name *priority map* to denote that both bottom-up and top-down mechanisms have a role in the visual attention process, especially in selective attention (Fecteau and Munoz, 2006; Serences and Yantis, 2006; Bisley, Ipata, Krishna, Gee and Goldberg, 2009; Ipata, Gee, Bisley, and Golberg, 2009; Bisley and Goldberg, 2010; Zelinsky and Bisley, 2015).

1.5.1. Visual input and bottom-up processes

Visual perception starts with the computation of the early visual features that are the attributes of the objects, such as the intensity, the contrast, the colors, the orientation and direction, along with other features (e.g., motion, shade's shape, etc.) (Itti et al., 1998; Itti and Koch, 2000). These computations are preferentially performed in the retina, SC, lateral geniculate nucleus (LGN) of the thalamus and the early visual areas (Suder and Worgotter, 2000). Inherited from previous theories, these early visual features are computed in a parallel and pre-attentive manner across the entire visual field (Treisman and Gelade, 1980; Itti et al., 1998; Itti and Koch, 2001).

The fact that initial visual input is processed in a bottom-up manner coexists perfectly with computational models more centered on the role of top-down attentional modulation of the priority maps (e.g., Deco and Rolls, 2005; Deco and Zhi, 2006). Although recent computation approaches pay less attention to the early visual steps, bottom-up processes play a role that has equal importance for computational visual attention models (Itti and

Koch, 2001). It seems that bottom-up processing of the visual features is devoted to how the different features contribute to evaluating the strength of the saliency of the objects. Guiding of bottom-up attention is based on the differences in the contrast of objects located next to each other (e.g., changes in feature contrast), and, perhaps more importantly, visual neurons are modulated by context objects placed inside and outside their receptive field (Nothdurft, 1990; Allman, Miezin and McGuinness, 1985; Itti et al., 1998).

After parallel processing of the different features, a map of each feature is created and then combined into a saliency map. Saliency maps are conceived as topographical representations of the visual field that contains the values that make locations salient. From a bottom-up approach, these values are responsible for guiding the attention to the specific salient locations, regardless of the feature that makes this object salient; that is, a saliency map operates more on the locations than on the features (Itti and Koch, 2001).

It has been proposed that divided attention is converged into the most salient location, following the “winner-take-all” construct, in which the focus of attention is just placed in the location where the neurons have highest saliency values (i.e., the most salient location takes all the focus of attention). Then, inhibition processes are engaged to suppress the most salient location and move the focus of attention to the next most salient location (i.e., moves through locations in a decreasing saliency order) (Koch and Ullman, 1985; Itti et al., 1998; Lee, Itti, Koch and Braun, 1999). At the neurophysiological level, the inhibition of return mechanism is the responsible for the suppression mechanisms enacted to move the focus of attention to the different locations (Itti and Koch, 2001).

1.5.2. Priority maps and top-down feedback

Priority map as a term (Fecteau and Munoz, 2006; Serences and Yantis, 2006; Bisley et al., 2009; Ipata et al., 2009; Bisley and Goldberg, 2010; Zelinsky and Bisley, 2015) was once adopted to overcome the idea that the processing of visual information could only be driven by objects’ features (e.g., Itti et al., 1998; Itti and Koch, 2000). That is, the priority map concept goes beyond the saliency map concept because the latter only operates in a bottom-up manner, or by space locations of visual objects, but the priority

map also takes into account the target maps that operate in top-down manner (Rutishauser and Koch, 2007; Zelinsky, 2008, 2012).

The importance of this term change relies on assuming that in any visual process both bottom-up and top-down mechanisms must be engaged. It is worth noting that, depending on the task is being studied, one could emphasize more the bottom-up aspects of the visual processing (i.e., free viewing tasks) or the top-down aspects (i.e., visual search tasks) because the characteristics of the tasks induce it (Zelinsky and Bisley, 2015). However, it is rather strange that prior knowledge does not influence what we are seeing or, in turn, that active guided visual scanning of the world is somewhat affected by the different features of the objects (Bisley, 2011; Zelinsky and Bisley, 2015). Therefore, a priority map is a representation of the visual world where a combination of bottom-up and top-down influences occur in order to process a visual scene (Bisley, 2011).

Figure 3. Graphic representation of bottom-up and top-down attentional processes. Priority maps are formed by the integration of cognitive information about the target (e.g., description of its identity, probable location) and visual features information (e.g., color, orientation). The focus of attention is guided to the most prominent locations in the priority maps. Prefrontal cortex (PFC), posterior parietal cortex (PPC) and superior colliculus (SC) have been signalled as the most probable locations for the priority maps in the human brain. Blue, red, and green arrows represent bottom-up signal processing, top-down signal processing, and eye movement-related signal processing, respectively. Extracted from Katsuki and Constantinidis (2014, p. 517).

Association areas, such as the PPC (lateral intraparietal (LIP) in monkeys), FEF and SC have been signaled as the most probable locations for the priority maps in the human brain (Serences and Yantis, 2006; Bisley and Goldberg, 2010; Krauzlis, Lovejoy and Zenon, 2013). Recent conceptions of the priority map model argue that priority maps need to have a topological representation of the space; thus, PPC, FEF and SC must have them in order to hold priority maps (Zelinsky and Bisley, 2015). It seems that, under simple visual task conditions (i.e., visual search pop-out conditions), neural responses of these areas are similar; however, as visual complexity increases, in terms of object identification or task demands, differences between PPC and FEF response have been observed (Zelinsky and Bisley, 2015). For instance, LIP neurons are sensitive to set size changes, but this effect is not visible in FEF neurons (Balan, Oristaglio, Schneider and Gottlieb, 2008; Churchland, Kiani and Shandlen 2008; Cohen, Heitz, Woodman and Schall, 2009; Mirpour and Bisley, 2012). Research is still being carried out on the way visual and motor systems interact and how priority maps, which are found in the pathway, operate to coordinate them. What is known is that the oculomotor system shares the same reference frame to map input and output information, and the same thing is thought about the visuomotor system (Zelinsky and Bisley, 2015). That being said, the area that mainly been studied is the PPC (or LIP area) in both humans and nonhumans primates (Bisley, 2011),

1.5.3. Priority maps and posterior parietal cortex

Recent conceptions of the priority maps of the PPC understand that allocation of the focus of attention is made using maps, where there is a convergence of contextual and prior information. The place on the map with a peak in information gains the whole focus of attention, thus working under the winner-take-all rule (Fecteau and Munoz, 2006; Serences and Yantis, 2006; Bisley et al., 2009; Ipata et al., 2009; Bisley and Goldberg, 2010). The objects or locations in the visual scene have different behavioral priorities (i.e., importance for the next behavioral action): highly relevant objects/locations have the greatest activity in the map; in turn, the least important objects/locations are represented by lower activity. The focus of attention is moved through the map every moment, and saccades are made accordingly when needed (Bisley and Goldberg, 2010).

For the purpose of creating a priority map, it seems that three signals must meet in PPC: a bottom-up visual signal, a top-down saccadic signal, and a top-down cognitive signal. By means of a free-viewing visual search task where an object is presented abruptly, Ipata and colleagues were able to decipher these signals (Ipata et al., 2009). The bottom-up signal is early (about 70 ms from the appearance of a stimulus) and maps all the stimuli of the visual scene equally (e.g., the different stimuli of a visual search task, which could either be targets or distractors). Following the bottom-up signal, a prediction of whether or not a saccade is going to occur is made in PPC, originating the saccadic signal (about 90 ms from the appearance of a stimulus). Finally, the cognitive signal, which represents the object's identity, is originated, and in the receptive field, is greater for a target stimulus than for distractors (Ipata et al., 2009). When these three signals are added together, the PPC is making a prediction of the direction of the eye movement and the identification of the stimulus. All the predictions are organized into a map of priorities, and the PPC is able to rely on these priorities to move the attentional focus (Ipata et al., 2009).

On the one hand, the priority maps of the PPC have a representation of all the stimuli of a visual scene. This constitutes the visual input coming from the retina and early visual areas. However, it seems that this representation has less or more activity (i.e., neurons fire at higher or lower rates) depending more on the saliency of the object than on the presence or absence of the object in the receptive field of the PPC neuron (Gottlieb, Kusunoki and Goldberg, 1998; Kusunoki, Gottlieb and Goldberg, 2000). From a bottom-up perspective, the presence of transient objects in the visual space (i.e., changes in luminance, in color, or in movement) gives rise to inherently salient representations in the priority maps (Yantis and Jonides, 1984; Balan and Gottlieb, 2006; Bisley and Goldberg, 2010). The salient representations attract the focus of attention, guiding it towards these stimuli locations.

On the other hand, the maps built from visual inputs need, by definition, to incorporate top-down modulation in order to be priority maps; sometimes these modulations must be strong influences over the maps (Bisley and Goldberg, 2010). Supporting this hypothesis, researchers have been observing that maps in early visual areas do not respond to task demands like the PPC does. For example, during visual search tasks, enhanced PPC response was observed more for targets than for distractors (Ipata et al., 2006; Buschman and Miller, 2007; Thomas and Paré, 2007; Mirpour, Arcizet, Ong and Bisley, 2009). It

seems that during visual search tasks, the focus of attention is guided through the visual scene using the priority map, where the targets are highlighted and the distractors are suppressed (Bisley and Goldberg, 2010). Inherited from bottom-up saliency models (Itti and Koch, 2001), it seems that the PPC also engages inhibition of return to suppress already visited locations in the space, making it possible for the visual attention system to progress in the search by dismissing potential objects that eventually do not match the target (Mirpour et al., 2009).

1.6. The Biased Competition Model

Contrary to the Feature Integration Theory, whose claim was that object selection occurs under serial processing conditions, The Biased Competition Model stands by defending that multiple objects in the visual scene are concurrently processed by different populations of neurons (Harter and Aine, 1984; Duncan and Humphreys, 1989; Bundesen, 1990; Desimone and Duncan, 1995; Duncan, 1996; Deco and Rolls, 2005; Deco and Zbil, 2006). The main hypothesis is that the visual cortex neurons engage in a competition to capture the focus of attention (i.e. “winner-take-all” construct). However, what are responsible for biasing the competition in favor of one group of neurons or another are the top-down forces originating from external visual cortex neurons (Deco and Rolls, 2005; Deco and Zbil, 2006); thus giving less importance to the bottom-up processes through the computational model (Itti and Koch, 2001).

The neurodynamic version of the Biased Competition Model proposed by Rolls and Deco (2002) is an evolved version of the original hypothesis, and it offers an integration of the bottom-up system, the top-down system and the interactive effects that occur between the two systems. The model is organized in multiple hierarchical modules, and it is reconciled with the classic visual “what” and “where” pathways (Deco and Lee, 2002; Deco and Lee, 2004; Deco and Rolls, 2005; Deco and Zbil 2006).

Formulation of the model, as it is, started as a solution to resolve whether the primary visual cortex (V1) could play a central role in visual attention beyond its involvement in visual perception (Deco and Lee, 2002). Previous research was relating long-latency responses of V1 neurons to different processes like top-down integration or higher perceptual processing. On the other hand, integration of object identity and object location

was thought to occur in high-order cognitive areas, but not in the early visual cortex (Deco and Lee, 2004).

The first formulation outlined three main representative modules. The first module represented the early visual system, including V1, the secondary visual cortex (V2), and the LGN of the thalamus. The second module represented dorsal cortical structures, responsible for processing space position. This second module was associated with parietal and prefrontal cortical regions (in later revisions the authors better specify that they refer to the posterior parietal cortex and to ventral and dorsal area 46 in the prefrontal cortex). The third module represented ventral cortical areas related to identifying object classes. This last module was thought to be located in inferotemporal (IT) areas. In this model, both the dorsal and ventral modules exert top-down bias over the early visual system via bidirectional connections. The system was understood as a network that operates in a recurrent and interactive manner. The way the module interactions occurred were explained as a succession of excitatory and inhibitory actions between the neurons that compose them (Deco and Lee, 2002; Deco and Lee, 2004).

A computational formulation was used to prove the hypothesis that the “what” and “where” pathways could converge in the early visual module, and that the recurrent interaction among the three modules played an important role in visual attention tasks such as visual search (Deco and Lee, 2004). The results of the operational computations are explained in a model composed of three modes of functioning, based on which the visual attention system operates. In the spatial attention mode, top-down bias from the prefrontal cortex was exerted on the dorsal pathway, with information about object location. This information would then be propagated to V1 which, in turn, would send it to ventral pathway neurons. In this way, the system resolved the location of a target, and with this location, object identification took place at this specific location. In the object attention mode, again top-down bias from the prefrontal cortex was exerted, in this case on the ventral pathway that received information about the object identity. This information would be sent to V1 which, in turn, would send it to the dorsal pathway neurons, thus directing the attention focus towards the specific location of the identified object. A third pre-attentive mode was mentioned where no top-down bias occurred, which was thus, directed by context stimuli. In conclusion, the main concern about how the early visual module could integrate and coordinate the information in order to process

the visual scene was explained by top-down effects and the convergence of information in the early visual cortex.

The main difference between the Feature Integration Theory (Treisman and Gelade, 1980) and the Biased Competition Model described by Deco and colleagues (Deco and Lee, 2002; Deco and Lee, 2004; Deco and Rolls, 2005; Deco and Zhi, 2006) was that, even though the physical search through the visual scene had to be done in a serial manner (i.e., scans by eye movements), the processing of the scene was defined as always being a parallel process. In this sense, depending on the necessary interactions between the modules in order to differentiate between target and distractors during the visual search task, shorter or longer behavioral reactions times would be found, and this fact would explain the effect of serial and parallel search.

Figure 4. Graphic representation of the brain areas involved in the Biased Competition Model of attention. The visual attention system is composed by the primary visual area (V1), extrastriate visual cortex (V2/V4/MT), inferior temporal visual cortex (IT), the posterior parietal cortex (PPC) and the lateral prefrontal cortex [dorsal area 46 (d46) and ventral area 46 (v46)]. Top-down and bottom-up information flows between these areas forming the dorsal (V1 – V2/V4/MT – PP – dorsal PFC) and ventral (V1 – V2/V4/MT – IT ventral PFC) streams. Red arrows indicate forward and backprojections between areas. Extracted from Deco and Rolls (2005, p. 238).

Subsequent revisions of the model updated its characteristics and expanded its details (Deco and Rolls, 2005). Specifically, the V2 module and the visual area 4 (V4) module were added to the ventral stream pathway; which runs from V1, through V2 and V4, to finish in IT. In turn, the V2 module and MT module (middle temporal visual area or V5)

were added to the dorsal stream pathway to drive the information from V1 to the PPC. In this updated version of the model, the flow of visual information runs from the retino-geniculate-striate pathway to V1, where it is directed to the ventral or the dorsal stream. The ventral stream is functionally linked to the processing of the object's identity, regardless of its location. In turn, the dorsal stream is responsible for maintaining a spatial map of the object location. Then, two sources of top-down bias are also specified in the area 46: the ventral area (v46) and the dorsal area (d46). These two modules specify the processing conditions of the ventral and dorsal streams, respectively. The v46 module exerts an attention bias towards IT neurons to focus on a specific object during visual search tasks, that is, the target. The d46 module provides PPC neurons with the specific location of a target during recognition tasks with spatial attentional cues.

The modes through which the model operates also have been updated. The modes make it possible to explain how visual perception of invariant objects is possible in this neurocognitive model. There are two modes: the learning mode and the recognition mode. The learning mode explains how the human brain incorporates a representation of objects into its knowledge. The multiple and repetitive presentation of objects to the visual system functions as a training for the V4 and IT neurons in the ventral stream. In this sense, training the ventral stream in object identity occurs under associative learning conditions. These neurons will establish bidirectional connections between them and capture the invariant features of the object, regardless of the different positions in which they appear.

The recognition mode explains how the visual perception system identifies or finds an object in the visual scene. This mode is subdivided into two modes: the visual spatial search mode and the visual object identification mode. When the brain is looking for an object in the space, the visual spatial search mode comes into play. For example, if a red apple is the object to look for, the identity of the object is known (e.g., look for a fruit that is an apple and red) but not its specific location in the space. In order to solve the problem and make use of already learned information about typical objects, prefrontal cortex v46 neurons will send, by means of backprojections, the object identity information to IT. The top-down bias on IT functioning, will produce an enhancement of the firing response of the groups of neurons in the ventral stream (IT-V4-V2-V1) related to the specific features of the object. That is, the top-down attentional bias will unbalance the competition through the ventral visual stream, favoring the group of neurons that will be processing the target object features (e.g., a red apple) and ignoring other neurons processing the

visual features of other objects in the scene (e.g., a yellow plum or a glass of water). The top-down information will add to the bottom-up information coming from the thalamus and converge in V1, resulting in increased firing of a particular group of neurons (the ones processing the red apple). As V1 is topologically organized, the enhanced firing of the neurons processing the target object will correspond to the information about its location (e.g., the fruit bowl at the counter), which will be sent through V2-V4-MT to PPC. At PPC, a specific group of neurons according to the topological information (e.g., the fruit bowl at the counter) will also increase its firing rate, making it possible to explicitly find the location of the target object.

In the visual object identification mode, the flow of information is just the opposite to the visual spatial search mode. Therefore, the information about the location of the target object is already known and sent, by means of backprojections, from prefrontal d46 neurons to PPC. In this case, continuing with the example, an object must be identified as the fruit bowl on the counter. The top-down bias over PPC increases the firing rate of the group of neurons that topologically codify that location but not the rate of other neurons processing other locations of the visual scene (e.g., the sink or the kitchen table). In turn, PPC bias the competition between neurons in MT and V2, favoring the ones related to the location of the target object. The information about location arrives to V1, through the backprojections of the dorsal stream pathway (PPC-MT-V2-V1), and it meets the bottom-up information about the shape of the object found at that location (the shape information comes from the retino-geniculate-striate pathway to V1). The integrated information (shape plus location) is sent by feedforward connections through the ventral stream to IT, which will finally identify the object (e.g., red apple) corresponding to the attentional location where PPC neurons had increased their firing rate (e.g., the fruit bowl at the counter).

In conclusion, the Biased Competition Model proposed by Deco and colleagues (Rolls and Deco, 2002; Deco and Lee, 2004; Deco and Rolls, 2004; Deco and Rolls, 2005) is a neurocognitive model that incorporates, in a simplified schema, how the brain processes the visual scene under specified conditions. This model is able to explain how the visual system operates, how it incorporates information about the object's identity or its location with the information that is directly coming from the eyes. Importantly, it explains how high-order cognitive cortical areas work in conjunction with early visual areas, by means of backprojections and feedforward connections, to resolve visual search and object

recognition tasks, which in essence are everyday tasks. Although the model's formulation and simulation has a wide computational component (Deco and Lee, 2004), it has been supported by experimental evidence (for a review see Deco and Rolls, 2005).

1.7. Conclusion

Many years after W. James addressed the question of *what attention is* (1890), the concept of attention has drastically evolved. On the one hand, theories and models of attention (especially visual attention) have steadily emerged to give, at each point in time, a better account of attention processes. On the other hand, thanks to empirical evidence collected through the different behavioral, neurophysiological and neuroimaging studies a more comprehensive picture of attention is being formed.

Basically, one of the main concerns of visual attention studies is how our brain is able to ignore the different elements of the context and, at the same time, maintain the focus of attention on the target elements. Since the very first models of visual attention, the way the system is able to change from divided to focused attention has been a main topic (Treisman, Skaes and Gelade 1977; Treisman and Gelade, 1980). The need to recur to different mechanisms to explain it, like parallel versus serial processing, has also been a debate (e.g., Treisman and Gelade, 1980; Wolfe, 1989; Desimone and Duncan, 1995; see also Eimer 2014, 2015). In addition, in order to describe the way attention might operate, it was necessary to differentiate between its stages and functions (Posner and Boies, 1971; Posner and Petersen, 1990). The later inclusion and discussion of the role of different parameters, either of the scene (e.g., the features of the objects, their locations) or of the subject who searches (e.g., the receptive fields, the saccades), raised the need for better accounts of how the visual input is mapped onto the brain (Itti et al., 1998; Itti and Koch, 2001) and whether or not, the representation of the visual scene is influenced by, for instance, prior knowledge or training (e.g., Serences and Yantis, 2006; Bisley et al., 2009; Bisley and Goldberg, 2010). Current neurocomputational theories are fitting more and more parameters, such as the feedforward connections between bottom-up and top-down information, along with the brain structures and networks that support these connections (Deco and Rolls, 2005; see also, Buschman and Kastner, 2015).

2. Brain areas and networks related to attention and visual search task.

As mentioned above, visual search tasks have been widely used to study visual attention because they conveniently enable the study of the different attention mechanisms. That is, behavioral, neurophysiological and neuroimaging studies try to map the complexity of the real world by using visual search paradigms (Peelen and Kastner, 2014). In fact, visual search is an appropriate visual attention laboratory task because it can be performed by non-humans primates and humans, and it covers almost all of the attention aspects: it is possible to perform it covertly or overtly, inside or outside the receptive fields, and it explores attention to features or objects, spatial or temporal aspects, and even cognitive aspects (like low prevalence objects, motivation, feedback) and motor execution (Eckstein, 2011; Chun et al., 2011).

Throughout the years, experimental evidence has been collected about search efficiency in terms of accuracy and reaction time in behavioral studies; or neurophysiological studies have explored the neural response associated with variations in search parameters such as location, target-distractors relations or eye saccades (e.g., single-unit recording studies, Positron Emission Tomography (PET) and fMRI studies) (see Kastner and Ungerleider, 2000; Eckstein, 2011; Nakayama and Martini, 2011; Eimer, 2014; Peelen and Kastner, 2014).

The following sections are dedicated to briefly reviewing the evidence related to the role that the different brain areas and networks engaged during visual search task play in visual attention, as they have been studied in neuroimaging studies (preferentially fMRI studies in humans). Task-related fMRI studies have found that visual search tasks generally includes a number of subcortical and cortical areas: visual cortex, thalamus, SC, PPC, FEF, insular cortex and VLPFC, dorsal anterior cingulate cortex (dACC), DLPFC (see Kastner and Ungerleider, 2000; Eimer, 2014).

On the other hand, the functional networks related to the visual search task have been studied by means of rs-FC. It is known that rs-FC networks are consistent, and that the connectivity values within nodes of the same network are high, however, it is low whenever connections between nodes of different networks is explored (Damoiseaux et al., 2006; Smith, et al., 2009; Power and Petersen, 2013). One of the most influential

works on visual attention and rs-FC linked the bottom-up processing of the visual scene with to the ventral attention network and the top-down influences to the dorsal attention network (Corbetta and Shulman, 2002). Recent studies on rs-FC, visual search, and attention control link the dual ventral/dorsal system to the orienting process (Petersen and Posner, 2012). Emphasis is now placed on the way the brain exerts top-down control during visual attention tasks (Seeley et al., 2007; Dosenbach et al., 2007; Dosenbach et al., 2008; Cole et al., 2013).

2.1. Brain areas related to attention and visual search task

2.1.1. *Occipital cortex*

Researchers agree that the occipital cortex, located at the most posterior part of the human brain, has at least three main visual field maps in humans (Wandell, Brewer and Dougherty, 2005). They correspond to V1, V2 and visual area 3 (V3) and are arranged circularly. V1 is located in the medial surface of the occipital lobe, specifically in the calcarine sulcus, and it extends over the posterior pole and lateral surface of the occipital cortex (Wandell et al., 2005; Wandell and Winawer, 2011). V2 and V3 are located around V1 occupying the calcarine cortex. These three visual field maps are found in both hemispheres and map the contralateral hemifield in a very accurate retinotopical manner: damage to specific portions of the visual cortex result in cortical blindness for the specific location that was mapped by the neurons lost (Horton and Hoyt, 1991a, 1991b). V1/V2/V3 are, mainly, a representation of the fovea and, to a lesser degree, of the fovea's periphery (Wandell and Winawer, 2011). Therefore, V1/V2/V3 are primarily, but not exclusively, devoted to processing basic visual features, providing humans with the ability to see (Wandell et al., 2005; Wandell, Dumoulin and Brewer, 2007).

Other visual field maps are found in the occipital cortex and extend beyond it to ventral and dorsal visual pathways areas (Wandell et al., 2007). Ventral aspects of the visual cortex, extending to IT, contain visual field maps related to processing object recognition. In this portion human V4 (hV4), ventral occipital visual field maps VO-1 and VO-2 are found, which are located adjacent to the ventral portion of V3 (Wandell and Winawer 2011), and anterior to VO-2 are the parahippocampal visual field maps

PHC-1 and PHC-2 (Arcaro, McMains, Singer and Kastner, 2009). Color processing has been linked to hV4 and ventral occipital maps; however, the other ventral maps are related to processing forms, such as objects or faces, words or places. For example, PHC is related to processing locations (Wandell et al., 2005; Arcaro et al., 2009; Wandell and Winawer, 2011). Dorsomedial portions of the visual cortex, extending to the posterior IPS, also have visual field maps. In this part, V3A, V3B and visual area 7 (V7) maps are located, distributed in a posterior to anterior manner. These visual field maps are associated with the perception of motion (anterior aspect of V3) and depth (Tootell, Mendola, Hadjikhani, Ledden, Liu et al., 1997; Wandell et al., 2005). Finally, there are additional visual maps in the human MT area (MT+ or V5) and in the lateral occipital complex (LOC). These maps are located on the lateral surface of the occipital lobe, extending from the occipital pole to the superior temporal sulcus. MT+ has more than one visual field map and responds strongly to motion (Amano, Wandell and Dumoulin, 2009; Wandell and Winawer, 2011). LOC responses have been linked to the processing of objects features and object's identification (Malach, Reppas, Benson, Kwong, Jiang et al, 1995; Wandell and Winawer, 2011).

In short, visual functions are supported by the entire occipital lobe. However, the visual cortex not only includes the occipital cortex, but it also extends into the temporal and the parietal cortex (Wandell et al., 2007). The primary occipital cortex and extrastriate areas are commonly found activated during visual attention tasks (Eckstein, 2011; Eimer, 2014; Peelen and Kastner, 2014).

2.1.2. Thalamus

The thalamus is a subcortical structure located in the forebrain, dorsal to the midbrain. In relation to visual perception functions, three thalamus nuclei have been related to them: the LGN, the reticular nucleus, and the pulvinar nucleus (Saalmann and Kastner, 2011).

The LGN is thought to be organized in a laminar structure with, at least, parvocellular and magnocellular subdivisions, and possibly including koniocellular cells as well (Derrington and Lennie, 1984; Sclar, Maunsell and Lennie, 1990; Saalmann and Kastner, 2011). In terms of modulatory activity, main visual afferents of LGN are the retinal sources, V1, and brainstem, in addition to the reticular nucleus, which sends inhibitory

input to the LGN (Bickford et al., 2000; Erişir, Van Horn, Bickford and Sherman 1997; Sherman and Guillery, 2006; Briggs and Ursey, 2009).

The reticular nucleus is a structure consisting of a layer of gamma-aminobutyric acid cells (GABAergic cells) that lies rostral and lateral to the dorsal thalamus (Lam and Sherman, 2015). Anatomically, it is organized in sectors. Neurophysiologically, the visual sector receives inputs from cortex, the pulvinar, and the LGN; and it sends inhibitory outputs to the LGN and the pulvinar (Saalmann and Kastner, 2011). The reticular nucleus has been signaled as exerting control over thalamic processing and visuo-spatial attention because the reticular nucleus has visual fields that are topographically organized. Thus, retinotopical organized information is thought to be sent to at least the LGN (McAlonan 2006; Crabtree and Killackey, 1989).

The pulvinar nucleus is the largest thalamic nucleus in the primate brain (Saalmann and Kastner, 2011; Arcaro, Pinsk and Kastner 2015). In terms of visual perception, four areas have been distinguished: lateral and ventral pulvinar with retinotopic organization, and ventromedial and dorsal areas without topographic organization (Saalmann and Kastner, 2011). The pulvinar has cortical and cortico-thalamo-cortical afferences and efferences, and because of its location, is thought to regulate corticocortical communications (Sherman and Guillery, 2006; Arcaro et al., 2015). The pulvinar has diverse representations of the contralateral visual field and, there have been at least two identified maps of the space in the lateral aspect of the ventral pulvinar (Arcaro et al., 2015). The pulvinar is interconnected with striate and extrastriate visual cortex areas; in its connections, a gradient from the rostral and lateral aspects to the caudal and medial parts of the pulvinar corresponds to posterior to anterior and ventral occipitotemporal cortical areas (Shipp, 2003; Arcaro et al., 2015).

Visual functions of the thalamus (LGN, reticular nucleus or pulvinar nuclei) have been related to the regulation of information transmission to the cortex and between cortical areas (Saalmann and Kastner, 2011). For instance, LGN activity is modulated by selective attention and has been related to the allocation of attention focus in specific visual field locations (O'Connor, Fukui, Pinsk and Kastner, 2002); the pulvinar nucleus is relevant for visuo-spatial functions that involve reorienting attention and spatial coding, and the reticular nucleus modulates LGN and pulvinar with inhibitory signals and seems to exert control over the retino cortical and cortico-thalamo-cortical pathways (Saalmann and Kastner, 2011). Indeed, recent studies show that the reticular nucleus receives inputs

from the prefrontal cortex to then bias the activity of the other visual thalamic nuclei during sensory selection processing (Wimmer et al., 2015). Increased thalamic activation has been found during the performance of visuo-spatial tasks (compared to baseline or control conditions). For instance, on a study that explored the functional neuroanatomy underlying a visual search task with differential attention demands, the right ventrolateral area of the pulvinar was found to be active during the performance of inefficient search tasks (i.e., response time increases as the number of distractors in the display is increased). This area of the thalamus was associated with supporting the control of eye movements while guiding visual attention through the space (Kim, Eliassen Lee and Kang, 2012).

2.1.3. Superior colliculus

The SC is a laminated midbrain structure (May, 2006). The SC is organized in three different cellular layers: superficial, intermediate and deep. Each of these layers has different connections and responds differently to visual stimuli (Krauzlis et al., 2013). In general, afferences to SC come from diverse sources that include retina and primary visual sensory information, and somatosensory, auditory and motor information. Structures communicating with the SC include cerebellum, basal ganglia and thalamus, and structures in the cortex, visual occipital, sensory and associative areas (May, 2006). The SC is thought to respond to and subserve a wide range of sensory, motor or cognitive functions (Krauzlis et al., 2013).

The SC is mainly related to visual spatial attention (Krauzlis et al., 2013). The SC neurons have contralateral topographic representations of the visual field, in which the central portion of the visual field is enlarged. The superficial layer of the SC responds to naturally salient visual stimuli and contains a map of the stimuli's location. The intermediate and deep layers respond to diverse types of sensory stimuli. In terms of attention, these layers make it possible to organize the orienting movements and selecting priorities into a map (Krauzlis et al., 2013).

Several visuo-spatial and visual attention studies have focused on the study of SC's roles. For instance, the interconnections between mesencephalic substantia nigra pars reticulata or the brainstem's pedunculopontine nucleus with SC' intermediate and deep layers support, in terms of motor processes, the eye movements necessary for orienting processes (Wallace, Rosenquit and Sprague, 1989 and 1990; Ciaramitaro, Todd and

Rosenquist 1997; Durmer and Rosenquist 2001). Importantly, the SC is a key area for evaluating saccades to target location, and it participates in selective attention processes (Horowitz and Newsome, 1999, 2001; Carello and Krauzlis, 2004; Kauzlis 2005; Dorris, Olivier and Munoz, 2007; Lisberger 2010; Nummela and Kauzlis, 2010). That is, SC intermediate and deep layers increase their activity when target stimuli are present, and this activity is proportional to the probability of making a saccade (Krauzlis et al., 2013). In relation to spatial attention, it has been demonstrated that the SC is implicated in overt and covert tasks (Ignashchenkova, Dicke, Haarmeier and Their, 2004). By using single-unit recording, Ignashchenkova and colleagues (2004) were able to study visuomotor neurons of the intermediate layer and relate their activity not only to the preparation of saccade but also to shifts in the focus of attention on covert visual tasks. However, it seems that the SC does not control spatial attention in a predicted coordinated way with visual occipital cortex neurons (Petersen and Posner, 2012), but independently through other mechanisms (Zénon and Krauzlis, 2012).

2.1.4. Posterior parietal cortex

The parietal cortex is associated with numerous cognitive functions, making the linkage between function and anatomical mapping a complex task (Humphreys and Lambon Ralph 2014). The parietal cortex is commonly subdivided into the lateral and medial cortex. The lateral cortex is, in turn, subdivided into dorsal and ventral areas. Whereas the dorsal PPC includes IPS and SPL, the ventral parietal cortex is composed of the supramarginal gyrus and angular gyrus (Nelson et al., 2010; Uddin et al., 2010; Caspers et al., 2011; Mars et al., 2011; Humphreys and Lambon Ralph 2014).

Humphreys and Lambon Ralph (2014) provide an overview of the functions associated with three major subdivisions of the lateral parietal cortex after conducting an activation likelihood estimation analysis of 386 studies. IPS and SPL have been related to top-down control of attention, numerical calculation, tool-praxis, executive semantics and phonology. In turn, the supramarginal gyrus has been associated with bottom-up control of attention and phonology. Finally, the angular gyrus has been related to automatic semantics, numeric and episodic retrieval, and sentence processing.

In relation to visual attention and visual search tasks, the PPC has been related to both feature-based and space-based attentional control (Egner et al., 2008; Szczepanski, Konen

and Kastner, 2010). In addition, the PPC has been identified as responsible for exerting top-down control of attention by using priority maps like those found in the FEF and SC (Gottlieb et al., 1998; Kastner and Ungerleider, 2000; Ipata et al., 2008; Bisley and Goldberg, 2010; Petersen and Posner, 2012). In recent real-world visual search investigations, it has been proposed that the PPC contributes to the maintenance of visual templates in both ventral and dorsal visual stream processing pathways (Peelen and Kastner, 2014). In a general sense, the PPC has been pointed out as the cortical area responsible for supporting a general processing system (Humphreys and Lambon Ralph, 2014)

2.1.5. Frontal cortex

Different areas of the human frontal cortex have been related to the performance of visual spatial and visual search tasks. These areas include the supplementary eye field (SEF), and FEF, dACC, supplementary motor area (SMA), aI and VLPFC, and DLPFC. These areas have been related to different functions underlying the performance of visual search and visual spatial tasks (Kastner and Ungerleider, 2000; Corbetta and Shulman, 2002; Muggleton, Juan, Cowey and Walsh, 2003; Reynolds and Chelazzi, 2004; Nachev, Kennard and Husain, 2008; Buschman and Kastner, 2015).

In a recent meta-analysis focused on the study of the brain regions involved in inhibitory processes for the top-down control of behavior during the performance of goal-directed cognitive tasks, three key regions were found to be involved in supervisory attentional control (Cieslik, Mueller, Eickhoff, Langner and Eickhoff, 2015). To do so, coordinate-based activation likelihood estimation analyses were conducted. The tasks included in the analyses were classified in three categories: action withholding (go/no-go task), inhibition of motor response (stop task), and interference control (congruency tasks). In turn, congruency tasks included, on the one hand, spatial tasks like the Simon task, stimulus-response compatible task, antisaccade task and spatial flanker task, and on the other, the Stroop task, which was considered a non-spatial congruency task. Results of the meta-analysis indicated that in the role of supervisory attentional control, that is, in the guiding, selection and maintenance of actions during the performance of non-routine goal-directed behaviors, the right aI / VLPFC, right inferior frontal junction, ACC and pre-SMA are the key cortical areas and domain-general. Other regions were associated

with top-down control, but they were not domain-general. For instance, on spatial interference tasks, the regions commonly involved in top-down control were located in the dorsal pre-motor cortex, PPC, inferior right frontal junction, right aI/VLPFC and dACC along with the pre-SMA, which in general constitutes the FPN involved in visual search and visuo-spatial tasks (Kastner and Ungerleider, 2000; Corbetta and Shulman, 2002; Corbetta, Patel and Shulman, 2008).

In relation to visual attention, two prefrontal cortex areas remain the most widely studied: the DLPFC (Brodmann area, BA, 46) and FEF (BA 8). It has been observed that the neural response of these areas increases when attention is directed to stimuli within their neuronal receptive field, and this increased activation occurs whether attention is shifted voluntarily or involuntarily (i.e., in a top-down or in a bottom-up manner) (Buschman and Miller, 2007; Armstrong, Chang and Moore, 2009; Gregoriou, Gotts, Zhou and Desimone, 2009). It is worth noting that investigations centered on the study of the time course of the DLPFC / FEF (and PPC) have shown that these regions create their own context maps that represent the saliency of the targets according to the task is represented (Cohen, Heitz, Schall and Woodman, 2009; Purcell, Schall and Woodman, 2013).

FEF neurons support a continuum of visual and movement functions: some respond only to visual stimulation, some respond before saccadic movements and others exhibit both visual and movement-related activity (Sommer and Wurtz, 2000). Microstimulation studies within the FEF have demonstrated that visual cortex activity is modulated by FEF neuronal activity; in turn, this modulation can lead to increased activity in visual areas, which varies according to the presence or absence of distractors and is related to the location of the target and the end point of saccades (Moore and Fallah, 2001; Moore and Armstrong, 2003; Moore and Fallah, 2004; Armstrong, Fitzgerald and Moore, 2006; Ekstrom, Roelfsema, Arsenault, Kolster and Vanduffel, 2009). Therefore, the FEF is seen as the interface between the saccadic system, the visual system, and the executive control system, not only because of the neural composition of the area, but also because a connection between saccadic movements and modulation of attention occurs within the FEF (Moore and Fallah, 2001, 2004; Noudoost, Chang, Steinmetz and Moore, 2010; Squire, Noudoost, Schafer and Moore, 2013; Katsuki and Constantinidis, 2014).

The study of the saliency maps and the neuronal time course associated with bottom-up attentional processing has led to associating the activity of the DLPFC (BA 46) (and

also, the PPC and FEF) to bottom-up automatic information processing and also to top-down mapping in relation to the importance of a target for task completion (Katsuki and Constantinidis, 2014). A recent neurophysiological investigation studied the activity of frontal and parietal areas in terms of the neuronal response in their receptive fields (Katsuki and Constantinidis, 2012). The main conclusion was that the latencies to detect target visual stimuli were the same in the DLPFC (BA 46), FEF (BA 8) and PPC (lateral IPS, LIP, and area 7a). Although in PPC receptive fields the initial response was faster, frontal and parietal areas responded in the same time when the relevant stimuli to be discriminated were presented (Katsuki and Constantinidis, 2012). Authors interpreted these results in light of top-down attention control theories, where the guiding and selection processes are biased by prior information about targets (Bisley and Goldberg, 2010). Therefore, the DLPFC will be another source of top-down modulation and is thought to exert influence over ventral and dorsal visual stream pathways (Noudoost et al., 2010).

2.2. Attention and cognitive control functional networks

Different functional brain networks have been identified as to exerting cognitive control: the dorsal attention network (DAN), the ventral attention network (VAN), the FPN and the CON / salience network (SAN) (Power et al., 2011; Power and Petersen, 2013). The visual search task is commonly seen as a visual attention task where cognitive control can be studied because subjects are asked to search for specific targets, thus preventing the focus of attention from being attracted by salient environmental stimulus. Moreover, because when visual search is goal-directed, it is predominantly based in top-down control rather than bottom-up (Corbetta and Shulman, 2002).

In the current panorama of the control-related systems in the human brain, the different cognitive control networks have been related to different processes within the attention-control system, with these differences usually based on task characteristics or the studied signals (Dosenbach et al., 2008; Power and Petersen, 2013). Briefly, Corbetta and Shulman differentiated between the DAN and VAN, two networks that have been found active during visual search tasks and related to top-down visuo-spatial attention and bottom-up reorienting processes, respectively (Corbetta and Shulman, 2002). Soon

after that, Dosenbach et al., (2006) described two different cognitive control networks, the FPN and the CON, which were very similar to the “executive control network” and the SAN, respectively, described in Seeley and colleagues (2007).

Figure 5. Attention and cognitive control functional networks. (A) Graphic representation of the brain areas involved in the dorsal attention network (in green) and in the ventral attention network (in blue). (B) Graphic representation of the brain areas involved in the frontoparietal network (in yellow) and in the cingulo-opercular network (in black). Extracted from Petersen and Posner (2012, p. 76)

Recent revisions on this topic emphasize that the functional network organization of the control system may be understood from the perspective of macrocircuits that can be decomposed in subnetworks (Power et al., 2011; Power and Petersen, 2013). In accordance with this view is the fact that early works differentiate few networks, but the current panorama includes the DAN, VAN, CON/SAN, and FPN. For instance, Fox and colleagues (2005) differentiated between two anticorrelated systems, the task positive and task negative. The presence of these two systems was observed during the performance of attention-demanding cognitive tasks, and their anticorrelation state became more pronounced as the attentional demand increased. Later, it was found that the DAN, the FPN and the CON make up the task positive system, and the default mode network (DMN) corresponds to the task-negative system (Power et al., 2011). Here the main characteristics of the attention-control networks are discussed in terms of brain areas involved and general functions associated with each of them.

2.2.1. *Dorsal and ventral attention networks*

Corbetta and Shulman (2002) described two functional brain networks whose functions were related to different visual attentional processes. On the one hand, the DAN, which included PPC and FEF, is involved in the selection of sensory information and responses. On the other hand, the VAN, which included the TPJ and the VLPFC, is engaged during the detection of behaviorally relevant sensory events.

The DAN is implicated in goal-directed stimulus-response selection processes (Corbetta and Shulman, 2002), that is, in situations like the visual search task where a prior known target must be found among distractors and a response to the situation is given according to the successful or unsuccessful finding of the target. The DAN was outlined as a system that links relevant sensory representations to relevant motor representations (Corbetta and Shulman, 2002). During the performance of visuo-spatial tasks, different studies noticed that the DAN's areas present sustained activity (Kastner, Pinsk, De Weerd, Desimone, and Ungerleider, 1999; Shulman et al., 1999; Corbetta, Kincade, Ollinger, McAvoy and Shulman, 2000; Hopfinger, Buonocore and Mangun 2000; Corbetta and Shulman, 2002). The sustained activity is bilateral and it is found when attending to either visual field. However, the fact that spatially selective responses to the contralateral visual field are found in the intraparietal sulcus and in the FEF led to the idea that the PPC and FEF are involved in the control of the focus of attention, and are suitable areas for holding priority maps (Hopfinger et al., 2000; Corbetta and Shulman, 2002).

The VAN has been found to be active during the detection of behaviorally relevant stimuli (Corbetta and Shulman, 2002). The VAN is strongly right-lateralized, and it is independent of the stimulus' presentation modality (Downar, Crawley, Mikulis and Davis, 2000). It has been proposed that, when a salient stimuli is detected, the VAN interrupts the processing ongoing in the DAN (Corbetta and Shulman, 2002); that is, the ventral system is able to capture and move the focus of attention from a target location to the relevant stimulus' location. Moreover, the VAN is associated with the transition from the rest- to ready-state and, thus, consistently found active when an unexpected stimulus appears (Downar et al., 2000; Konishi, Donaldson and Buckner, 2001; Corbetta and Shulman, 2002; Shulman, d'Avossa, Tansy and Corbetta, 2002; Fox, Snyder, Barch, Gusnard and Raichle, 2005).

In target detection studies like visual search and oddball tasks, the DAN areas show sustained activity, and the VAN areas are active at or after detection and when a salient stimulus appears (Corbetta and Shulman, 2002; Mantini, Corbetta, Perrucci, Romani and Del Gratta, 2009). Indeed, the DAN is influenced by voluntary attention shifts during continuous cognitive and behavioral tasks (Shulman et al., 2003; Visscher et al., 2003; Fox et al., 2005). Moreover, the VAN, contrary to the DAN, is not engaged by central cues, which have information about the task to be performed (Corbetta and Shulman, 2002). Therefore, the DAN is usually associated with voluntary spatial orienting of the attention focus.

In conclusion, the DAN and VAN have distinctively been characterized as two attention-control networks with opposite functioning in terms of reorienting processes. Whereas the DAN is functionally related to voluntary shifts in attention, the VAN supports the reorienting processing when relevant stimuli are present.

2.2.2. *Frontoparietal network*

The FPN is a cognitive control network related to initiating and adjusting control on cognitive attention-demanding tasks (Dosenbach et al., 2006; Dosenbach et al., 2007; Dosenbach et al., 2008). According to Petersen and colleagues, the core nodes of this network are the: DLPFC, dorsal frontal cortex, middle cingulate cortex, IPL, IPS and precuneus (Dosenbach et al., 2008; Power and Petersen, 2013).

In a study using resting-state functional connectivity MRI (rs-fcMRI) data, Petersen and colleagues were able to implement graph-theoretical analysis in combination with seed-based functional connectivity analyses, with being these seeds being derived from previous mixed block/event related fMRI studies, in order to study the FPN features in terms of cognitive control processing (and the CON) (Dosenbach et al., 2006; Dosenbach et al., 2007). Interestingly, authors explored the brain networks from the perspective that they could be organized according to small-world properties that operate in different time scales and make different contributions to task control (Dosenbach et al., 2007; Dosenbach et al. 2008). Findings showed that the IPS, precuneus, midcingulate and lateral frontal cortex were only related to cue information. Error-related events were linked to the right IPL and DLPFC (Dosenbach et al., 2007). Only the left IPL showed sustained

activity throughout the tasks. The main conclusion was that the FPN is responsible for control initiation and provides flexibility in adjusting control in response to feedback (Dosenbach et al., 2007).

Recent studies are focusing on the possibility that the FPN could function as a *flexible hub* of cognitive control (Cole et al., 2013; Zanto and Gazzaley, 2013). This hypothesis is based on rs-fcMRI studies where the functional connectivity patterns of different brain regions are studied in relation to the characteristics of tasks and their organizational schemas. Briefly, the analysis consisted of estimating a between-regions of interest (264 brain regions or nodes) connection coefficient across 64 different tasks. Authors distinguished ten different a priori known brain networks: visual, auditory, motor, SAN, CON, DMN, DAN, VAN, FPN, and subcortical. The main results were, first, that the FPN had the highest global variable connectivity, that is, the FPN had the best intra-network connectivity. Second, it was found that the FPN was the only network that showed significant connections with each of the other brain networks. Third, FPN organization varied depending on the task being performed. Finally, the connectivity patterns of FPN were organized systematically and these patterns were transferred from known to new task contexts (Cole et al., 2013).

In conclusion, the main function of the FPN seems to be related to the implementation of top-down control. Specifically, the FPN is thought to support the adjustment to the stimulus-response relation in response to feedback by interpreting the trial-by-trial information. In order to properly implement this kind of top-down control, it is plausible that the FPN is highly interconnected with all the other brain networks.

2.2.3. *Cingulo-opercular network / salience network*

Dosenbach and colleagues first described the CON, consisting of the dACC / middle superior frontal cortex and aI / frontal operculum, and they found it to be associated with start-cue and error-feedback related processes, along with task-set maintenance (Dosenbach et al., 2006). Ten mixed blocked/event-related designs were introduced in the analyses. These studies had different types of stimuli, visual or auditory inputs and verbal or motor outputs. The aim of the study was to explore the neural activations related to three signals: start-cue, sustained activity, and performance feedback activity. Several

brain regions were found to be activated across tasks and related to the three types of signals. After conducting conjunction analyses, the authors interpreted that dACC / middle superior frontal cortex and bilateral aI / frontal operculum were consistently related to start-cue and sustained effects and, for a great number of tasks, to error-related activity. The authors concluded that these areas may form a human task-set system. That is, the dACC / middle superior frontal cortex and aI / frontal operculum formed a core network for implementing goal-directed tasks (Dosenbach et al., 2006).

Seeley and colleagues found, by means of independent component analysis (ICA) in rs-FC data, that the dACC and orbitofrontal insular cortex were organized into a network, the SAN. ICA analysis revealed that the nodes of this network established connections with subcortical and limbic structures (i.e., superior temporal pole, amygdala or thalamus), and even with DLPFC and SMA / pre-SMA. A measure of anxiety levels before the scan and the scores on the Trail Making Test were used in correlation analyses, along with ICA results. The authors found that pre-scan anxiety scores were correlated to dACC and left DLPFC, but not to nodes of the FPN. The SAN was related to the processing of errors and conflict, and indicated that the dACC and orbitofrontal insular cortex could be specialized modules for processing sympathetic efferences and interoceptive feedback (Seeley et al., 2007).

In a rs-fcMRI study (Power et al., 2011), two different subnetworks were found to be related to cingulo-opercular areas by means of graph-based analysis. These subnetworks were related to the CON and the SAN. The areas designated as the CON were spatially found anterior to the areas defined as the SAN in: the ACC, lateral and anterior PFC and dorsal aI. The most notable difference was found in the aI region. Functionally, the two subnetworks were similar, but the CON was mostly related to start-cue activity. Through the analysis, strong borders between the regions were found, indicating that the rs-fcMRI signals of the two networks may be different (Nelson et al., 2010; Power et al., 2011).

In conclusion, it might be said that a cingulo-opercular control system is functionally related to task control but, within it, two different subsystems co-exist: the CON and the SAN; with both of them being involved in monitoring sustained activity and processing error-related activity, although the CON is mostly engaged during the start-cue phase.

2.3. Conclusion

Different fMRI techniques and analysis approaches are leading to the differentiation and characterization of the attention and cognitive control brain networks. Each different network supports different processes during attention demanding tasks. In terms of their relation to reorienting the attention process, the DAN and VAN seem to have opposite functions, with the DAN engaged during voluntary shifts and focus of attention and the VAN being stimulus-driven. The DAN is the main support for task performance during visual search tasks where specific stimuli have to be found among distractors, preventing the shift in the focus of attention to undesired locations. By contrast, the VAN is able to interrupt DAN ongoing activity, supporting the presence of a salient target, as in detection tasks and searches where the detection of targets has been automatized and “pop-out” of the screen. In goal-directed task performance, the FPN is relevant to task-set implementation, and so is the CON for monitoring the behavioral performance throughout the task. The CON and FPN seem to complement each other. The CON has consistently being found to be active throughout task performance and it has been related to general feedback processing; however, the FPN is transient and, more related to the processing of start-cue information and to managing the necessary adjustments to the stimulus-response relations.

3. Automaticity, cognitive training and brain plasticity

3.1. The concept of automaticity

Generally speaking, automatic behavior is understood as the kind of actions that humans are able to perform without thinking, in the absence of awareness and apparently effortless. William James defined automatic behavior as the activities that are performed quickly, effortlessly, without dedicating much thinking and almost conducted with no conscious awareness (James, 1890).

Commonly, psychological theories about automaticity have also defined this construct in terms of its features and the psychological processes that should occur when a person is performing an action under automatic processing (Shiffrin and Schneider, 1977; Posner and Snyder, 1975; Bargh, 1994). Therefore, classic conceptions of automaticity agreed that automatic and non-automatic (usually, termed controlled processing) differed in their describing features. Other theoretical proposals have been concerned with the development of automatic behavior, focused on the conditions or the processes necessary for developing it (e.g., Spelke et al., 1976; Logan, 1988).

Automaticity theories were linked to the study of attention. From a psychological perspective, attention was understood as a module necessary to perform relevant actions, but with a limited capacity to process the environmental information (Kahneman, 1973; Shiffrin and Schneider, 1977; Logan, 1979). The behavioral experiments conducted in the late 1970s and early 1980s made it possible to develop two-process models of automaticity, where evidence-based distinctions between controlled and automatic processing were defined (e.g., Shiffrin and Schneider, 1977; Logan, 1978 and 1979; Schneider and Fisk, 1982). Automatic behavior was considered fast, effortless, autonomous, stereotypic and unavailable to conscious awareness (LaBerge, 1981; Kahneman and Treisman, 1984; Schneider, Dumais and Shiffrin, 1984; Logan, 1985). Therefore, the fundamental difference between controlled and automatic processing of information was the limitation in attention (Shiffrin and Schneider, 1977; Logan, 1979 and 1980). However, these concepts were labels for a continuous process.

Controlled processing was understood as the type of information processing that is used when the behavior is actively and consciously driven by the subject of the action (Schneider and Shiffrin, 1977). In dual-processing theories, controlled processing had a

limited capacity and was defined as effortful; thus, only a few bits of information could be processed at a time (Fisk and Schneider, 1982; Schneider and Chein, 2003). The benefits of controlled processing were that the processes necessary to carry out an action could be easily learned, in a few attempts, and easily modified and applied in novel situations (Schneider and Chein, 2003). On the other hand, automatic processing was understood as an effortless information process, not dependent on attention capacity because it was over-learned and always occurred as a consequence of a particular stimulus that triggered a set of actions (Schneider and Shiffrin, 1977).

Automatic processing was understood as an unconscious way of processing information that required considerable training and constant conditions to be developed. It was agreed that attention was gradually withdrawn as automatic processing was acquired (LaBerge and Samuels, 1974; Shiffrin and Schneider, 1977; Logan, 1978). Thus, once automatic processing was established, it did not require any supervisory attention from the subject performing the action (Fisk and Schneider, 1984; Schneider and Chein, 2003). In relation to attention processing, whereas in controlled behaviors, information was processed in a serial manner (e.g., one or a few items at a time), automatic information processing occurred in a parallel way (e.g., no existence of a limited capacity at all) (Schneider and Shiffrin, 1977; Shiffrin and Schneider, 1977; Fisk & Schneider, 1982).

Other descriptive features of automatic processing focused on the automatic behavior, for instance, the difficulty into returning to controlled processing once automaticity to drive and action is achieved. Other examples are the ease of automatic processing in triggering an action in response to the presence of a specific and associated stimulus, and the way this stimulus-response was seen as more dependent on the significance of the stimulus than on the context itself. Finally, there is relative independence between automatic behavior development and the learning of the stimulus-response relation itself (e.g., it was seen more as a matter of practice than successive modifications of the stimulus-response relation) (Shiffrin and Schneider, 1977; Shiffrin & Schneider, 1977; Shiffrin, Dumais, and Schneider, 1981; Schneider and Chein, 2003).

A recent review on the concept of automaticity proposes viewing the descriptive features of automaticity as factors (e.g., the amount of attention and time dedicated to complete an action), in order to establish how they interact with the underlying processes of automatic behavior (Moors, 2015). In addition, this framework proposes going beyond

the distinction of bottom-up and top-down information processing, respectively linked to controlled and automatic processing, by including multiple levels of organization of factors in relation to the stimulus, to the person, and to their possible combinations (Moors, 2015). Interestingly, attention is seen as a factor that modulates the stimulus perception from both prior knowledge and the current perception, thus bringing a link between the classic question of whether or not attention takes part in automatic processing and the priority map theories.

The major highlight is the consideration of automaticity as a gradual construct rather than an exclusive category (e.g., either controlled or automatic). That is, behavior (or the processes underlying it) should be considered as more or less automatized. Thus, in the event of comparing and deciding whether two actions are conducted under controlled or automatic processing, all the factors that describe them should be kept exactly equal, except one (Moors, 2015). However, the empirical evidence supporting this theory is yet to come. It is a challenge for current brain investigations on automaticity, training and brain plasticity, to meet the necessary requirements to actually differentiate controlled processing from automatic.

3.2. Visual attention, automaticity and brain plasticity

In recent decades, structural and functional MRI investigations have been accumulating evidence in favor of adult brain plasticity and its study at the macrostructure level (Pascual-Leone, Amedi, Fregni and Merabet, 2005; May, 2011; Guerra-Carrillo, Mackey and Bunge, 2014). Pascual-Leone and colleagues defended the idea that the brain is, by definition, plastic; that is, behavioral and environmental factors constantly induce and mold the brain (Pascual-Leone et al., 2005). The plasticity of the human brain lasts across the lifespan and is the basis of development and learning (Pascual-Leone et al., 2005).

On the one hand, studies have shown that structural brain changes due to training, display experience-based anatomical variations (e.g., cortical thickness, regional gray matter volume) in the cerebral structures related to the task being trained (Lövdén, Wenger, Mårtensson, Lindenberger and Bäckmana, 2013). For instance, Draganski and colleagues observed increased gray matter volume in a group of subjects who learned to

juggle for three months. The changes were specific to the training stimulus and to the jugglers, and the controls did not display any anatomical changes. Brain changes affected the bilateral MT+ / V5 and left posterior IPS, which are specific motion selective areas. These changes were transient, showing gray matter volume expansion from the first to the second scan, which was reduced in the third scan (Draganski et al., 2004). Several cross-sectional and longitudinal studies have observed training-related anatomical changes in relation to, for instance, visuo-spatial navigation (Maguire et al., 2000; Lövdén et al., 2012), language (Golestani, Paus and Zatorre, 2002; Golestani and Zatorre, 2004; Golestani and Pallier, 2007; Ilg et al., 2008; Mårtensson et al., 2012; Stein et al., 2012), memory (Draganski et al., 2006; Engvig et al., 2010) and music skills (Sluming et al., 2002; Gaser and Schlaug, 2003a and 2003b; Bengtsson et al., 2005; Hyde et al., 2009; Palomar-García et al., 2016).

On the other hand, it has been proposed that after training on a particular task, the areas in the brain initially involved on these tasks are susceptible to showing functional changes. In fact, functional changes have been observed in relation to brain areas recruited during task-performance or in relation to rs-FC networks, either on perceptual, motor or cognitive tasks (Kelly and Garavan, 2005; Buschkhuel, Jaeggi and Jonides, 2012; Kelly and Castellanos, 2014). After following a training program, increased or decreased activity has been found in brain areas related to the task being practiced. Moreover, expertise execution of a task could lead to more complex changes involving both decreases and increases (i.e., redistribution processes), or recruiting different areas than those recruited during novel task execution (i.e., reorganization processes) (Poldrack, 2000; Kelly and Garavan, 2005; Kelly, Foxe and Garavan, 2006; Buschkhuel, Jaeggi and Jonides, 2012).

It is generally assumed that different plasticity mechanisms follow after training on sensory or motor tasks or training on cognitive tasks (Kelly and Garavan, 2005; Kelly and Castellanos, 2014). In general, sensory and motor tasks give rise to increased activation of common sensorimotor areas (e.g., Münte, Altenmüller, Jäncke, 2002; Ungerleider, Doyon, Karni, 2002; Debaere, Wenderoth, Sunaert, Van Hecke and Swinnen, 2004; Waldschmidt and Ashby, 2011). However, tasks that require high-order cognitive functions during their performance show decreased activation in the set of cerebral regions that specifically support the task (e.g., Garavan, Kelley, Rosen, Rao and Stein, 2000; Jansma, Ramsey, Slagter, Kahn, 2001; Hempel et al., 2004; Schneiders, Optiz,

Krick and Mecklinger, 2011). In addition, training leads to more recruitment of task-specific regions and less reliance on common attention and control regions like the prefrontal cortex, ACC and PPC (Kelly and Garavan, 2005).

In relation to automaticity and the change from controlled to automatic processing, Jansma et al., (2001) used the Sternberg task (Sternberg, 1966) to study the effects of practice on the working memory system at the brain level. The Sternberg task is a memory search paradigm in which participants are asked to memorize a task set (usually letters) and then decide, trial-by-trial, whether the stimulus presented was part of the task set or not. In this study the effects of practice were investigated in both consistent and varied mapping paradigms. The experimental paradigm, which was completed by a group of healthy volunteers, consisted of completing a training session of 840 trials (in 45 minutes) and one fMRI session. During the fMRI scan, participants completed two Sternberg tasks and one control task, which was a choice task. Regarding the Sternberg tasks, one had been previously trained and was based on a consistent mapping paradigm (i.e., targets did not change throughout the task), and the other was a novel unpracticed task based on a varied mapping paradigm (the targets changed every 10 trials). The fMRI analyses first examined the voxel-based brain regions elicited by each task, and then regions of interest (ROIs) analyses were used to examine practice effects. The ROIs were extracted from the same experiment and subjects by using the subtracting method, and by calculating the novel task minus the control task contrast. The ROIs corresponded to: the bilateral DLPFC (BA 9), frontopolar area (BA 10), SMA, SPL (BA 7), precuneus and cuneus. Multivariate and post-hoc t-test analyses were further used to evaluate the brain changes in these ROIs. When the novel task was compared to the practice task, reduced activation was found in all of them, except in the precuneus and cuneus. The reduced activation was interpreted as a reorganization of the underlying cognitive processes, specifically relying less on the working memory system after practice (Jansma et al., 2001). No other brain areas, apart from the ROIs, were newly engaged after practice (i.e., reorganization processes). Only the right sensorimotor cortex showed increased activation, which has been interpreted as a secondary effect of training (Jansma et al., 2001). The relevance of this study is that it aimed to differentiate between controlled and automatic information processing in relation to working memory processing, and to investigate the neural correlates of developing automatic behavior.

In relation to visual attention investigations focused on training effects and automaticity development or establishment, there have been a few experimental contributions (Chein and Schneider, 2005; Kübler, Dixon and Garavan, 2006). A double condition paired-associate task was used in Chein and Scheneider (2005) to investigate, among other objectives, the effects of training on the attention-control system, on particular, and in the brain, in general. Functional MRI was used to map the brain while the participants completed the task, which had two conditions: words with a low imageability index score and difficult shapes to verbalize. The participants completed a 2-hour training session under each condition with one set of five pairs per condition (80 trials). The fMRI task consisted of two phases: the passive encoding phase, in which participants were shown pairs of stimuli (trained or untrained); and the testing phase, in which participants had to match the cue with the correct probe by pressing a button. After each trial, feedback with the correct association was given.

Afterwards, in the fMRI analysis, when the untrained condition data were compared to the trained condition data (without taking the stimulus type into account), reduced brain activity was found cortically in: the bilateral inferior and middle occipital cortex along with lingual gyrus, bilateral fusiform gyrus (FG) and left middle temporal gyrus, bilateral PPC, precuneus, bilateral insula / VLPFC, dorsal prefrontal cortex / ACC (BA 6/32), bilateral DLPFC (BA 9 /46); and, subcortically, in the thalamus and brain stem. Practice-related increases were found in medial parietal cortex (precuneus and posterior cingulate cortex). No other engaged brain areas were found when participants were performing the untrained condition compared to the trained condition.

In Kübler and colleagues (2006), two objectives were set: first, to investigate the brain changes associated with the development of automaticity; second, to investigate the brain changes when there was reassertion of control over a recently developed automatic behavior. A visuo-spatial search task was used to study the effects of training. The task consisted of the presentation of different search frames consisting of blue rectangles and red squares on a white background. The targets were either a red horizontal rectangle or a red vertical rectangle. The other stimuli in the frame were the distractors. There were three different search frames with 8, 15 or 20 elements randomly located within an invisible circle. A frame could contain no targets, one target or two targets. During the first part of the experiment, the participants had to detect the presence of red horizontal rectangles, pressing a button as fast as possible, but without compromising their accuracy.

In the same way, during the second part of the experiment, the participants had to detect the presence of the vertical rectangle. The change from one type of target to the other was “the switch”; that is, the participants were supposed to automatize the search process before the switch, and then, the reassertion of control was studied with the data after the switch. The fMRI experiment was a pre-post study completed within one day. Between the two fMRI scans, the participants completed a training program with 3456 trials (2.5 hours).

Regarding task automation, the fMRI analysis results showed decreased activation in: the left-lateralized PPC, bilateral precentral cortex (BA 6), dorsomedial frontal cortex (BA 8) and dACC (BA 32), DLPFC (BA 9/46), inferior frontal gyrus (BA 44/45) and VLPFC (BA 47). However, the primary motor, left posterior parietal, temporal and occipital cortices did not change in terms of fMRI signal response magnitude after training. The reassertion of control over the previous automatized task led to increased activation in: the IPL, left medial and superior frontal cortex, right middle frontal gyrus (BA 46) and bilateral DLPFC (BA 9).

Therefore, the general finding is that training studies using visuo-spatial search tasks have found extensive decreased activity in the prefrontal, premotor, cingulate, and parietal cortices (Chein and Schneider, 2005; Kübler, et al., 2006). However, these lasttest investigations could have included more control measures to separate task training from task repetition effects (e.g., control group and/or no-trained conditions). Thus, more evidence has to be collected, and the results have to be replicated. The general interpretation of the reduced activity of the frontoparietal control regions was based on visual attention and cognitive-control theories. When automatic behavior is established, there is less need for attention control to complete the tasks, without this withdrawal of attention affecting the accuracy of the subject of the action (Kelly and Garavan, 2005).

Recent theoretical explanations of cerebral changes related to attention demands assume that during initial performance of cognitive tasks (e.g., visuo-spatial tasks, working memory-based tasks), a high recruitment of brain-related areas to the task is observed, along with the cognitive control areas. During the novice stage, it is thought that controlled processes are engaged while formation of stimuli-response associations occurs (i.e., metacognitive system). In addition, during this stage supervisory control and constant monitoring are necessary for task execution. As expertise is acquired and automatic behavior is established, the cognitive control system is released, and brain

operates by engaging a representation system based on memory and the stored associations between stimulus and responses (Chein and Schneider, 2012). Although its principles make sense, in general, more evidence is needed to fully support this theory in terms of specific functional brain areas and network changes.

3.3. Conclusion

Some decades ago, it began to be possible to use neuroimaging techniques to study the effects of learning and training in the adult brain. These investigations began comparing the anatomical differences at the cross-sectional level in relation to different cognitive domains (spatial navigation, language, motor skill or music). Later on, some experimental approaches have focused on the investigation of automatic behavior development, that is, automatic information processing, which can be understood as a special way of learning, closely related to training on perceptual, motor or cognitive tasks. The investigations in this field still start from conceptualizing automatic behavior by using the features that differentiate automatic from controlled processing (e.g., recruitment of less attention demand, faster execution, less variability in accuracy). In general, automaticity of perceptual and motor tasks shows increased activity in brain related areas, but higher-order cognitive tasks, on which special stimulus-response associations are made, show decreased activation in extensive frontoparietal areas (e.g., visuo-spatial tasks, working memory tasks, executive tasks). In the case of visual attention tasks, a lack of appropriate control in the few existing investigations could have led to introducing confounds into the general conclusions. Thus, the changes associated with attention control areas are not broad, but circumscribed to specific visual attention and top-down cognitive control areas.

Chapter 2. Experimental section

1. Overview of the experiments

Visual scenes contain multiple objects located in and around the visual space that compete to attract the focus of attention (Eimer, 2014). The visual attention system is often presented as a dual stream system (Katsuki and Constantinidis, 2014). On the one hand, the ventral stream mainly supports the processing of salient stimuli, with almost automatic redirection of the visual attention focus and, thus, understood as a bottom-up or stimulus-driven stream. On the other hand, the dorsal stream, is directed by *a priori* known information, supports the processes related to finding relevant targets and suppresses irrelevant stimuli processing (i.e, top-down or goal-directed control of attention) (e.g., Kastner and Ungerleider, 2000; Corbetta and Shulman, 2002; Noudoost et al., 2010; Eimer, 2014; Katsuki and Constantinidis, 2014). The visual search task is an experimental paradigm that makes it possible to study, under well-controlled conditions, the behavioral characteristics and neural processes related to visual scene processing by the visual attention system (Eckstein, 2011).

The visual search task offers the possibility to, mostly but not exclusively, study the mechanisms related to the dorsal stream functioning and the top-down control mechanisms (Eimer, 2014). On the other hand, “oddball tasks”, which involve the detection of a salient target (i.e., oddball) presented infrequently (e.g., 5–15%) in a stream of frequent standard stimuli, would be more suitable for studying the ventral stream functioning (Kim, 2013, meta-analysis). However, this distinction between the dorsal and ventral system must be nuanced and understood from an experimental perspective, because bottom-up and top-down systems are in constant interaction and influence each other (Bisley, 2011; Shomstein, 2012; Zelinsky and Bisley, 2015). Indeed, the visual search task makes it possible to study the different processes associated with selective attention (e.g., response preparation, orienting of attention, target selection and identification) (Eimer, 2014) and the priority maps which are the “locations” where the bottom-up and top-down information is processed and, thus, where ventral and dorsal stream information meet (Itti and Koch, 2001; Fecteau and Munoz, 2006; Serences and Yantis, 2006; Bisley, et al., 2009; Ipata et al., 2009; Bisley and Goldberg, 2010; Zelinsky and Bisley, 2015;).

To date, investigations involving the use of visual search tasks have made it possible to characterize the different brain areas involved during their performance (Corbetta and Shulman, 2002). Generally, the visual search task has been related to the visual dorsal stream system, which involves the V1, V2 and V3 in the occipital cortex, and, at least, the PPC, FEF and DLPFC (BA 9/46) (e.g., Kastner and Ungerleider, 2000; Eimer 2014; Buschman and Kastner, 2015). Moreover, in rs-fcMRI studies, the visual search task has been related to DAN engagement (e.g., Corbetta and Shulman, 2002). On the other hand, a number of behavioral investigations have used the visual search task to study the automation mechanisms that lead to the development of automatic behavior and the changes from controlled to automatic information processing with the consequent but assumed release of the attention system (Spelke et al., 1976; Shiffrin and Schneider, 1977; Logan, 1979, 1980; Shiffrin and Dumais, 1981). However, no studies have linked the behavioral categorization effect to its underlying brain basis, and a few studies have been dedicated to investigating the underlying brain changes related to the behavioral automation of tasks that involve the attention-control system by using the visual search task (Chein and Schneider, 2005; Kübler et al., 2006). One concern related to the few practice effects studies focused on the changes in the visual attention system is their lack of appropriate control measures, for instance, the inclusion of untrained conditions or a control group in the experimental procedure in order to discard repetition effects. Therefore, studying the cerebral mechanisms supporting these behavioral effects will contribute empirical neurobiological evidence to the theoretical models whose aim is to describe the visual attention-control system.

Functional MRI is one of the many neuroimaging techniques that currently makes it possible to measure the brain activity during the performance of experimental visual search tasks. The main advantages of the fMRI technique are its non-invasiveness and its ability to in-vivo measure of ongoing human processes under a diverse number of conditions. In addition, fMRI techniques have good temporal resolution and excel in spatial resolution. Thus, they are suitable for mapping the brain response. In this regard, fMRI studies have emerged to measure the brain during the performance of perception, attention and high-order cognitive processes related tasks, but also to measure the brain during resting-state conditions, where the spontaneous functional activity of the brain is recorded (i.e., intrinsic functional connectivity, iFC). Data analysis methods have also evolved accompanying the evolution of fMRI human data acquisition. Task-activation

fMRI and iFC analysis are only two approaches among the many others applicable to fMRI data. In other words, fMRI data sets should be studied under many different perspectives, allowing them better characterize the human brain processes.

Taking into account, on the one hand, the existing literature on the categorization effect, and the development of automatic processing and its relationship with the visual attention system functioning; and, on the other, the fact that the few studies focused on attention system changes due to training effects had some methodological concerns, some questions must still be addressed. The use of the visual search task and the fMRI technique could help to fill some gaps and provide neurobiological evidence for the current visual attention theoretical and neurocomputational models.

The first question addressed in this thesis is related to whether or not the behavioral categorization effect (i.e., differences in reaction times) observed during the performance of visual search tasks is observable at the brain activity and connectivity levels. At the behavioral level, the categorization effect has already been well established. Brand (1971) observed that during visual search task performance, when a target stimuli had to be searched, its detection was faster when it was surrounded by stimuli from another category than when it was among stimuli from the same category. For instance, participants detected a letter between numbers faster than a letter between other letters (Brand, 1971; Ingling 1971). In this regard, the performance of within-category searches has been associated with serial and exhaustive attentive processing, that is, associated with greater attentional demand, whereas, between-category searches are supposed to recruit fewer attentional sources because they are performed by means of parallel automatic processing. However, the hypothesized attention effects underlying the categorization effect have not been described at the brain level. Specifically, the question is: *provided the categorization effect, are there any cerebral differences that correspond to the behavioral differences?* Due to the aforementioned features of the fMRI technique and the suitability of the visual search task to study the visual attention-control system, the use of this neuroimaging technique and the implementation of the visual search task seemed to be a plausible strategy to address this question.

Closely related to this first question, the following question arises: *it is possible to objectively predict the individual differences related to visual search task performance?* Nowadays, some studies have already shown the validity of the rs-fcMRI into predicting individual differences (Hampson, Driesen, Skudlarski, Gore and Constable, 2006;

Baldassarre, Lewis, Committeri, Snyder and Corbetta, 2012; Sala-Llonch et al., 2012; Hamerlech and Malach 2013; Ventura-Campos, et al., 2013). Measures obtained from rs-fcMRI excel because they make it possible to obtain brain data that are free of task stimulation. Therefore, it is not biased toward stimulus-driven or task-set driven processing (unless and until a previous task, like a cognitive training program, has modified the brain connectivity pattern). Another advantage of rs-fcMRI is the ease of correlating the obtained brain data with behavioral data that reflect the effects to be studied (i.e., categorization effect).

Furthermore, the study of the rs-FC of brain areas typically involved in the top-down attentional-control system may be an optimal source of empirical evidence to prove theoretical models. Psychological models of attention, such as the Priority Map model (e.g., Serences and Yantis, 2006) and the Biased Competition model (Deco and Rolls, 2005), offer a theoretical and computational explanation of how the attentional system works, along with a schema of the brain areas involved in the information processing. In these models, feedforward connections between cerebral attention areas and primary and association cortex are assumed (e.g., DLPFC, FEF, PPC, IT, occipital cortex). For instance, priority map models of attention, defend the existence of certain cerebral locations (e.g., PPC, FEF) where the bottom-up and top-down information is processed, and the focus of attention is directed based on all the information available in order to, for example, locate a particular object in the space (e.g., Serences and Yantis, 2006; Bisley and Goldberg, 2010; Krauzlis et al., 2013). However, to demonstrate the existence of these feedforward circuits between the attentional areas, it is necessary to study the connectivity between them. One methodological approach is to use task-fMRI to locate the specific brain areas involved in an attention task (e.g., visual search task), and then study the iFC of these areas by studying the brain data obtained with rs-fcMRI. With this approach, hypotheses suggested in theoretical models can be easily studied.

Another question related to the attention-control system and the need for more study is the relationship between behavioral automation and brain changes. Previous fMRI task-driven studies addressing brain changes due to cognitive training have consistently found functional activity decreases in the attention-control system brain areas. (Chein and Schneider, 2005). This effect is usually found when task performance has been automated, which usually requires the completion of a high number of task trials (i.e., at least 600 trials) (Shiffrin and Scheneider, 1977). Behavioral studies have already

determined that automation is easily developed when the conditions in which the task is performed are kept constant, that is, with no change in task rules, stimuli, and stimulus-response relations (i.e., consistent mapping paradigms) (Shiffrin and Schneider, 1977). Nevertheless, the effects of training could be easily confounded (or not sufficiently distinguish) with task repetition effects because appropriate control measures have not been introduced in the experimental paradigms (e.g., Kübler et al., 2006). When this situation is found, a question arises: *which cerebral areas are changing as a consequence of training and task automation development, and which areas are just changing due to task repetition (e.g., less training, transient effect)?* Therefore, in this thesis, we also aim to investigate, by means of fMRI, the brain changes when a cognitive task is practiced, and differentiate the training effects from the repetition effects.

Last but not least, the brain connectivity changes due to automaticity development and cognitive training remain less studied. In this regard, different methodologies are now available to study iFC changes from both task-fMRI and rs-fcMRI brain data. One emerging approach is graph-based iFC analysis. In graph-based analysis, a number of different measures can be derived, and brain connectivity maps can be obtained (Achard, Salvador, Whitcher, Suckling and Bullmore, 2006; Rubinov and Sporns, 2010; Sepulcre et al., 2010). For instance, the connectivity of the brain areas that change due to cognitive training can be quantified in terms of the number of areas that are changing in a specific region (e.g. nodes forming a hub) or the number of connections from a node (e.g., links) that are increasing or decreasing. Previous studies have already shown that connectivity between cerebral regions can be studied in terms of its spatial segregation, thus determining whether the connectivity links in a region are preferentially regional (e.g., local links) or communicating spatially separated regions (e.g., interregional or distant links) (Sepulcre et al., 2010). Therefore, as these novel procedures are available to be applied to fMRI data, we aim to investigate the iFC brain changes due to cognitive training from a graph-based perspective.

To summarize, the objective of this thesis is to provide and complement with empirical neurobiological data some behavioral psychological effects already observed in the Psychology of Attention field of knowledge, such as the categorization effect during the visual search task and the automaticity effect when cognitive training is performed on a naïve task (in this case, the visual search task). In order to complete the objectives of this thesis, the fMRI technique is used, and task-drive and resting-state brain

data are collected and analyzed using different approaches to accomplish a number of different objectives.

2. Objectives and hypothesis

The main objective of this thesis is to study the behavior and brain basis of the visual search processes, the development of automatic behavior through training on the visual search task, and the relationship between visual search task underlying processes, visual attention theoretical models, and neuroplasticity theories. The specific aims of this research are:

1. To study the behavioral and brain processes underlying visual search task performance in general and, in particular, the brain processes related to the categorization effect.
2. To prove the validity of the visual search task and both task-activation and intrinsic connectivity data obtained with the fMRI technique to test visual attention models.
3. To study transversally and longitudinally the specific effects that the behavioral automation of the visual search task have on brain task-activation response compared to the effects of task repetition, the relationship between automaticity and neurocomputational models of visual attention, and between automaticity and neuroplasticity theories.
4. To study the changes in brain connectivity related to visual search task automation and its relationship with neuroplasticity theories.

In relation to these objectives, the following hypotheses were formulated:

- Visual search task performance underlying brain processes closely correspond to the brain areas related to visual attention. That is, the visual search task would engage the activation of visual attention areas, which are, cortically: the visual occipital cortex, PPC, FEF, aI/VLPFC, dACC and DLPFC; and, subcortically: the thalamus and the SC.

- The categorization effect during visual search task performance elicits different brain task-related activation patterns. That is, activation differences in the frontoparietal areas (PPC, FEF, aI/VLPFC, dACC and DLPFC) will be noticeable when comparing the within-category searches (i.e., stimuli belonging to the same category, for instance, letters) and the between-category searches (i.e., stimuli from different categories, for example, letters and numbers); with the task-activations being greater for the within-category searches than for the between-category searches.
- It is expected that the study of the rs-fcMRI patterns of the brain areas involved during the task will predict the behavioral differences in task performance. That is, differences in task execution are expected to be associated with different resting-state responses.
- Intensive training on the visual search task may lead to behavioral automation of task performance, with the participants who complete a training program being able to produce faster responses to trained stimuli than control participants after training; and to produce faster responses to trained stimuli than to untrained stimuli after training.
- A change in the functional organization of the brain visual attention system is expected after training on the visual search task. That is, brain processes underlying the behavioral automation would show, after training, decreased task-related activation of the brain areas already involved in the visual search task performance before training.
- The change of the functional organization of the brain visual attention system after training would also affect its iFC. We expect to find an increased number of regional (i.e., local) and interregional (i.e., distant) functional connections after training. This change will indicate an enhancement in its functional efficiency (i.e., strengthen connections).
- The effects of training are different from the repetition effects. The inclusion of control measures (i.e., control group data, untrained condition data) would allow

better characterizing of the training effects and their differentiation from repetition effects that might had been reported in previous fMRI studies.

These hypotheses were tested in experimental studies using the fMRI technique. Their results have been compiled in research articles that have been sent for review for publishing in international journals, or they have already been published. These research articles are included here as they have been sent to or published by the journals.

3. Experimental studies

Study 1: Functional connectivity between superior parietal lobule and primary visual cortex at rest predicts visual search efficiency

Study 2: Reduced posterior parietal cortex activation after training on a visual search task

Study 3: Visual search task related changes in local and distant intrinsic functional connectivity

Study 1

Functional connectivity between superior parietal lobule and primary visual cortex at rest predicts visual search efficiency

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ABSTRACT

Spatiotemporal activity that emerges spontaneously ‘at rest’ has been proposed to reflect individual *a priori* biases in cognitive processing. This research focused on testing neurocognitive models of visual attention by studying the functional connectivity (FC) of the superior parietal lobule (SPL) given its central role in establishing priority maps during visual search tasks. Twenty-three human participants completed a functional MRI session that featured a resting state scan, followed by a visual search task based on the alphanumeric category effect. As expected, the behavioral results showed longer reaction times (RTs) and more errors for the within-category (i.e. searching a target letter among letters) than the between-category search (i.e. searching a target letter among numbers). The within-category condition was related to greater activation of the superior and inferior parietal lobules, occipital cortex, inferior frontal cortex, dorsal ACC and the superior colliculus than the between-category search. The resting state FC analysis of the SPL revealed a broad network that included connections with inferotemporal cortex, dorsolateral prefrontal cortex and dorsal frontal areas like SMA and FEF. Noteworthy, the regression analysis revealed that the more efficient participants in the visual search showed stronger FC between the SPL and areas of primary visual cortex (V1) related to the search task. We shed some light on how the SPL establishes a priority map of the environment during visual attention tasks and how FC is a valuable tool for assessing individual differences while performing cognitive tasks.

ACRONYMS PAGE

AAL: anatomical labelling atlas
AC-PC: anterior-posterior commissure
ACC / dACC: dorsal anterior cingulate cortex
aI: anterior insula
ANOVA: analysis of variance
BOLD: blood-oxygenation level-dependent
DLPFC: dorsolateral prefrontal cortex
EPI: echo-planar image
FC: functional connectivity
FEF: frontal eye field
fMRI: functional magnetic resonance imaging
FWE: family-wise error
FWHM: full-width at half-maximum
HRF: haemodynamic response function
Hz: hertz
IPL: inferior parietal lobule
IT: inferotemporal cortex
***k*:** cluster extent size
M_{AGE}: average age
mm: millimetres
MNI: Montreal Neurological Institute
MPRAGE: magnetization prepared rapid gradient-echo
ms: milliseconds
OC: occipital cortex
rs-fMRI: resting state functional magnetic resonance imaging
RTs: reaction times
RVSP: rapid serial visual presentation
SMA: supplementary motor area
SPL: superior parietal lobule
SVC: small volume correction

T: tesla

TE: echo time

TR: repetition time

V1: primary visual cortex / visual area 1

V2: visual area 2

V3: visual area 3

1. INTRODUCTION

Functional connectivity (FC) is a measure of the temporal dependency of functionally linked, but spatially separated, brain regions which can be obtained from resting state functional MRI data. The interpretation of the FC is diverse. One recent proposal is that it may reflect differences among individuals, and that these differences would be cognitive biases (Harmelech and Malach, 2013). Evidence in favor of this hypothesis comes from several studies that have correlated learning or performance measures with neural activity “at rest” (Hampson et al., 2006; Baldassare et al., 2012; Sala-Llloch et al., 2012; Ventura-Campos, et al., 2013). These studies generally indicate the capacity that FC (between distant areas) or regional homogeneity (within local voxels) has to predict individual differences while performing perception, memory or intelligence tasks. Most of these studies provide no supporting theory, but if we consider that FC is a powerful tool, neurocognitive models of information processing might be empirically tested. Hence we set out to conduct the present study to validate visual attention processing models (see Posner and Petersen, 1990; Deco and Rolls, 2005).

Theoretical visual attention models have described the relevant role of the superior parietal lobule (SPL; the equivalent of the lateral intraparietal area in the monkey), which establishes priority maps of the environment where stimuli are represented, according to their behavioral priority, by incorporating both bottom-up and top-down influences (Bisley and Goldberg, 2010; Ptak, 2012). Evidence in favor of this role comes from studies conducted in patients, in monkeys and using neuroimaging techniques (Bisley and Goldberg, 2010). For instance, fMRI studies have shown that the SPL (and the occipital cortex) is sensitive to the number of memorised objects and their complexity during visual search (Todd et al., 2004; Xu et al., 2006). In fact visual attention models have predicted that occipital cortex (OC) uses the priority map to guide attention and to ensure that the high-order spatial properties of stimuli are represented in the network (Bisley and Goldberg, 2010). To exert attention and working memory functions, the SPL is also connected to inferotemporal cortex (IT) and dorsolateral prefrontal cortex (DLPFC) (Deco and Rolls, 2005).

Visual search tasks offer the possibility of empirically testing visual attention models. During this task, the category effect has been described as a more efficient search which only occurs when target and distractors do not belong to the same category (Brand, 1971). This effect is often studied using alphanumeric stimuli because the semantic categorization of numbers and letters is an automatic highly learned process. It also seems to occur pre-attentionally, probably in the primary visual cortex, and has some influence on the binding process (Esterman, et al., 2004). The main objectives of the present task and the resting state fMRI study were to: 1) describe, for the first time, the neural basis of the categorization effect; 2) report the FC of the SPL in the resting state to show how its connectivity with cortical areas might support neurocognitive visual attention models; 3) test the priority map function of SPL by investigating the modulating role of visual search performance on the FC between the SPL and primary visual cortex.

2. MATERIALS AND METHODS

a. Participants

Twenty-three healthy undergraduate students from the Universitat Jaume I participated in this study ($M_{AGE} = 22.26 \pm 2.36$, 13 men) and they were paid for their participation. All the participants were right-handed (Oldfield, 1971), had normal or corrected-to-normal vision, and reported neither neurological or psychiatric history, nor past or current use of any drugs. They all provided written informed consent prior to scanning. The study was approved by the Ethics Committee of the Universitat Jaume I.

b. Stimuli

Search frames

The search frames consisted of black ink letters on a white background. Each search frame had six stimuli, arranged circularly around a fixation point (eccentricity = 1° , stimulus separation = 45°). The stimuli font-family was “*Arial BOLD*” and font size was 37 points (x-Height = 1.31 cm). The fixation point had the same font-family and its font size was 18 points (x-Height = 0.64 cm). The target stimuli under the letters conditions were *B F J K* and the numbers conditions were *1 3 6 7*. The letter distractors were *C D G*

H L M and the number distractors were 0 2 4 5 8 9. Each search frame consisted of either six distractors or five distractors and one target (see **Figure 1**). Targets and locations were randomized under all the conditions. Finally, no stimulus could appear twice in a row in the same location.

Control task

The stimuli used in the control task were arranged and presented according to the search frames described above. There were only two types of frames, either a six *A*-letters array or a six *X*-letters array. Therefore, *A*'s and *X*'s were never blended in the display (see **Figure 1**).

Instruction display

At the beginning of each block, an instruction display informed participants which task they should perform. The instruction display presented targets in black ink on a white background in a single centered row (font-family/size: “*Arial BOLD*”/37 points (x-Height = 1.31 cm)). There were three different instruction displays: 1) *A*, which indicated to perform the control task; 2) *B F J K*, which indicated to search those letters; 3) *1 3 6 7*, which indicated to search those numbers.

c. Experimental paradigm

In order to carry out this research, the classical visual search task was adapted to an fMRI block design. It entailed the manipulation of two factors: 1) searching a target among stimuli of the same category, namely a “within-category search”; 2) searching a target among stimuli of another category, namely a “between-category search”. There were two within-category search conditions and two between-category search conditions. During the within-category searches, participants could search for either target letters among distractor letters or target numbers among distractor numbers. In turn during the between-category searches, participants could search for target letters among distractor numbers or target numbers among distractor letters.

The task design consisted of six search blocks per experimental condition (or 12 within-category and 12 between-category searches) and 12 control condition blocks. The task had 36 active blocks in all, counterbalanced throughout the task. In all the blocks,

fifty per cent of the trials constituted a target-present frame. Each block had 12 trials, which consisted of 300 ms of a fixation point, 1500 ms of a search frame and 200 ms of a blank screen. Each block started by presenting the instruction display, which remained on the screen for 2000 ms. Every time a block finished, the screen remained completely blank for 8000 ms, which resulted in 36 passive blocks in all (see **Figure 1**). The entire task lasted 21 minutes.

During the task, participants had to give manual responses only with their right hand. The positive answers were made with the right thumb and the negative ones with the right forefinger. Participants had to give positive answers when they detected a target (either the As in the control task or the letters and numbers defined as targets under the visual search conditions) and negative answers when there were no targets. Participants were asked to answer as quickly as possible, but without compromising accuracy.

Figure 1. Schematic representation of the experiment procedure. The organization of the visual search task is illustrated with trial and block timing details; in addition an example of the stimuli used in the control task and the search conditions are included. The targets have been circled for descriptive purposes.

Practice

Participants received written instructions about how to do the task. Then they did a practice task that very much resembled the in-scanner task: the stimulus design matched that used during the in-scanner task; a similar laptop was used, with the same display features and the same hardware for manual responses. Noteworthy, the practice stimuli were not used in the in-scanner task. The practice task included two blocks per search condition and four control blocks, and lasted 6 minutes and 8 seconds (including the passive blocks and the instructions displays). Participants had to obtain eighty per cent correct responses to be able to participate in the fMRI experiment, and all the participants included in this study reached this criteria ($M_{\% \text{ HITS}} = 83.09 \pm 2.34$).

d. Data acquisition

The fMRI data were acquired in a 1.5 T Siemens Avanto scanner (Siemens, Erlangen, Germany). Each participant was placed in the scanner in the supine position and fixation cushions were used to reduce head motion. Firstly, participants completed a resting state (rs-fMRI) session in which the screen remained blank. Participants were instructed to remain still with eyes opened, to not think in anything in particular and to avoid sleeping. The rs-fMRI session was followed by the in-scanner performance of the visual search task (task-fMRI). A gradient-echo T2*-weighted echo-planar MR sequence was used to obtain 270 volumes of rs-fMRI data (24 interleaved ascending slices, 3.5 x 3.5 mm in-plane voxel size, slice thickness 4 mm, interslice gap 0.8 mm, repetition time (TR) = 2000 ms, echo time (TE) = 48 ms, flip angle 90°, 64 x 64 matrix) and 499 volumes for the fMRI task (29 interleaved ascending slices, 3.5 x 3.5 mm in-plane voxel size, slice thickness 3.6 mm, interslice gap 0.4 mm, TR = 2500 ms, TE = 50 ms, flip angle 90°, 64 x 64 matrix). Task-based fMRI data acquisition was accurately synchronized with the stimuli presentation using an electronic trigger throughout the task. Prior to the rs-fMRI and the task-fMRI scans, a high-resolution T1-weighted MPRAGE anatomical image was obtained for each participant (19 interleaved slices, 1 x 1 x 1 mm in-plane voxel size, TR = 2200 ms, TE = 3.8 ms, flip angle 90°, 256 x 256 x 160 matrix). All the scanner acquisitions were done in parallel to the anterior-posterior commissure plane (AC-PC) to cover the entire brain. The total time inside the scanner was 40 minutes, distributed as

follows: 10 minutes for the T1 scan, 9 minutes for the rs-fMRI scan and 21 minutes for the task-fMRI scan.

Stimulus presentation was controlled via E-Prime software (Schneider et al., 2002), professional version 2.0, installed in a Hewlett-Packard portable workstation (screen-resolution 800 x 600, refresh rate of 60 Hz). Participants watched the laptop screen via MRI-compatible goggles (VisuaStim, Resonance Technology, Inc., Northridge, CA, USA) and their responses were collected via MRI-compatible response-grips (NordicNeuroLab, Bergen, Norway). The E-Prime's logfile saved several measures, including the stimuli presentation timing (onset) and duration, along with each participant's accuracy and reaction time to each stimulus.

e. Behavioral analysis

In terms of accuracy and reaction times, participants' performance was processed with the IBM SPSS Statistics software (Version 22 Armonk, New York, USA). A 2X2 ANOVA was conducted with Type of Search (within-category search *vs.* between-category search) and Type of Target (letters *vs.* numbers) as within-subjects factors.

f. Pre-processing the task-fMRI data

Functional MRI data were processed by SPM8 (Wellcome Department of Imaging Neuroscience, London, England). Prior to pre-processing, each subject fMRI data set was aligned to the AC-PC plane by using its own anatomical image. Subsequently, standard pre-processing was conducted, including correction of slice timing differences for interleaved ascending acquisitions (using the middle slice, which was the 29th, as the reference slice) and two-pass procedure in realignment (first, registration to the first image, then registration to the mean image) to correct head motion through acquisition. Spatial normalization was conducted using the mean resliced image as the source and the echo-planar image (EPI) provided by SPM8 as the template. During normalization to the Montreal Neurological Institute space (MNI), functional images were re-sampled to 3 mm³. Finally, functional images were spatially smoothed using an isotropic Gaussian kernel of 6-mm full-width at half-maximum (FWHM).

g. Pre-processing the resting state fMRI data

The rs-fMRI datasets were processed with the DPARSF Advanced software (Chao-Gan and Yu-Feng, 2010). Pre-processing included the slice-timing correction for interleaved ascending acquisitions (the 23th slice was used as the reference point) and realignment to correct involuntary head motion. Then, within the nuisance regression step, and in order to reduce respiratory and cardiac effects on blood-oxygenation level-dependent (BOLD) signal, several sources of spurious variance were removed: the linear trend in the time series, six parameters from rigid body head motion (obtained from motion correction) and three parameters corresponding to the global mean signal, the white matter signal and the cerebrospinal fluid signal (Biswal et al., 1995). Next, spatial normalization to the MNI space (3 mm³) using EPI templates and spatial smoothing with an isotropic Gaussian kernel of 6-mm FWHM were conducted. Then, temporal filtering removed low and high frequency drift effects (0.01–0.08 Hz). Last, motion censoring (motion “scrubbing”) was conducted. Although no participant showed more than 0.5 mm of maximum displacement in any direction or 0.5° of any angular motion during the scan, three participants had less than 6.7 minutes of data (< 200 volumes) after the scrubbing process, so they were not included in the subsequent rs-fMRI analysis (Yan, et al., 2013).

h. Task-fMRI data statistical analysis

The experimental effects in each voxel were estimated by the General Linear Model and by modelling the data at the block level. The BOLD signal was estimated by convolving stimuli with canonical HRF, six motion realignment parameters were included to explain signal variations due to head motion, that is, as covariates of no interest. The first-level analyses resulted in three contrast images: 1) all the visual search conditions *vs.* control condition; 2) within-category search *vs.* control condition; and 3) between-category search *vs.* control condition. In the second-level analyses, t-statistics was computed to perform a whole-brain paired *t* test to study the brain differences between the within-category and between-category searches in all the brain. The results were below the threshold of $p < 0.05$, family-wise error (FWE)-corrected for multiple comparisons at the voxel level. Also, a whole-brain one sample *t* test which tested all the visual search conditions > the control condition was computed ($p < 0.05$ FWE cluster-

corrected using a threshold of $p < 0.001$ at the uncorrected voxel level, $k = 52$); this result was saved as a binary-image mask.

i. Definition of SPL ROIs

The left and right anatomical regions (or masks), labelled as SPL in the Automated Anatomical Labelling atlas (AAL, Tzourio-Mazoyer et al., 2002), were used to localize the specific area of the left SPL and the right SPL involved in the visual search task by means of the SPM Wake Forest University PickAtlas software (Maldjian et al., 2003). For this purpose, small volume correction (SVC) was used when each AAL SPL mask was introduced as a region of interest in the within-category > between-category search paired t test comparison. The results were below the threshold of $p < 0.05$, FWE-corrected for multiple comparisons at the voxel level. Then the coordinates of the peak maxima activation of the t test were used as the center for the definition of two 6-mm radius spheres (onward, seed regions) for further rs-fMRI analyses.

j. Resting state fMRI data statistical analysis

The voxel-wise FC analyses were performed separately with each SPL seed region and were processed by the DPARSF advanced software. For each participant, a whole-brain Pearson's correlation was performed and yielded an r -map. Subsequently, this individual r -map was normalized to a z -map with Fisher's z transformation. Finally, SPM 8 was used to conduct two different analyses: 1) a whole-brain one-sample t test to reveal the connectivity between SPL and all the other voxels of the brain "at rest" ($p < 0.05$ FWE cluster-corrected using a threshold of $p < 0.001$ at the uncorrected voxel level, left SPL $k = 89$ voxels and right SPL $k = 57$ voxels) (Woo, et al., 2014); 2) whole-brain multiple regression analyses between each participant's z -map and performance measures (accuracy scores and reaction times (RTs)). In these multiple regression analyses, in order to localize the visual input related to the visual search, the one sample t test task-fMRI result was used as an inclusive binary-image mask ($p < 0.05$ FWE cluster-corrected using a threshold of $p < 0.001$ at the uncorrected voxel level, $k = 52$). The regressors were introduced as direct measures of each condition (e.g., the accuracy scores of searching letters among letters) or as subtractions of the within-category minus the between-

category search (i.e., the general difference, the difference between the letters condition or the difference between the numbers condition). The multiple regression analyses results of the within-category search RTs > between-category search RTs were below the threshold of $p < 0.05$ FWE cluster-corrected using a threshold of $p < 0.001$ uncorrected at the voxel level ($k = 40$ voxels) (Woo, et al., 2014).

Subsequently, Pearson's correlation analyses were conducted by means of SPSS between SPL-V1 FC z -values and 1) the subtraction of the within-category search RT minus the between-category search RT; 2) that same subtraction considering only the letter conditions; 3) that same subtraction considering only the number conditions.

3. RESULTS

a. Behavioral results

The behavioral results appear in **Figure 2**. Regarding accuracy, the 2x2 ANOVA yielded a main effect of Type of Search ($F_{(1,22)}=52.10$ $p=0.001$), and indicated that the between-category search was better performed than the within-category search. This effect was significant for both letters and numbers ($p < 0.05$). This main effect was driven by the significant Type of Search x Type of Target interaction ($F_{(1,22)}=5.12$ $p=0.034$), which indicated that the main effect of Type of Search was stronger for letters than for numbers (see the left panel of **Figure 2**).

Regarding RTs, a main Type of Search effect was also found ($F_{(1,22)}=339.66$ $p=0.001$), which suggested that the within-category search was more slowly performed than the between-category search. Once again, this effect was significant for both letters and numbers ($p < 0.05$). This interaction was qualified by the significant Type of Search x Type of Target interaction effect ($F_{(1,22)}=24.82$ $p=0.001$), which indicated that the main effect of Type of Search was stronger for letters than for numbers (see right panel of **Figure 2**).

Figure 2. Visual Search Task behavioral performance. A) **Accuracy:** a main effect of Type of Search ($F_{(1,22)}=52.10, p=0.001$) and a significant Type of Search x Type of Target interaction ($F_{(1,22)}=5.12, p=0.034$) were found. B) **Reaction times (RTs):** a main effect of Type of Search ($F_{(1,22)}=339.66, p=0.001$) and a significant Type of Search x Type of Target interaction ($F_{(1,22)}=24.82, p=0.001$) were found. Error bars indicate SEM. The z coordinates are in the MNI space. L = left, R = right.

b. Functional MRI task results

The paired t test comparison of the within-category search minus the between-category search ($p < 0.05$, FWE-corrected for multiple comparisons at the voxel level) yielded greater activation in bilateral medial and lateral OC, bilateral fusiform gyrus, bilateral inferior parietal lobule (IPL) extending to intraparietal sulci and SPL, bilateral dorsal anterior cingulate cortex (dACC), bilateral dorsolateral prefrontal cortex (DLPFC), bilateral anterior insula (aI), bilateral superior colliculus and bilateral cerebellum (anterior part and vermis). Left lateralized activation was observed in the frontal eye field (FEF) and in the thalamus (see **Table 1** for detailed information about peak coordinates and z -values, and **Figure 3**). No significant results were found in the reverse contrast.

Figure 3. Results of the Visual Search task-fMRI whole-brain analysis. Brain regions showing increased activation as a result of the whole-brain paired t test comparison of the within-category minus the between-category search ($p < 0.05$, FWE voxel-corrected). The z coordinates are in the MNI space. L = left, R = right.

Table 1. Task-fMRI analysis. List of significant brain activations as a result of the paired t test comparison made between the within-category search and the between-category search contrast images.

	BA	Cluster extent	x	y	z	Z-value	p
<i>WITHIN-CATEGORY SEARCH > BETWEEN-CATEGORY SEARCH</i>							
L Insula	47	54	-33	26	1	6.82	<0.001
R Occipital cortex and fusiform gyrus	19	401	39	-79	7	6.81	<0.001
R Superior and inferior parietal lobule	7	105	21	-61	43	6.78	<0.001
L Occipital cortex, fusiform gyrus, superior and inferior parietal lobule	19 / 7	753	-24	-76	25	6.73	<0.001
L FEF	6	76	-42	2	31	6.59	<0.001
L Cerebellum 6, crus 1 and vermis 6		70	-6	-73	-20	6.38	<0.001
R Anterior cingulate cortex	32	117	6	17	43	6.32	<0.001
R Insula	47	63	36	20	1	5.82	<0.001
L Inferior frontal cortex (pars triangularis)	45	21	-51	26	25	5.78	<0.001
R Superior colliculus		22	6	-28	-8	5.52	<0.001
L Thalamus		6	-12	-16	4	5.23	<0.001

Whole-brain analyses conducted at $p < 0.05$, FWE-corrected for multiple comparisons at the voxel level. The x , y and z coordinates are in the MNI space.
L = Left; R = Right.

c. Resting State Functional Connectivity results

The connectivity analyses centered on studying the FC of the SPL with all the other brain voxels. For this purpose task-related seed regions left SPL (MNI: -21, -64, 40) and the right SPL (MNI: 21, -64, 49) were used (see **Figure 4**).

Figure 4. Results of the SPL Functional Connectivity analysis. The left and right SPL seed regions were obtained from the within-category search > between-category search task-fMRI and were defined as 6-mm radius spheres. Brain regions showing a synchronous pattern of spontaneous fluctuations at rest were obtained after conducting a whole-brain one-sample t test with the individual z -maps of each SPL was performed ($p < 0.05$ FWE cluster-corrected). The z coordinates are in the MNI space. L = left, R = right.

The FC analysis revealed that the brain regions connected with the left or the right SPL are similar (see **Table 2** for detailed information). The conducted one-sample t test analysis with the FC z -maps of the left SPL seed region revealed that left SPL established significant brain connections in the resting state with the right superior and inferior parietal lobules, bilateral posterior areas (precuneus, middle OC), bilateral IT and fusiform gyrus, bilateral supplementary motor area (SMA) and FEF, bilateral DLPFC (BA 9), and bilateral inferior and middle frontal cortex (BA 44 and BA 45) (see upper part of **Figure 4**). In turn, the right SPL was significantly connected to bilateral middle

and superior occipital gyrus, right lingual gyrus, bilateral fusiform gyrus, bilateral inferior and middle temporal gyrus, left superior and inferior parietal lobule, right angular gyrus, bilateral SMA and FEF, left precentral gyrus and finally left cerebellum (see lower part of **Figure 4**).

Table 2. Functional connectivity of the SPL seed regions. List of significant brain activations as a result of the one-sample *t* test of the individual SPL FC z-maps.

		BA	Cluster extent	x	y	z	Z-value	<i>p</i>
Left SPL FC								
L/R	Superior and inferior parietal lobule, precuneus, superior and middle occipital cortex.	7/19/18	3721	-21	-63	39	9.41	<0.001
L	DLPFC and inferior frontal cortex	9 / 44	207	-45	3	27	5.65	<0.001
L	Inferior temporal gyrus, fusiform gyrus, inferior occipital gyrus	37 / 20	421	-48	-57	-15	5.50	<0.001
L	Inferior and middle frontal cortex	45	228	-51	27	27	5.38	<0.001
R	Inferior temporal gyrus and fusiform gyrus	37 / 20	157	45	-45	-21	5.09	<0.001
R	DLPFC	9	121	51	9	33	4.72	<0.001
L	SMA and FEF	6 / 8	143	-24	6	57	4.59	<0.001
R	SMA and FEF	6 / 8	179	27	3	54	4.46	<0.001
R	Inferior and middle frontal cortex	45	89	45	42	24	3.96	<0.001
Right SPL FC								
L/R	Superior and inferior parietal lobule, angular gyrus, superior and middle occipital cortex.	7 / 39 / 19	5152	24	-63	48	8.14	< 0.001
L	SMA / FEF	6 / 8	244	-24	-3	63	6.20	< 0.001
L	Inferior and middle temporal gyrus, fusiform gyrus, inferior occipital cortex, cerebellum crus 1 and crus 2	37 / 20 / 19	542	-45	-57	-9	5.96	< 0.001
R	Inferior and middle temporal gyrus, fusiform gyrus	37 / 20 / 19	531	57	-57	-9	5.85	< 0.001
R	SMA / FEF	6 / 8	911	30	0	63	5.72	< 0.001
L	Inferior and middle frontal cortex	45	63	-42	39	24	4.68	0.004
R	Lingual gyrus	18	57	6	-63	3	4.64	0.008
L	Precentral gyrus	6	164	-48	3	21	4.54	< 0.001
R	Inferior frontal cortex	45	58	51	39	12	3.81	0.007

Whole-brain analyses conducted at $p < 0.05$, FWE-corrected for multiple comparisons at the cluster level (minimum cluster size $k = 89$ voxels for left SPL and $k = 57$ voxels for right SPL). The x, y and z coordinates are in the MNI space.

L = Left; R= Right.

SPL = superior parietal lobe, DLPFC = dorsolateral prefrontal cortex, SMA = supplementary motor area,

FEF = frontal eye field.

d. Regression analyses on functional connectivity

The FC analyses of the SPL allowed us to study the connectivity of the SPL with all the other brain regions. The results were restricted to visual search areas by means of an inclusive binary-image mask, which was obtained from the above-mentioned all search conditions > control task one sample *t* test (see Supplemental Material). The aim of conducting regression analyses between the SPL and performance measures was to study how individual differences modulate the SPL FC and its functional role of establishing priority maps while performing visual search tasks. To this end, whole-brain multiple regression analyses with the FC *z*-maps of each SPL seed region and the accuracy or the RTs defined as regressors were conducted. The left SPL seed region FC *z*-maps gave significant results only when RTs expressed the general difference of the within-category minus the between-category search; this yielded a negative correlation between this measure and the connectivity of the SPL and the primary visual cortex (V1) ($r_{\text{pearson}} = -0.82$, $p < 0.001$, $n = 20$) (see **Table 3** and **Figure 5**). This correlation pattern was found only when RTs reflected the difference between the letters conditions ($r_{\text{pearson}} = -0.77$, $p < 0.001$, $n = 20$) or the numbers conditions ($r_{\text{pearson}} = -0.81$, $p < 0.001$, $n = 20$) (see **Table 3**); that is, FC predicted participants' performance during the search task: the SPL-V1 correlation led to faster RTs in the within-category search (compared to the between-category search) and, in turn, the SPL-V1 anticorrelation led to slower RTs. As multiple regression analyses results were located on the visual cortex and to ensure that activations correspond to area V1, the superposition of functional maps to cytoarchitectonic maps was conducted. The cluster peak maxima activation was located on V1 (62% of probability) and the majority of the cluster voxels belonged to that area (54% of probability) ("Overlap between structure and function" toolkit from the SPM Anatomy Toolbox; Eickhoff S et al. 2005; Eickhoff et al. 2006; Eickhoff et al. 2007). No other significant correlations with the left SPL or the right SPL seed regions were found when using RTs or accuracy measures.

Figure 5. Results of the multiple regression rs-fMRI analysis. Results of the multiple regression analysis with the individual left SPL FC z-maps and the RTs as regressors. The connectivity between the SPL and V1 ($p < 0.05$, FWE-cluster corrected) (symbolic blue line) correlated negatively with the target-detection speed during the visual search task ($r_{\text{pearson}} = -0.82$, $p < 0.001$, $n = 20$; RTs values expressed the general difference of the within-category minus the between-category search).

Table 3. Results of the multiple regression analysis with the left SPL FC z-maps and the reaction time measures. **A)** Results found when RTs expressed the general difference in search speed (within-category search RTs > between-category search RTs). **B)** Results found when RTs expressed the difference in search speed under the letters conditions. **C)** Results found when the RTs expressed the difference in search speed under the numbers conditions.

	Sign	BA	Cluster extent	x	y	z	z	p
<i>A) General difference: within-category > between category</i>								
Primary visual cortex (V1)	N	17	40	0	-84	-9	4.66	<0.001
<i>B) Letters condition difference within-category > between category</i>								
Primary visual cortex (V1)	N	17	17	-3	-84	-9	3.99	<0.001
<i>C) Numbers condition difference within-category > between category</i>								
Primary visual cortex (V1)	N	17	36	0	-84	-9	4.41	<0.001

A) Whole-brain analysis conducted $p < 0.05$, FWE-corrected for multiple comparisons at the cluster level (minimum k extent = 40 voxels). B) Whole-brain analysis conducted $p < 0.001$, uncorrected voxel level. C) Whole-brain analysis conducted $p < 0.001$, uncorrected voxel level.

The x, y and z coordinates are in the MNI space.

N = Negative correlation.

4. DISCUSSION

This research focused on the study of the FC of the SPL in the resting state, and also on the capacity of FC to explain individual differences while performing visual search tasks. For this purpose, participants completed an fMRI session, which consisted of an rs-fMRI scan, followed by the performance of a visual search task. Significant behavioral and functional differences were found in relation to task performance. As expected, the within-category search led not only to lower accuracy scores and slower RTs than the between-category search, but also an increased activation of the visual search brain-related areas, including the SPL, was observed. Activation in the SPL served to localize the specific area in this region involved in the task. The voxel-wise study of FC at rest revealed that this area of the SPL was functionally connected to spatially distant brain areas like the IT and the DLPFC. The connectivity relation between the SPL and V1 also predicted performance during the visual search task. In line with the priority map model (Bisley and Goldberg, 2010), our results demonstrated that FC at rest between parietal and occipital areas was able to determine individual efficiency in terms of target detection during a complex new search. Thus FC at rest may be used to test neurocognitive models of cognition.

As the categorization effect predicts, participants outperformed the between-category conditions compared to the within-category conditions (Brand, 1971). In fact our behavioral results support the claim that learned artificial categories of stimuli, like alphanumeric stimuli, have an impact on attention, specifically object identification, because they are processed pre-attentionally in early visual processing stages (Esterman et al., 2004; Hamilton et al., 2006). According to recent accounts of visual search, selection of targets depends on task demands, whereas serial selection occurs under highly demanding conditions, like the within-category searches of our visual search task; parallel selection is performed during less challenging tasks, like between-category searches (Woodman and Luck, 2003; Eimer and Grubert, 2014; see Eimer 2014 for a review).

On the other hand, the functional network involved in the visual search task – OC, IPL and SPL, FEF, insular cortex, dACC, DLPFC, inferior frontal gyrus, thalamus, superior colliculus – showed an increased BOLD signal under the within-category

conditions compared to the between-category ones. Diverse areas, such as the posterior parietal cortex, FEF, DLPFC or thalamus, participate in attentional selection processes by establishing priority maps and sending signals to the OC (Eimer, 2014). The activity in inferior frontal gyrus and insula may be related to the processing of alphanumeric stimulus, whereas superior colliculus is involved in attentional movement (Posner & Petersen, 1990). Taking all together, it could be argued that when targets and distractors share categorical features, a subsequently influence occurs on target identification and, hence, on attentional control demands. This condition could lead to the necessity of processing information in a serial mode and, in turn, this processing could be reflected in generally increased brain activation in visual search-related areas.

Activation of SPL areas is especially relevant when studying visual attention systems. The functional activation that occurred while the visual search task was performed came very close to that observed in previous studies (Todd, 2004; Xu, 2006; Yantis et al., 2002). The role of this area is to represent the visual world, including the relative relevance of stimuli for the task on a multi-object display. Specifically, the SPL calculates a priority map of possible targets according to their behavioral and task relevance, and takes into account bottom-up inputs from visual areas (Bisley and Goldberg, 2010). Also, when a target number appears on a rapid serial visual presentation (RVSP) stream of letters, increased activation on the SPL is linked to a shift in attention (Yantis et al., 2002). Thus the role that the SPL plays in our study might be related to the process that pre-attentionally establishes a map, which includes information about the category of each alphanumeric stimulus in the visual array to guide the focus of attention during the search task.

Having obtained the specific coordinates of the SPL from the fMRI search task, we calculated the FC of this area. It is widely assumed that FC reflects the interregional coherence of activity fluctuations in underlying neuronal networks. As predicted by some theoretical models of the visual attention system, like the computational approach proposed by Deco and Rolls (2005), neurons in this specific area of the SPL, which were involved in visual search, synchronously fluctuated with both IT and DLPFC. In addition, other frontal regions like the SMA and FEF, also correlated with SPL activity. Overall,

our SPL FC represents a large-scale network which supports visual search and working memory tasks. The only area in the model that did not show an obvious correlation with the SPL was V1. In FC studies of V1 at rest, strong correlations of V1 are found only with adjacent visual areas (i.e., V2, V3) (Shmuel and Leopold, 2008; Raemakers et al., 2014). Since strong FC is usually observed within visual areas, we can expect lower correlations with other distant areas, such as the SPL.

Despite no evident correlation having been found between both areas, the relationship between SPL and V1 was driven by response speed when detecting targets in the same category: the faster the response during the within-category trials, the better correlated the FC pattern between the left SPL and bilateral V1 in the resting state; in turn, anticorrelated SPL-V1 connectivity was related to slower responses. This pattern of correlation was only found between left SPL and bilateral V1, but not on right SPL. Differences in FC between left and right SPL are to be related to the type of stimuli used in this study and the nature of the task. Both left and right SPL are involved in verbal and non-verbal tasks, but, whereas left SPL is engaged before letter or number stimuli, right SPL is found activated when task demands require arithmetical operations (Dehaene et al., 1999; see Humphreys and Lambon Ralph, 2014). The SPL-V1 correlation is consistent with the idea that the top-down control of the attention function performed by the SPL, which allowed shifts of focus of attention through different objects in space, was made in conjunction with the primary visual cortex. This is precisely what is proposed in the priority map model, which attributes the role of establishing priority maps to the SPL by creating a topographic map of the space where target-related and environment-related information is integrated, and it is also able to modulate its visual perception activity to control and direct attention to specific objects (Bisley and Goldberg, 2010; Ptak, 2012; Shomstein, 2012). Moreover, it seems that the SPL, by means of the priority maps, intercedes in the performance of the visual search task depending on search demands; that is, the more demanding the task, as in within-category searches that rely on serial processes (Eimer, 2014), the more need of the SPL to direct the focus of attention. But if SPL-V1 are strongly correlated, participants are prone to better perform the task. Previous literature has related FC to the prediction of individual differences in perceptual working memory and language tasks, which either featured learning paradigms or did not (Hampson et al., 2006; Baldassare et al., 2012; Sala-Llloch et al., 2012; Ventura-Campos,

et al., 2013; see Harmelech and Malach, 2013). What our data support is that FC is a powerful tool to study the personal predisposition to processing information. In this particular case, the relationship between visual search task performance and connectivity between the SPL and V1 evidenced the role of the SPL in guiding the attention system, and can serve to predict individual differences in search speed.

5. CONCLUSION

The visual search task has allowed us to characterize brain activity in the categorization effect and to link the task-related pattern of activation to information processing by the attention system. We have taken a further step using an FC analysis to test a hypothesis which has stemmed from visual attention theoretical models. By studying the FC of the SPL, we provide empirical data that support a neurocomputational visual search model (Deco and Lee, 2004; Deco and Rolls, 2005). The SPL is a core node of a large-scale cortical network that includes DLPFC and IT, necessary to perform visual attention and working memory tasks. In addition, our analysis has also shed light on how the FC between spatially separated cortical regions, such as SPL and V1, is directly related to visual attention task performance.

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AUTHOR DISCLOSURE STATEMENT

No competing financial interests exist.

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SUPPLEMENTAL MATERIAL

Supplementary Figure 1. Inclusive mask used on FC multiple regression analyses. The mask, which was obtained from the *all visual search conditions > control task* one sample *t* test ($p < 0.05$ FWE cluster-corrected using a threshold of $p < 0.001$ at the uncorrected voxel level, $k = 52$), was defined as a binary-image (in red). Then, it was used on FC multiple regression analyses as an inclusive mask. Therefore, the results of the FC multiple regression analyses were located within the mask, at the visual cortex (in greenish-blue).

Study 2

Reduced posterior parietal cortex activation after training on a visual search task

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ABSTRACT

Gaining experience on a cognitive task improves behavioral performance and is thought to enhance brain efficiency. Despite the body of literature already published on the effects of training on brain activation, less research has been carried out on visual search attention processes under well controlled conditions. Thirty-six healthy adults divided into trained and control groups completed a pre-post letter-based visual search task fMRI study in one day. Twelve letters were used as targets and ten as distractors. The trained group completed a training session (840 trials) with half the targets between scans. The effects of training were studied at the behavioral and brain levels by controlling for repetition effects using both between-subjects (trained *vs.* control groups) and within-subject (trained *vs.* untrained targets) controls. The trained participants reduced their response speed by 31% as a result of training, maintaining their accuracy scores, whereas the control group hardly changed. Neural results revealed that brain changes associated with visual search training were circumscribed to reduced activation in the posterior parietal cortex (PPC) when controlling for group, and they included inferior occipital areas when controlling for targets. The observed behavioral and brain changes are discussed in relation to automatic behavior development. The observed training-related decreases could be associated with increased neural efficiency in specific key regions for task performance.

KEYWORDS

Attention, automaticity, functional Magnetic Resonance Imaging, priority maps, visual selection.

ABBREVIATIONS

(d)ACC: (dorsal) anterior cingulate cortex

AC-PC: anterior commissure-posterior commissure

ANOVA: analysis of variance

BA: Brodmann area

BOLD: blood-oxygenation level-dependent

DLPFC: dorsolateral prefrontal cortex

EPI: echo-planar imaging

FG: fusiform gyrus

fMRI: functional Magnetic Resonance Imaging

FWE: family-wise error

FWHM: full-width at half-maximum

HRF: hemodynamic response function

M: mean

MNI: Montreal Neurological Institute

MPRAGE: Magnetization Prepared Rapid Acquisition Gradient Echo

N: number of participants

PPC: posterior parietal cortex

RMS movement: Root Mean Squared movement

ROI(s): region(s) of interest

RT(s): reaction time(s)

SD: standard deviation

SMA: supplementary motor area

TE: echo time

TR: repetition time

VLPFC: ventrolateral prefrontal cortex

WAIS: Wechsler Adult Intelligence Scale

1. INTRODUCTION

Classic psychology paradigms showed that performance improves after completing a training program (Kristofferson, 1972; Neisser et al., 1963; Neisser, 1963; Schneider and Shiffrin 1977; Shiffrin and Schneider, 1977; Prinz, 1979; Rabbitt et al., 1979). This behavioral improvement seems to be accompanied by brain activation changes and is observable after training in different cognitive domains (Anguera et al. 2013; Banai and Amitay, 2015; Klingberg, 2010; Waldschmidt and Ashby 2011). However, few functional magnetic resonance imaging (fMRI) training studies have included control measures in their paradigms; therefore, they have not eliminated the repetition effects from their results, which could bias their interpretations (e.g., Chein and Schneider, 2005; Kübler et al., 2006). Our main objective was to study the behavior and brain changes related to training, but by controlling for repetition effects using both between-subjects (trained *vs.* control groups) and within-subject (trained *vs.* untrained stimuli) controls.

Some decades ago, psychological theories found that training on a task can lead to automaticity. Two-process models distinguished controlled processing from automatic processing. These models argue that when a task has not been trained, it is performed through controlled processes. This processing has been defined as slow and effortful. By contrast, automatic processing has been characterized as being fast and effortless (Posner and Snyder 1975; Posner, 1978; Schneider and Shiffrin, 1977). Automatic behavior is achievable after completing a number of training trials (600 trials at least) presented under consistent mapping conditions, and it has to produce quantitatively faster responses than controlled processing without obtaining worse accuracy scores (e.g., maintaining or improving them) (Shiffrin and Schneider, 1977).

In relation to brain activity, theoretical predictions hypothesize that gaining experience on a cognitive task, such as a visual search task, could result in the reduced cognitive recruitment of attention-related brain areas (Schneider and Chein, 2003). Early task performance occurs under controlled processing and leads to high activation; then,

after reaching a certain level of automaticity, brain activation drops considerably (Chein and Schneider, 2005, 2012). Rather than being fast and effortful, automatic processing has been redefined as efficient and economical in terms of brain activity (Saling and Phillips, 2007).

To date, some functional neuroimaging studies have focused on studying the effects of training on brain functioning. In a meta-analysis carried out with 29 cognitive or motor training studies, reduced activity in diverse cortical areas was the main result reported (Chein and Schneider, 2005). Reductions were found in terms of the extent and magnitude of neural activity, and they involved a consistent brain network: bilateral dorsolateral prefrontal cortex (DLPFC), left ventral prefrontal cortex, anterior cingulate cortex, left insular cortex, bilateral parietal cortex, and occipito-temporal areas, including the fusiform gyri (FG). The authors interpreted that most training-related decreases were located in association areas, whose function is to exert attentional control, regardless of the task or stimuli domain. In particular, these authors claimed that this attention control network was engaged during initial task performance (novice performance), and its involvement dropped as a result of training (Chein and Schneider, 2005). An example of this finding is the fMRI experiment presented along with the meta-analysis results (Chein and Schneider, 2005). A double condition paired-associate task was used in this experiment: words with a low imageability index score and difficult shapes to verbalize. The participants completed a 2-hour training session in each condition with one set of five pairs per condition (80 trials). When the untrained condition was compared to the trained condition, the brain activity results showed that the majority of brain changes involved reduced neural activity, and these reductions generally overlapped the aforementioned meta-analysis results.

In the case of visuospatial search tasks, some fMRI experiments have studied automaticity when task automation has already been established, and fewer studies have examined how the brain implements the automaticity process (Kelly and Garavan, 2005; Raichle et al. 1994). One exception is the study by Kübler et al. (2006), where one objective was to study the establishment of automaticity. The participants completed a training session that lasted 2.5 hours (3456 trials). As in Chein and Schneider (2005), the

results showed decreased activation in diverse brain areas of the prefrontal, premotor, cingulate and parietal cortices after training. However, other areas typically involved in visuospatial search tasks did not change (i.e., the primary motor, left posterior parietal, temporal and occipital cortices). Main conclusions were that training led to more reduced brain activity in frontal areas than in posterior cerebral areas, and that this reduction indicated less dependence on attentional processes (Kübler et al. 2006).

In summary, training-related fMRI studies have suggested decreased brain activity after training, at least in the attention control system. However, in order to determine whether brain changes are the result of training, two measures should be included in the experimental designs: a control group and an untrained condition. Presence of a statistical comparison between initial and final task performance (at least 10 minutes of training) was an inclusion criterion in Chein and Schneider's meta-analysis (2005). Twenty-four of the 29 studies included in the meta-analysis were consulted, and none had a control group. In Chein and Schneider (2005), an untrained condition was included in the experimental design, but no control group. Kübler et al. (2006) did not include either of these control measures. Therefore, as far as we know, no experiments carried out in the visual attention domain have reported the objective of studying training-related changes at the brain level with an experimental design that included a control group and an untrained condition, in order to fully characterize the training effects.

Here, we present a pre-post one day fMRI study that included two groups of participants (a trained group and a control group) and two search conditions (trained and untrained targets). We chose to use the visual search task because it has been widely used to study attentional control (Buschman and Kastner, 2015; Bisley, 2011). Searching for letters among letters is a highly demanding task (like searching for objects in a real environment), but it allows the use of familiar stimuli and an experimental set-up (Bueichekú et al., 2015; Shiffrin and Schneider, 1977). We used a letter-based consistent mapping search, which has not been previously used to study training effects on the visual attention system.

We hypothesized that: 1) the participants who completed the training program would produce faster responses to trained targets than those who only repeated it, due to greater automation; 2) after training, the trained participants would produce faster responses to trained targets compared to their responses before training and to untrained targets during the post-training session; 3) automation processes would result in decreased activation of the brain areas already involved in the visual search task; 4) the inclusion of control measures in the experimental paradigm would allow a better understanding of the training effects, and they would be differentiated from repetition effects.

2. MATERIALS AND METHODS

2.1. Participants

Thirty-six healthy undergraduate students from the Universitat Jaume I participated in this study and were paid for their participation. All the participants were right-handed (Oldfield, 1971), had normal or corrected-to-normal vision, and reported no neurological or psychiatric history, or past or current use of any drugs. Participants were randomly assigned to a trained group ($N = 18$, 9 men; age: $M = 20.78$ $SD = 1.35$) or to a control group ($N = 18$, 9 men; age: $M = 20.94$, $SD = 2.01$). A between-groups t -test was used to determine that the experimental groups did not differ in age ($t(34) = -0.29$ $p = 0.10$). Intellectual level was evaluated with the Matrix Reasoning Test (WAIS-III-R) (Trained group: $M = 21.56$ $SD = 2.17$; Control group: $M = 21.83$ $SD = 1.47$). A between-groups t -test was used to determine that the experimental groups did not differ in intellectual level ($t(34) = -0.45$ $p = 0.14$). All the participants provided written informed consent prior to scanning. The study was approved by the Ethics Committee of the Universitat Jaume I.

2.2. Stimuli

2.2.1. Search frames

A schematic representation of the stimuli appears in **Figure 1A**. The search frames consisted of black ink letters on a white background. Each search frame had six stimuli arranged circularly around a fixation point (visual angle: letters = 0.50° ; fixation point =

2.2.2. Control task

A control task was included in the experimental paradigm to measure a baseline response time and a baseline cerebral response, and it matched the visual array used in the search frames of the visual search conditions. The control task displays consisted of black ink letters on a white background. There were only two types of frames: a six *A*-letters array and a six *X*-letters array. *A*'s and *X*'s were arranged circularly around a fixation point (visual angle: letters = 0.50°; fixation point = 0.24°; distance between letters and fixation point = 1.32°). *A*'s and *X*'s were never mixed on the display.

2.2.3. Instruction display

At the beginning of each block, an instruction display informed participants which task they should perform. The instruction display presented targets in black ink on a white background in a single centered row (visual angle: letters = 0.50°). There were three different instruction displays: 1) *A*, which indicated that participants would perform the control task; 2) *B C D F G H*, which indicated that they would search for these letters; 3) *L M N P Q R*, which indicated that they would search for these letters.

2.3. Experimental paradigm

2.3.1. In-scanner task

In order to carry out this research, the classic visual search task was adapted to an fMRI block design. The block organization and timing details are represented in **Figure 1A**. The experimental task lasted 25 minutes. The task consisted of 42 active blocks and 42 passive blocks. The active blocks consisted of: 14 control task blocks, 14 search blocks that corresponded to targets *B C D F G H* and 14 search blocks that corresponded to targets *L M N P Q R*. These blocks were counterbalanced throughout the experiment. In all the blocks, fifty per cent of the trials constituted a target-present frame. Each block had 12 trials, which consisted of 300 ms of a fixation point, 1500 ms of a search frame, and 200 ms of a blank screen. Each block started by presenting the instruction display, which remained on the screen for 3000 ms. All the passive blocks consisted of periods of 8000 ms when the screen remained completely blank.

There were no restrictions to eye movement. However, considering the distance between the fixation point and the stimuli (visual angle = 1.32°), eye movements were not strictly needed to perform the task. Participants had to give manual responses only with their right hand. Positive answers were given with their right thumb, and negative ones with their right forefinger. Participants had to give positive answers when they detected a target (either the As on the control task or the letters defined as targets in the visual search conditions) and negative answers when there were no targets. Participants were asked to answer as quickly as possible, but without compromising accuracy.

2.3.2. Practice before fMRI

For the practice task, an identical laptop was used, with the same display configuration as the one used to present the in-scanner task. The same hardware was used for manual responses with identical settings. Participants received written instructions about how to do the task. The practice task lasted 7 minutes and consisted of: 4 control task blocks, 2 search blocks that corresponded to targets *B C D F G H*, 2 search blocks that corresponded to targets *L M N P Q R*, and 8 passive blocks (blank screen). Regarding stimulus design, block organization, block timing and instruction displays, the practice task was identical to the in-scanner task. In the case of the search frames, none of the search templates that appeared during the practice task were used later during the in-scanner task or the training task (i.e., *C T G D B R*, with C in the top center position and the rest of the letters organized circularly and clockwise). Participants had to obtain eighty per cent of correct responses in order to participate in the fMRI experiment. All the participants included in this study reached this criterion (percentage of hits: Trained group: $M = 85.10$ $SD = 4.15$; Control group: $M = 84.76$ $SD = 4.61$). No between-groups differences were observed on the practice task, as assessed with a between-groups *t*-test analysis ($t(34) = 0.23$ $p = 0.32$).

2.3.3. Training between sessions (only the trained group)

The training task was done outside the scanner. For the training task, an identical laptop was used with the same display configuration as the one used to present the in-scanner task. The same hardware for manual responses was used with identical settings. The training session took place between the pre- and post-training fMRI sessions (see **Figure 1B**). Training on the visual search task was intensive and presented as a block

design. Randomly, half the participants from the trained group were trained in searching for targets *B C D F G H*, while the other half were trained in searching for targets *L M N P Q R*. Therefore, after training, the trained group experienced two types of search conditions: 1) trained search; 2) untrained search. From this point on, we will refer to the trained or untrained condition instead of repeating the groups of targets. It was noteworthy that the control group participants did not perform any training or cognitive tasks between scans. Thus, searching for either of the two groups of targets would not represent any difference for the control group.

The stimuli and timing details of the training task matched the fMRI task. The presentation of a fixation point (300 ms) was followed by the search frame (which had five distractors and one target or six distractors), and then by a white screen (200 ms). The only difference was that during training, the search frame disappeared as soon as the participant gave a response. Thus, participants could improve their performance at their own pace. Every 42 frames (a block), participants received a feedback report with their mean accuracy and median reaction time for that block. Every 210 frames (five blocks), participants took a 31-second rest. Participants completed 840 trials (twenty blocks) during the training session, and they spent $M = 29.97$ minutes ($SD = 2.13$) on the training task. All the participants were asked to refrain from consuming any substance (e.g. coffee, tobacco and stimulating beverages), apart from food or water, before the Pre-training session and between the Pre- and Post-training sessions.

2.3.4. Summary of the experiment timing

The experiment was conducted in one day. First, all the participants performed a practice task that lasted 7 minutes. Next, all the participants did the first fMRI scan, which lasted 35 minutes: 10 minutes of anatomical data acquisition, followed by 25 minutes of task-fMRI acquisition. A 45-minute period separated the first and second fMRI scans; this period had the same duration for both the trained and control groups. During this period, the trained group participants did the training task (outside the scanner) which lasted, on average, $M = 29.97$ minutes $SD = 2.13$ (an average was used here because the participants had to complete the 840 trials at their own pace). The control group participants did nothing during this period. Finally, after this 45-minute period ended, all the participants did the second fMRI scan, which lasted 35 minutes, as in the case of the

first scan: 10 minutes of anatomical data acquisition and 25 minutes of task-fMRI acquisition.

2.4. Image acquisition

The fMRI data were acquired in a 1.5 T Siemens Avanto scanner (Erlangen, Germany). The same protocol was used during the Pre- and Post-training sessions. Each scan session lasted 35 minutes. All the participants were placed in the scanner in the supine position. Fixation cushions were used to reduce head motion. A gradient-echo T2*-weighted echo-planar MR sequence was used to obtain 602 volumes for the fMRI task (29 interleaved ascending slices, 3.5 x 3.5 mm in-plane voxel size, slice thickness 3.6 mm, interslice gap 0.4 mm, TR = 2500 ms, TE = 50 ms, flip angle 90 °, 64 x 64 matrix). Prior to task-fMRI data acquisition, one high-resolution T1-weighted MPRAGE anatomical image was obtained per participant (TR = 2200 ms, TE = 3.8 ms, flip angle 90°, 256 x 256 x 160 matrix, 1 x 1 x 1 mm in-plane voxel size). All the scanner acquisitions were performed in parallel to the anterior commissure-posterior commissure plane (AC-PC), and they covered the entire brain.

Stimulus presentation was controlled by the E-Prime software (Schneider et al., 2002), professional version 2.0, which was installed in a Hewlett-Packard portable workstation (screen-resolution 800 x 600, refresh rate of 60 Hz). Participants watched the laptop screen through MRI-compatible goggles (VisuaStim, Resonance Technology, Inc., Northridge, CA, USA), and their responses were collected by MRI-compatible response-grips (NordicNeuroLab, Bergen, Norway). The E-Prime's logfile saved several measures, including stimulus presentation timing (onset) and duration, along with participants' accuracy and reaction times (RTs) to each stimulus.

2.5. Behavioral analysis

In terms of accuracy and RTs, participants' performance was processed with the IBM SPSS Statistics software (Version 22 Armonk, New York, USA). For each experimental condition, a repeated measures 2x2 ANOVA was conducted, with the Experimental Group (Trained group vs. Control group) as the between-subjects factor and Session (Pre-

training session vs. Post-training session) as the within-subjects factor. Only correct trials were used in all the behavioral analyses.

2.6. Functional MRI task analysis

2.6.1. Pre-processing

Functional MRI data were processed by SPM8 (Wellcome Department of Imaging Neuroscience, London, England). Prior to pre-processing, each subject's fMRI data set was aligned to the AC-PC plane using its own anatomical image. Subsequently, standard pre-processing was conducted, which included the correction of the slice timing differences for interleaved ascending acquisitions (using the middle slice, which was the 29th, as the reference slice) and a two-pass procedure in realignment (registered to the first image, and then registered to the mean image) to correct head motion during acquisition. No head motions were found in any participant's data that had more than 2.0 mm of maximum displacement in any direction, or 2.0° of any angular motion while the scan lasted. In order to control the movement effect throughout the experiment, the Root Mean Squared movement values (RMS movement, of translation and rotation parameters) were used to conduct a repeated measures 2x2 ANOVA with the Experimental Group (Trained group vs. Control group) as the between-subjects factor and Session (Pre-training session vs. Post-training session) as the within-subjects factor. No significant differences were found (RMS movement: $F(1,34) = 0.588$ $p = 0.449$). Spatial normalization was conducted using the mean resliced image as the source and the echo-planar image (EPI) provided by SPM8 as the template. During normalization to the Montreal Neurological Institute space (MNI), functional images were re-sampled to 3 mm³. Finally, functional images were spatially smoothed using an isotropic Gaussian kernel of 6 mm full-width at half-maximum (FWHM).

2.6.2. Statistical analysis

The experimental effects in each voxel were estimated by the General Linear Model and by modeling the data at the block level. The blood-oxygenation level-dependent (BOLD) signal was estimated through the convolution of the stimuli with the canonical hemodynamic response function (HRF). Six motion realignment parameters were

included to explain signal variations due to head motion, that is, as covariates of no interest. The first-level analyses resulted in three contrast images per session: 1) *trained targets > control task*; 2) *untrained targets > control task*; 3) *search (both trained and untrained targets) > control task*. These images were used in the following analyses.

2.6.2.1. Cross-sectional analyses

The cross-sectional analyses were conducted to test the null hypothesis that the mean brain responses yielded by the groups during the pre-training session were equal. For this analysis, the contrast image *search > control task* was used to conduct a two-sample *t*-test between the trained group and the control group.

2.6.2.2. Task effects

To find out exactly which brain regions were involved in the visual search task and facilitate the discussion of the training effects on the brain (e.g., whether the areas that change their activation due to training are generally activated during the visual search task or are unrelated to this task), a whole-brain one-sample *t*-test with all the participants' pre-training session data was conducted (*search > control task*).

2.6.2.3. Training effects: interaction analysis

The aim of the interaction analysis was to study the training effects by controlling for repetition effects using between-subjects controls. For each condition, an interaction analysis was conducted with the data from both groups and both sessions (i.e., SPM's flexible factorial analyses). In each possible direction, the following comparison was made: *Trained group (Pre- vs. Post-training session) vs. Control group (Pre- vs. Post-training session)*.

2.6.2.4. Training effects: within-subjects analysis

In order to later discuss the differences between not including any control measures and including some, we considered it necessary to make similar comparisons to those made in previous studies (Kübler et al., 2006). Therefore, a within-subjects analysis was conducted for each condition (i.e., paired *t*-test). In each possible direction, the following comparison was made: *Pre- vs. Post-training session*.

2.6.2.5. Post-training effects: within-subjects analysis

The aim of this analysis was to study the training effects by using the trained group's own data as a control measure; thus, the trained and untrained data were compared. Therefore, a within-subjects analysis with the post-training session data of the trained group was conducted (i.e., paired *t*-test). In each possible direction, the following comparison was made: *Trained Condition vs. Untrained condition session*.

2.6.2.6. Threshold used in all the fMRI task analyses

The results of all the analyses had a voxel-wise threshold of $p < 0.001$ uncorrected and a threshold of $p < 0.05$ Family Wise Error (FWE)-corrected for multiple comparisons at the cluster level, determined by Monte Carlo simulations using the AlphaSim method (Ward, 2002) in the REST software (<http://www.restfmri.net>). The AlphaSim method is designed to operate properly in SPM and allows automatic estimation of image smoothness using 3dFWHM (Ward, 2002). The cluster size criterion for each contrast appears in each result. It varies because, as we used AlphaSim and 3dFWHM, we accounted for the intrinsic smoothness of the data and the spatial smoothing added during preprocessing, ensuring that we did not underestimate the real smoothness of the image in each contrast (Bennet et al., 2009; Ward, 2002).

3. RESULTS

3.1. Behavioral results

The speed response of all the trained group participants improved during the training session (see **Supplementary Figure 1**). The percentage of change from the pre- to post-training sessions was calculated with the trained condition data (RT values) by subtracting the last two blocks of the pre-training session from the first two blocks of the post-training session, and then transforming the result into a percentage score. The participants in the trained group improved their speed by 31%, but the control group showed little improvement (0.25%).

For each experimental condition, a repeated measures 2x2 ANOVA with the Experimental Group (Trained group vs. Control group) as the between-subjects factor and Session (Pre-training session vs. Post-training session) as the within-subjects factor was computed. In relation to the RT values for the trained condition data, a significant main effect of Session ($F(1,34) = 172.85$ $p < 0.001$) was found, indicating that in general participants were faster during the post-training session than during the pre-training session. This main effect was driven by a significant Group x Session interaction ($F(1,34) = 25.99$ $p < 0.001$), indicating that trained participants were faster than control participants in the post-training session compared to the pre-training session. In the untrained condition data, a significant main effect of Session was also found ($F(1,34) = 53.19$ $p < 0.001$), again indicating that participants were faster in the post-training session than in the pre-training session, but no significant Group x Session interaction was found. Finally, in the control task data, a significant main effect of Session ($F(1,34) = 14.62$ $p < 0.001$) was found, indicating that participants were faster in the post-training session than in the pre-training session, but no significant Group x Session interaction was found. In summary, both groups of participants improved their response speed throughout the task, but the effects of training were only observed on the trained targets (see **Figure 2** and **Supplementary Table I**).

FIGURE 2. Training on the visual search task made the trained participants faster than the controls. A significant Group x Session interaction ($F(1,34) = 25.99$ $p < 0.001$) was found in the trained condition behavioral analysis. This interaction indicated that the trained participants, compared to the controls, were faster during the post-training session than during the pre-training session. Values express the averaged median RTs per condition and session. Error bars express SD. Blue bars represent the trained group data, and red bars represent the control group data.

With regard to the accuracy values (see **Supplementary Table I**), a main effect of Session was found in the trained condition data ($F(1,34) = 17.00$ $p < 0.001$) and the untrained condition data ($F(1,34) = 5.52$ $p < 0.001$), but not in the control condition data. No significant interactions were found. The accuracy data indicate that both groups gave more accurate responses in the post-training session than in the pre-training session in the search conditions, but not in the control condition (see **Supplementary Figure 2**).

3.2.Task-fMRI results

3.2.1. Cross-sectional analyses

Cross-sectional analyses were conducted to verify that the group had no brain response differences while performing the visual search task during the pre-training session. The between-groups t -test yielded no significant differences ($p < 0.05$ FWE cluster-corrected). Therefore, the subsequent between-groups brain differences were due to training effects.

3.2.2. Task effects

The whole-brain fMRI analysis of the pre-training session studied task effects by comparing all the visual search conditions with the control task. The contrast *Search (Trained and Untrained condition) > Control task* revealed significant activations in the brain areas related to visual search tasks. Cortical activations were mainly bilateral, and they were located in the inferior occipital gyrus, fusiform gyrus (FG) and lingual gyrus, calcarine sulcus, middle occipital gyrus, cuneus and precuneus, and extended to the posterior parietal cortex (PPC), supplementary motor area (SMA)/dorsal anterior cingulate cortex (dorsal ACC), precentral gyrus (BA 6), inferior frontal gyrus (pars opercularis, BA 44; pars triangularis, BA 45), and ventrolateral prefrontal cortex / anterior insula (VLPFC/aI, BA 47). Right lateralized activations were found in the angular gyrus and anterior prefrontal cortex (BA 10). Subcortically, activations were predominantly found in the bilateral thalamus, bilateral hippocampus, bilateral superior colliculus, bilateral medial cerebellum (lobes IV, V, VI, VII and VIII), and bilateral lateral cerebellum (lobe VI). The results were $p < 0.05$ FWE cluster-corrected with a cluster criterion of $k = 116$ voxels (see **Figure 3**).

FIGURE 3. Visual search task general activation. The task effects analysis (*search > control task*) revealed that the visual search task is supported by a broad neural network that recruits the: occipital cortex, inferotemporal cortex, PPC, dorsomedial frontal areas and lateral prefrontal cortex. The color bar represents t -values. Results are $p < 0.05$ FWE cluster-corrected. L = Left. R = Right. Coordinates are in the MNI space.

3.2.3. Pre-post training effects: interaction analysis

The aim of the interaction analyses was to study the training effects by controlling for repetition effects using between-subjects controls. These analyses assessed the brain changes from the pre- to post-training sessions, in terms of increases or decreases in cerebral activation. When studying the effects of the trained condition [contrast: *Trained group (Pre- > Post-training session) > Control group (Pre- > Post-training session)*], the trained participants had less activation in the right PPC (BA 40/7) (MNI: $x = 36$ $y = -46$ $z = 46$; z -value = 4.06; cluster extent = 107 voxels) than the control participants during the post-training session compared to the pre-training session ($p < 0.05$ FWE cluster-corrected with a cluster criterion of $k = 31$ voxels) (see **Figure 4**). The reverse contrast yielded no significant differences. The same comparisons with the untrained condition data were all non-significant. Hence, this analysis found that only the trained participants had reduced right PPC activation after training, and this occurred only when they performed the trained condition, but not the untrained condition.

FIGURE 4. Visual search task training effects on pre-post comparison. Reduced PPC activation was found to be the effect of training when controlling for repetition effects using between-subjects controls. Contrasts correspond to: Trained condition data *Trained group (Pre- > Post-training session) > Control group (Pre- > Post-training session)*. Color bar represents t -values. Results are $p < 0.05$ FWE cluster-corrected. R = Right. Coordinates are in the MNI space.

3.2.4. Pre-post training effects: within-subjects analysis

A within-subjects analysis for each condition was conducted separately (i.e., paired t -test), in order to better compare our results with those found in a previous study (Kübler et al., 2006). These comparisons and their results were similar to the fMRI analyses in previous studies, as they did not include the control group data. **Figure 5** includes the results of the pre-post comparisons in the trained group for each condition.

FIGURE 5. Visual search task repetition effects. General decreased activation was found in the visual search brain-related areas in pre-post comparisons of (A) the trained condition and (B) the untrained condition in the trained group (i.e., the control group data were not included as a control measure). Color bar represents t -values. Results are $p < 0.05$ FWE cluster-corrected. L = Left. R = Right. Coordinates are in the MNI space.

When studying the effects of the trained condition (contrast: *Pre- > Post-training session*), lower activation was found in the right dorsolateral prefrontal cortex (DLPFC), left inferior frontal cortex, extending to the left precentral gyrus, bilateral SMA/dorsal ACC, bilateral VLPFC/aI, bilateral PPC, left superior occipital gyrus, right inferior

occipital gyrus, bilateral inferior temporal gyrus, left FG, left calcarine sulcus and bilateral cerebellum (lobe VI, lobe VII) during the post-training session than during the pre-training session (**Supplementary Table IIA** and **Figure 5A**) ($p < 0.05$ FWE cluster-corrected with a cluster criterion of $k = 15$ voxels). The results of the same contrast conducted with the untrained data revealed lower activation in the SMA / dorsal ACC, bilateral inferior frontal cortex, left precentral gyrus, right DLPFC, left VLPFC / aI, right PPC and angular gyrus during the post-training session compared to the pre-training session (**Supplementary Table IIB** and **Figure 5B**) ($p < 0.05$ FWE cluster-corrected with a cluster criterion of $k = 35$ voxels). Therefore, the trained participants showed a reduced magnitude of the fMRI signal response in the common visual search areas after training. The reverse comparison yielded no significant effects for either condition.

No large differences were observed between groups in **Supplementary Figure 3**, which overlaps the results obtained from the pre-post comparison with each group separately (comparison: *Pre- > Post-training session conducted with the trained condition data*). As in the case of the trained participants, the control participants exhibited reduced activation in the lateral frontal areas, SMA / dorsal ACC, and early occipital areas. The PPC had reduced activation only in the trained participants. Hence, to study the effects of training, it seemed necessary to remove the repetition effects by including, for instance, a control group that only repeated the task. Removing the repetition effects made the analysis more precise and isolated the training effects to specific areas.

3.2.5. Post-training effects: within-subjects analysis

The aim of this analysis was to study the training effects using the trained group's own data as a control measure; thus, the untrained condition served as a within-subject control measure. We found that after training, the trained participants had lower activation in the bilateral PPC, bilateral FG, left inferior occipital gyrus, and right lingual gyrus in the trained condition compared to the untrained condition (contrast: *Untrained condition > Trained condition*) ($p < 0.05$ FWE cluster-corrected with a cluster criterion of $k = 25$ voxels) (see **Table I** and **Figure 6**). The reverse contrast yielded no significant differences. This analysis indicated that reduced PPC activity is related to performing the trained condition after the training. However, we also found that other visual and language

areas showed reduced activation, an effect that was eliminated when controlling for repetition effects.

FIGURE 6. Visual search task training effects in post-training session: between-conditions comparison. Reduced PPC activation was again found to be the effect of training; however, the bilateral FG and left inferior occipital cortex also showed decreased activation. Contrast corresponds to: *Trained group (Untrained condition > Trained condition)*. Color bar represents *t*-values. Results are $p < 0.05$ FWE cluster-corrected. L = Left. R = Right. Coordinates are in the MNI space.

Table I. List of brain activations as a result of the post-training session: within-subjects analysis. The training effects were studied using the trained group's own data as a control measure; thus, the trained vs. untrained condition comparison was conducted in each direction.

	BA	Cluster extent	MNI SPACE			Z-value
			x	y	z	

Trained condition > Untrained condition						
No significant effects were found.						
Untrained condition > Trained condition						
L FG	37	43	-36	-55	-11	5.11
L inferior occipital gyrus	19	37	-30	-73	-5	4.46
R PPC	19	177	27	-70	31	4.44
R FG	37	32	33	-52	-8	4.40
L PPC	7	116	-21	-73	43	4.32
R Lingual	19	28	15	-49	-9	4.15

FOOTNOTES: Results were $p < 0.05$ FWE cluster-corrected with a cluster criterion of $k = 25$ voxels. L = Left. R = Right. FG = fusiform gyrus. PPC = posterior parietal cortex.

4. DISCUSSION

This pre-post fMRI research consisted of studying the behavior and brain changes related to training effects on a visual search task. Our main concern was that previous visual search training studies have not included enough control measures. Therefore, our study controlled for repetition effects using both between-subjects (trained *vs.* control participants) and within-subject (trained *vs.* untrained stimuli) controls. Training in visual search tasks led to brain changes and behavioral improvements in terms of efficiency. Trained participants showed significantly reduced right PPC activation and clearly improved visual search after training. This reduction in PPC recruitment was observed when comparing the trained participants to the control participants in the pre-post cerebral data of the trained condition, and also in the post-training session comparison, which tested the differences between the trained and untrained conditions. In this latter comparison, we also found other posterior areas with reduced brain activity after training (i.e., FG and inferior occipital cortex). The results should be interpreted as showing brain changes due to training. However, when appropriate controls were implemented, the changes were not global and distributed in different brain regions, but instead they were circumscribed to the brain areas directly associated with the task. In this case, brain activity reduction was consistently found in the PPC, which plays a key role in focusing attention during visual selection tasks.

4.1. Behavioral changes due to task automation

Training effects were observed on RTs, but not on accuracy. All the participants were generally faster in the post-training session than in the pre-training session. Compared to the control participants, the trained participants had improved RTs: intensive training in visual search had an effect, as it made participants find targets significantly faster than before training, without compromising their accuracy. The RT values in this condition remained short and stable during the post-training session, indicating some degree of automation. This change in performance was visible from the beginning of the post-training session. It was marked for the trained condition, but it was not observed for the untrained condition. Thus, the training implemented in this study was specific to the trained targets and did not produce any effect on the untrained targets. Our results agree with previous behavioral visual-attentional studies showing that consistent mapping

allows automation processes to begin after completing at least 600 training trials, and a quantitative reduction in RTs was observable (without interfering with accuracy) (see Shiffrin and Schneider, 1977). The controls' search speed also improved slightly, especially during the post-training session when they started accumulating a significant number of trials. The changes in the control group's RTs could be related to adaptation effects to task processes in the initial phase of automation. Previous cognitive studies have related control group improvements to retest effects due to task repetition (Garavan et al. 2000; Schneiders et al. 2011).

4.2. Training effects on brain activity: overall changes

As expected, and although not all the areas were involved during the pre-training session, task performance shows decreased activation after extensive training during the post-training session, and the areas that changed showed this effect (Schneider and Chein, 2003). Previous neuroimaging studies of training-related changes have found fMRI signal decreases in different areas, including the PPC and occipital cortex (Kelly and Garavan, 2005). In general, training-related decreases have been associated with increased neural efficiency in the brain network underlying task performance (Kelly and Garavan, 2005). Efficiency at the neuronal synaptic level is assumed to underlie post-training reduced activation (Petersen et al., 1988; Poldrack, 2000).

Intensive training on the visual search task also led to reduced PPC activation after training. In general, decreases in PPC (and also ACC and PFC) have been related to less reliance on attentional control processes (Chein and Schnedier, 2005; Kelly and Garavan, 2005). A similar visual-search task study found that participants who automated the task experienced decreased cerebral activation in the brain network underlying task performance, including frontal and posterior areas (Kübler et al. 2006). The authors interpreted these cerebral changes as indicating the need for fewer attentional and control processes because the frontal cortex is related to these functions and because automatic behavior is assumed to depend less on attention. However, in terms of attention, our results indicated that improvement in speed after training on the visual search task implied less use of the brain areas that are specifically related to attentional functioning. This difference in the post-training results may be due to the fact that the experimental design did not include a control group and/or an untrained condition. In our study, training effects

were studied by comparing the trained participants to the control participants, and the trained condition data to the untrained condition data; that is, two sources of control were used to study the effects of training and separate them from those produced by only repeating the task. The robust finding was that the trained participants' PPC showed reduced activation after training, when all these control measures were used. Consistently, the PPC became less activated when comparing the pre- > post-training session data or the post-training session untrained condition > trained condition data.

In our opinion, repetition effects differed from training effects. Repetition effects were observable when the control group data were not included in the statistical comparisons, and they revealed changes in other brain areas apart from the PPC (see **Figure 5**). For instance, the pre-post comparison within the trained group resulted in reduced activation in the lateral and middle frontal areas, dorsal ACC, PPC, infero-temporal cortex, early visual cortex areas, and the cerebellum. It is worth noting that the control group's brain activity changes were located in some of the areas already observed in the trained group, for example, lateral frontal areas, SMA / dACC, or early visual cortex areas (see **Supplementary Figure 3**). Previous neuroimaging studies have focused on training-related changes when comparing initial and final brain activity. These studies have found broad brain networks with decreased activation after training (Chein and Schneider, 2005; Kübler et al., 2006). Although it is true that repeatedly performing a task leads to decreased activation of the brain areas already involved in the task, our data indicate that brain changes due to training were not broad, and they appeared only when repetition effects were removed, and when comparing trained and untrained participants. On the other hand, considering the control group data, their decreased activation may not only be due to repetition effects. One limitation of this study is that we do not have any way to mark where the repetition effects ended and, if they did, where the training effect began for the control group data. In other words, it is possible that some of the control group's brain changes were showing an initial phase of expert performance.

4.3. Training effects: changes in occipital cortex

We found that bilateral FG and inferior occipital cortex (BA 19) areas showed reduced brain activation in the post-training session when the trained condition was compared to the untrained condition. Although the stimuli used in our visual search task were letters,

the FG area that showed decreased activation after training did not match the visual word form area location, which is lateral to our coordinate (Hannagan et al., 2015; Cohen et al., 2000). However, a very close match was found between our FG activations and the results of a previous perceptual learning fMRI investigation (Mukai et al., 2007). The underlying neural mechanisms of repeatedly perceiving a stimulus were studied by means of a contrast-discrimination training paradigm, showing decreased activation of FG and inferior occipital cortex areas (BA 18 and 19), in addition to other areas such as the intraparietal sulcus, frontal eye field and supplementary frontal eye field. The explanation offered for the reduced activation found in visual cortex areas was that visual neurons showed a more precise response to the trained stimulus or a sharpened tuning of neuronal representations as a result of the training process. It seems that repetition suppression is the underlying mechanism responsible for the decreased activation (Wiggs and Martin, 1998). Repetition suppression may reflect neuronal adaptation. In earlier conceptions, the repetition suppression mechanism was seen as unspecific to the stimulus' meaning or the task goal (i.e., distinction between targets and distractors) (Desimone, 1996; Wiggs and Martin, 1998). However, the strength of the neuronal adaptation (i.e., the amount of reduction) varies depending on the stimulus features, and it could reflect selectivity between the neuronal activity and the stimulus (Larsson and Smith, 2012; Grill-Spector and Malach, 2001). Thus, greater repetition suppression associated with the trained condition compared to the untrained condition could explain the reduced activity observed in visual occipital areas when this comparison was made.

In addition, attention modulation is also observable in the visual occipital cortex. Attention modulation takes place during attentional feature-based and visuospatial tasks, and it can also modulate repetition suppression (Larsson and Smith, 2012; Guggenmos et al., 2015). Neurocomputational models of visual attention defend that high-order cognitive areas like the DLPFC and PPC exert a top-down bias that specifies the processing conditions of the occipital cortex (Deco and Rolls, 2005). This attentional modulation has been investigated in single-unit studies, which have observed that early visual cortex areas enhance their response after receiving top-down bias (Deco and Rolls, 2005; Lee et al., 2002). Therefore, the reduced activity observed in visual occipital areas could reflect complex effects involving both sharpened tuning of neuronal representations due to repetition suppression and attention modulation exerted by attention control areas.

4.4. Training effects: the role of the PPC

In agreement with previous literature, our different analyses consistently showed that intensively training a visual search task can lead to reduced PPC activation. Changes associated with developing expertise have different effects across brain regions; for instance, attention control processes are needed less and, thus, tend to reduce brain activity (Chein and Schneider, 2005, 2012). The PPC has been identified as being responsible for selecting a stimulus as a target or rejecting it (Kastner and Ungerleider, 2000). In order to do so, it processes bottom-up and top-down information by setting up a priority map. This map of space allows the PPC to evaluate different visual objects and decide which are relevant and which meet task requirements (Bisley and Goldberg, 2010; Ptak, 2012). Therefore, its role is not only to form priority maps for the selection process, but also to guide the focus of attention through it. Cognitive theories, such as the Biased Competition Model, state that even if visual stimuli, or their basic features, are processed in visual areas, high-order cerebral areas also take part in processing the visual world. Thus, the involvement of parietal areas during the visual search task is justified (Bueichekú et al., 2015; Bundesen 1990; Deco and Rolls, 2005; Deco and Zbil, 2006; Desimone and Duncan, 1995; Duncan and Humphreys, 1989; Duncan, 1996; Harter and Aine, 1984).

Moreover, PPC activity has also been associated with the mnemonic representation of visual objects (Sarma et al., 2016). Indeed, visual search tasks have memory components that could require PPC engagement. According to recent models of visual search, visual working memory participates in visual search tasks during the formation of attentional templates in the preparation phase or during the identification process (Eimer, 2014). Different possibilities have been proposed to explain the memory functions of the PPC (Ester et al., 2015). Consistent with the priority map theory, one explanation would be that the PPC stores salient, already encoded, or relevant locations for task completion (Bisley and Goldberg, 2010). Another possibility is that the priority maps also have content information like the spatial distribution of objects in space (Ester et al., 2015). Some authors argue that the PPC only stores general representations of task performance, such as the categorization and meaning of stimuli and the selection of rules and actions (D'Esposito and Postle, 2015; Rowe et al., 2008; Freedman and Assad, 2006). Other authors have been able to link PPC mnemonic functions with both the maintenance of task rules and the maintenance of the specific features of the visual objects (Ester et al.,

2015; Rasposo et al., 2014). Recent training studies with categorization tasks have concluded that the PPC has a limited and task-specific role in visual working memory (Sarma et al., 2016).

We stress that the precise location of the PPC areas that changed after training varied depending on the comparison made. The pre-post comparison of the trained targets yielded differences in a more anterior part of the right PPC, whereas the comparison made after training between the untrained and trained targets involved more posterior areas of the bilateral PPC and the adjacent occipital cortex. Both locations participated in processing targets during the pre-training session (**Figure 4**) and have recently been involved in searching for changes in the features of stimuli (Becker et al. 2014). The results reported here may help to understand the different roles played by these different PPC areas. Anterior PPC parts seem to participate in the change in a target's meaning. This location is similar to the parietal reductions found by Kübler et al. (2006), who used a different search task. Hence, this PPC part was related to processing the different significance of the same stimuli after their processing was automated. By contrast, processing the untrained targets required greater participation of the more posterior occipito-parietal areas than the trained ones did. Therefore, this area seems more involved in detecting the physical differences between trained and untrained targets, that is, the different features of the targets. It is worth noting that this involvement is bilateral. Future studies should determine the relevance of these differences.

5. CONCLUSIONS

Intensive training on the visual search task led to faster responses in the trained participants and improvements in their cognitive efficiency while performing the task. We conclude that repeatedly performing a task leads to reduced brain activation in the brain areas underlying task performance. We were able to differentiate task repetition from training effects; both moved in the same direction, but the former leads to broad brain network changes, whereas training affects specific areas. During the performance of the trained condition group after training, PPC and occipital cortex areas showed reduced activation. Less activation of occipital cortex areas after training has been associated with repetition suppression, but attention modulation could also explain this reduction. Reduced PPC activation has consistently been found to be the effect of training.

This result could indicate that the reorganization of the functioning of this area occurred due to training. Improvement of the priority maps that control the visual selection processes and the guiding of attention may well be responsible for the changes in the PPC.

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CONFLICT OF INTEREST

None declared.

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SUPPLEMENTARY FIGURES

SUPPLEMENTARY FIGURE 1. Evolution of the participants' RTs values during the experiment. The trained group's speed responses to trained targets improved during the practice session held outside the scanner (reduction in RTs: trained group 31% vs. control group 0.25%). The RT values of the trained group remained short and stable in the trained condition during the post-training session. In this graph, the averaged median RT values in each condition are plotted according to time (expressed in task blocks). The trained group data appear in blue tones; the control group data appear in red tones.

SUPPLEMENTARY FIGURE 2. Results of the accuracy analysis. Values express the averaged correct responses per condition and session (in percentages). Blue bars represent the trained group data, and red bars represent control group data. Error bars express SD.

SUPPLEMENTARY FIGURE 3. Overlap of the cerebral changes related to performing the task repeatedly. The results of the pre-post comparison in each group separately revealed that when the control measures were not introduced, the effects of training did not differ much from the effects of repeating the task. Both groups showed reduced activation in the visual search-related areas during the post-training session. However, the specific brain areas related to training, that is, the PPC, only showed reduced activation in the trained group.

FOOTNOTES: The trained group data appear in BLUE; the control group data appear in RED. For viewing purposes, the results are presented with a threshold of $p < 0.05$, uncorrected at the voxel level. L = Left. R = Right. Z coordinates are in the MNI space.

SUPPLEMENTARY TABLES

SUPPLEMENTARY TABLE I. Percentage of correct responses and mean RTs in milliseconds, followed by standard deviations.

	PRE-TRAINING SESSION			POST-TRAINING SESSION		
	Control condition	Trained Condition	Untrained Condition	Control condition	Trained Condition	Untrained Condition
Trained group	99.54 % 440±68 ms	88.89 % 904±114 ms	89.35 % 909±115 ms	98.15 % 393±49 ms	93.06 % 605±119 ms	91.20 % 714±192 ms
Control group	100.00 % 415±66 ms	91.20 % 885±105 ms	91.67 % 888±130 ms	99.54 % 383±51 ms	93.98 % 753±133 ms	94.44 % 771±162 ms

SUPPLEMENTARY TABLE II. List of brain activations related to practice effects in the trained group. Results of the pre-post comparisons for: **A)** Trained condition; **B)** Untrained condition.

	BA	Cluster extent	MNI SPACE			Z-value
			x	y	z	

A) TRAINED CONDITION

Pre-session > Post-session

L inferior temporal gyrus	37	187	-42	-55	-8	5.00
L fusiform gyrus	37		-39	-49	-20	4.10
L cerebellum VI			-36	-61	-20	3.68
R inferior occipital gyrus	19	139	39	-70	-14	4.89
R inferior temporal gyrus	37		51	-61	-11	3.98
R cerebellum VI			33	-52	-23	3.90
R middle frontal cortex	46	363	39	32	19	4.85
R inferior frontal cortex pars opercularis	44		39	8	31	4.22
R DLPFC	46		33	35	28	4.08
R SMA	8	109	6	26	49	4.59
R dorsal ACC	32		9	26	40	3.84
L VLPFC/aI	47	146	-42	20	31	4.42
L precentral gyrus	44/6		-48	11	31	4.09
L inferior frontal cortex pars triangularis	45		-48	35	19	3.67
L PPC	19	39	-21	-79	43	4.40

L PPC	40	97	-36	-52	49	4.40
L calcarine sulcus	17		-12	-67	52	3.41
L PPC	7		-24	-58	49	3.37
R PPC	7	512	24	-67	49	4.32
R PPC	40		36	-46	43	4.27
L VLPFC/aI	47	33	36	23	-5	3.75
R VLPFC/aI	47	21	-30	26	-2	3.68
R cerebellum VII		15	3	-79	-20	3.67
R cerebellum VI			12	-70	-20	3.30
R middle frontal cortex	8	17	30	5	58	3.66

Post-session > pre-session

No significant effects were found.

B) UNTRAINED CONDITION

Pre-session > Post-session

B SMA	48/8	119	9	26	49	5.41
Dorsal ACC	32		9	26	37	4.30
R inferior frontal cortex pars opercularis	48/44	163	33	17	31	4.79
R DLPFC	9		39	11	52	4.09
L inferior frontal triangularis	48/45	81	-45	23	28	4.21
L precentral gyrus	44/6		-48	14	31	3.85
R PPC	7	204	33	-61	37	3.98
R angular gyrus	39		42	-58	49	3.98
L VLPFC/aI	47	35	-39	20	-5	3.99
R precuneus	7	35	12	-76	49	3.95

Post-session > pre-session

No significant effects were found.

FOOTNOTES: The results were $p < 0.05$ FWE cluster-corrected with a cluster criterion of **(A)** $k = 15$ voxels; **(B)** $k = 35$ voxels. X, Y, Z coordinates are in the MNI space. L = Left. R = Right. ACC = anterior cingulate cortex. DLPFC = dorsolateral prefrontal cortex. VLPFC / aI = ventrolateral prefrontal cortex / anterior insula. PPC = posterior parietal cortex.

Study 3

**Visual search task related changes in local and distant intrinsic
functional connectivity**

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Jorge Sepulcre.**

Under review

ABSTRACT

Brain plasticity occurs over the course of the human lifetime. New experiences reorganize our neuronal synapsis in a variety of time scales. Diverse studies have investigated the experience-driven changes in the adult human brain, and we know that brain activity adapts after learning and cognitive training, ranking from priming effects in modal areas to higher-order changes in heteromodal regions. Yet, learning and training effects must induce large-scale brain connectivity changes, which remain largely unknown. Here, we used task-fMRI data and graph-based approaches to study functional connections underlying the visual-search learning network of the human brain. First, at the behavioral level, we found that trained participants (N=19) reduced their response speed by 31% as a result of training on a visual search task, whereas the control group (N=19) hardly changed. Then, we show that trained participants change regional connections in cortical areas devoted to visual attention processing, as well as, distributed connections linking primary visual with association and multimodal cortices. The observed behavioral and connectivity findings expand our understanding of neuroplastic changes after learning experiences.

KEYWORDS: Attention; Automaticity; Cognitive training; Connectivity; Functional Magnetic Resonance Imaging; Graph-theory; Plasticity.

ABBREVIATIONS

AC-PC: anterior commissure-posterior commissure

ANOVA: analysis of variance

BA: Brodmann area

BOLD: blood-oxygenation level-dependent

CARET: Computerized Anatomical Reconstruction Toolkit

DLPFC: dorsolateral prefrontal cortex

DPARSF: Data Processing Assistant for Resting-State fMRI

EPI: echo-planar imaging

fMRI: functional Magnetic Resonance Imaging

FWE: family-wise error

FWHM: full-width at half-maximum

iFC: intrinsic functional connectivity

M: mean

mm: millimeters

MNI: Montreal Neurological Institute

mPFC: dorsomedial prefrontal cortex

MPRAGE: Magnetization Prepared Rapid Acquisition Gradient Echo

ms: milliseconds

N: number of participants

PPC: posterior parietal cortex

RMS movement: Root Mean Squared movement

RT(s): reaction time(s)

SD: standard deviation

SPM: Statistical Parametric Mapping

TE: echo time

TR: repetition time

VLPFC: ventrolateral prefrontal cortex

VST: Visual search task

WAIS: Wechsler Adult Intelligence Scale

1. INTRODUCTION

It is generally assumed that practicing a task helps performing it better. In this regard, some studies have been focused on studying the brain plasticity (Pascual-Leone, Amedi, Fregni and Merabet, 2005; Lövdén, Wenger, Mårtensson, Lindenberger and Bäckmana, 2013; Guerra-Carrillo, Mackey and Bunge, 2014), and on finding the neural correlates underlying the training effects (Kelly and Garavan, 2005; Kelly and Castellanos, 2014). Despite the progress made in this field, it remains largely unknown how brain connectivity reorganizes to integrate new learning experiences. But it is important to describe how the communication between brain areas changes in order to understand neuroplasticity processes. Therefore, our main objective was to study the training effects on the brain connectivity.

Training on a cognitive task is thought to lead to the development of automaticity. In turn, automaticity has been linked to the study of attention, and the use of visual search tasks (VST) since they entail a degree of complexity and are associated with the attentional system activity (Buschman and Kastner, 2015). Two-process models of information processing defend that as automatic behavior is achieved, the recruitment of the attention system is gradually withdrawn, and thus cognitive efficiency is enhanced (LaBerge and Samuels, 1974; Shiffrin and Schneider, 1977; Logan, 1978; Schneider and Chein, 2003). At the behavioral level, automatic behavior is achievable after completing a number of training trials (600 trials at least) presented under constant stimulus-response conditions (i.e., consistent mapping). To refer to automatic behavior, the performance of a task has to improve. For instance, it has to produce quantitatively faster responses than its naïve performance, and always without obtaining worse accuracy scores (e.g., maintaining or improving them) (Shiffrin and Schneider, 1977). In relation to brain activity, training on cognitive tasks usually leads to extensive reductions of the association areas' activity, whose function is linked to exerting attentional control (Chein and Schneider, 2005; Kübler, Dixon and Garavan, 2006). In fact, the training effects on the brain can be isolated and linked to specific areas. For instance, training on VST leads to developing automatic task performance, and activity reductions on the posterior parietal cortex (PPC) and inferior occipital cortex are observed after training (Bueichekú,

Miró-Padilla, Palomar-García, Ventura-Campos, Parcet et al., 2016). On the other hand, less studies have been focused on intrinsic functional connectivity. In general, increased brain connectivity has been found when training on sensorimotor tasks. Connectivity changes usually affect the task-dependent regions, association areas and higher-level cognitive areas (i.e., lateral and medial aspects of the parietal, premotor and prefrontal cortices). When reaching the asymptotic performance, increased connectivity is only found between task-dependent regions (Kelly and Castellanos, 2014).

The main goal of this study was to investigate the training effects of a VST on brain connectivity. Thus, local and distant connectivity changes were studied using a graph-based approach, and comparing a group of trained participants to a control group. Graph-based approaches allow for analyzing individual properties of networks or global connectivity, thus becoming flexible analytical approaches (Achard, Salvador, Whitcher, Suckling and Bullmore, 2006; Rubinov and Sporns, 2010). The degree centrality (or degree) is a brain network measure that quantifies the number of connections (i.e., links) departing from a voxel (i.e., node) (Rubinov and Sporns, 2010). Some nodes (i.e., hubs) display a high number of links, and are thought to converge the information from diverse pathways (Sepulcre, Sabuncu, Yeo, Liu and Johnson, 2012; Buckner, Sepulcre, Talukdar, Krienen, Liu, Hedden et al., 2009). Therefore, the connectivity patterns between task-dependent regions can be directly studied with degree analysis, and although do not exactly correspond to anatomical pathways or resting-state connectivity strengths (Buckner et al., 2009), they provide a measure of the functional connectivity, which can be applied to the study of the training effects on brain connectivity. In this study we hypothesized that: 1) the trained participants, compared to the control participants, would produce faster responses to trained targets in post-training session due to task automation; 2) the cerebral areas related to the attention-control system would exhibit increased number of local and distant functional connections after training, as the VST is supported by this system and an enhancement in the functional connectivity is expected after training.

2. MATERIALS AND METHODS

2.1. Participants

Thirty-eight healthy undergraduate students from the Universitat Jaume I participated in this study and were paid for their participation. All the participants were right-handed (Oldfield, 1971), had normal or corrected-to-normal vision, and reported no neurological or psychiatric history, or past or current use of any drugs. Participants were randomly assigned to a trained group ($N = 19$, 10 men; age: $M = 20.84$ $SD = 1.45$) or to a control group ($N = 19$, 10 men; age: $M = 20.84$, $SD = 2.01$). A between-groups t -test was used to determine that the experimental groups did not differ in age ($t(36) = 0$ $p = 1$). Intellectual level was evaluated with the Matrix Reasoning Test (WAIS-III-R) (Trained group: $M = 21.58$ $SD = 2.11$; Control group: $M = 21.74$ $SD = 1.49$). A between-groups t -test was used to determine that the experimental groups did not differ in intellectual level ($t(36) = -0.27$ $p = 0.79$). All the participants provided written informed consent prior to scanning. The study was approved by the Ethics Committee of the Universitat Jaume I.

2.2. Stimuli

2.2.1. Search frames

A schematic representation of the stimuli appears in **Figure 1A**. The search frames consisted of black ink letters on a white background. Each search frame had six stimuli arranged circularly around a fixation point (visual angle: letters = 0.50° ; fixation point = 0.24° ; distance between letters and fixation point = 1.32°). Targets and distractors were always letters. Thus, search frames were always “within-category searches”. There were two sets of target stimuli: *B C D F G H* and *L M N P Q R*. Distractors were always *J K Ñ S T V W X Y Z*. The role of targets and distractors did not change across tasks (consistent mapping search). Each search frame consisted of the presentation of either six distractors or five distractors and one target. Stimuli locations were randomized in all the conditions. Finally, no stimulus appeared twice in a row in the same location.

2.2.2. Control task

A control task was included in the experimental paradigm to measure a baseline response time and a baseline cerebral response, and it matched the visual array used in

the search frames of the visual search conditions. The control task displays consisted of black ink letters on a white background. There were only two types of frames: a six *A*-letters array and a six *X*-letters array. *A*'s and *X*'s were arranged circularly around a fixation point (visual angle: letters = 0.50°; fixation point = 0.24°; distance between letters and fixation point = 1.32°). *A*'s and *X*'s were never mixed on the display.

2.2.3. Instruction display

At the beginning of each block, an instruction display informed participants which task they should perform. The instruction display presented targets in black ink on a white background in a single centered row (visual angle: letters = 0.50°). There were three different instruction displays: 1) *A*, which indicated that participants would perform the control task; 2) *B C D F G H*, which indicated that they would search for these letters; 3) *L M N P Q R*, which indicated that they would search for these letters.

FIGURE 1. Schematic representation of the experimental procedure. Examples of the control condition (A), and the search condition (B) of the visual search task. Active blocks started with an instruction display, followed by the presentation of twelve trials. Passive blocks consisted in blank screens. The experimental conditions were counterbalanced throughout the VST.

2.3. Experimental paradigm

2.3.1. In-scanner task

In order to carry out this research, the classic visual search task was adapted to an fMRI block design. The block organization and timing details are represented in **Figure 1A**. The experimental task lasted 25 minutes. The task consisted of 42 active blocks and 42 passive blocks. The active blocks consisted of: 14 control task blocks, 14 search blocks that corresponded to targets *B C D F G H* and 14 search blocks that corresponded to targets *L M N P Q R*. These blocks were counterbalanced throughout the experiment. In all the blocks, fifty per cent of the trials constituted a target-present frame. Each block had 12 trials, which consisted of 300 ms of a fixation point, 1500 ms of a search frame, and 200 ms of a blank screen. Each block started by presenting the instruction display, which remained on the screen for 3000 ms. All the passive blocks consisted of periods of 8000 ms when the screen remained completely blank.

There were no restrictions to eye movement. However, considering the distance between the fixation point and the stimuli (visual angle = 1.32°), eye movements were not strictly needed to perform the task. Participants had to give manual responses only with their right hand. Positive answers were given with their right thumb, and negative ones with their right forefinger. Participants had to give positive answers when they detected a target (either the *As* on the control task or the letters defined as targets in the visual search conditions) and negative answers when there were no targets. Participants were asked to answer as quickly as possible, but without compromising accuracy.

2.3.2. Practice before fMRI

For the practice task, an identical laptop was used, with the same display configuration as the one used to present the in-scanner task. The same hardware was used for manual responses with identical settings. Participants received written instructions about how to do the task. The practice task lasted 7 minutes and consisted of: 4 control task blocks, 2 search blocks that corresponded to targets *B C D F G H*, 2 search blocks that corresponded to targets *L M N P Q R*, and 8 passive blocks (blank screen). Regarding stimulus design, block organization, block timing and instruction displays, the practice task was identical to the in-scanner task. In the case of the search frames, none of the search templates that appeared during the practice task were used later during the in-scanner task or the training

task (i.e., *CTGDBR*, with C in the top center position and the rest of the letters organized circularly and clockwise). Participants had to obtain eighty per cent of correct responses in order to participate in the fMRI experiment. All the participants included in this study reached this criterion (percentage of hits: Trained group: $M = 84.94$ $SD = 4.10$; Control group: $M = 84.94$ $SD = 4.55$). No between-groups differences were observed on the practice task, as assessed with a between-groups *t*-test analysis ($t(36) = 0.003$ $p = 0.998$).

2.3.3. Training between sessions

The training task was done outside the scanner. For the training task, an identical laptop was used with the same display configuration as the one used to present the in-scanner task. The same hardware for manual responses was used with identical settings. The training session took place between the pre- and post-training fMRI sessions (see **Figure 1B**). Training on the visual search task was intensive and presented as a block design. Randomly, half the participants from the trained group were trained in searching for targets *B C D F G H*, while the other half were trained in searching for targets *L M N P Q R*. Therefore, after training, the trained group experienced two types of search conditions: 1) trained search; 2) untrained search. From this point on, we will refer to the trained or untrained condition instead of repeating the groups of targets. It was noteworthy that the control group participants did not perform any training or cognitive tasks between scans. Thus, searching for either of the two groups of targets would not represent any difference for the control group.

The stimuli and timing details of the training task matched the fMRI task. The presentation of a fixation point (300 ms) was followed by the search frame (which had five distractors and one target or six distractors), and then by a white screen (200 ms). The only difference was that during training, the search frame disappeared as soon as the participant gave a response. Thus, participants could improve their performance at their own pace. Every 42 frames (a block), participants received a feedback report with their mean accuracy and median reaction time for that block. Every 210 frames (five blocks), participants took a 31-second rest. Participants completed 840 trials (twenty blocks) during the training session, and they spent $M = 28.62$ minutes ($SD = 2.70$) on the training task.

All the participants were asked to refrain from consuming any substance (e.g. coffee, tobacco and stimulating beverages), apart from food or water, before the Pre-training session and between the Pre- and Post-training sessions.

2.3.4. Summary of the experiment timing

The experiment was conducted on one day. First, all the participants performed a practice task that lasted 7 minutes. Next, all the participants did the first fMRI scan, which lasted 35 minutes: 10 minutes of anatomical data acquisition, followed by 25 minutes of task-fMRI acquisition. A 45-minute period separated the first and second fMRI scans; this period had the same duration for both the trained and control groups. During this period, the trained group participants did the training task (outside the scanner) which lasted, on average, $M = 29.97$ minutes $SD = 2.13$ (an average was used here because the participants had to complete the 840 trials at their own pace). The control group participants did nothing during this period. Finally, after this 45-minute period ended, all the participants did the second fMRI scan, which lasted 35 minutes, as in the case of the first scan: 10 minutes of anatomical data acquisition and 25 minutes of task-fMRI acquisition.

2.4. Image acquisition

The fMRI data were acquired in a 1.5 T Siemens Avanto scanner (Erlangen, Germany). The same protocol was used during the Pre- and Post-training sessions. Each scan session lasted 35 minutes. All the participants were placed in the scanner in the supine position. Fixation cushions were used to reduce head motion. A gradient-echo T2*-weighted echo-planar MR sequence was used to obtain 602 volumes for the fMRI task (29 interleaved ascending slices, 3.5 x 3.5 mm in-plane voxel size, slice thickness 3.6 mm, interslice gap 0.4 mm, TR = 2500 ms, TE = 50 ms, flip angle 90 °, 64 x 64 matrix). Prior to task-fMRI data acquisition, one high-resolution T1-weighted MPRAGE anatomical image was obtained per participant (TR = 2200 ms, TE = 3.8 ms, flip angle 90°, 256 x 256 x 160 matrix, 1 x 1 x 1 mm in-plane voxel size). All the scanner

acquisitions were performed in parallel to the anterior commissure-posterior commissure plane (AC-PC), and they covered the entire brain.

Stimulus presentation was controlled by the E-Prime software (Schneider et al., 2002), professional version 2.0, which was installed in a Hewlett-Packard portable workstation (screen-resolution 800 x 600, refresh rate of 60 Hz). Participants watched the laptop screen through MRI-compatible goggles (VisuaStim, Resonance Technology, Inc., Northridge, CA, USA), and their responses were collected by MRI-compatible response-grips (NordicNeuroLab, Bergen, Norway). The E-Prime's logfile saved several measures, including stimulus presentation timing (onset) and duration, along with participants' accuracy and reaction times (RTs) to each stimulus.

2.5. Analysis

2.5.1. Behavioral analysis

In terms of accuracy and RTs, participants' performance was processed with the IBM SPSS Statistics software (Version 23 Armonk, New York, USA). A repeated measures 2x2x2 ANOVA was conducted with the Experimental Group (Trained group *vs.* Control group) as the between-subjects factor and Condition (Control task *vs.* Trained condition) and Session (Pre-training session *vs.* Post-training session) as the within-subjects factors. The untrained condition data was not included in the analysis. For behavioral analysis, only correct trials data was used.

2.5.2. Intrinsic functional MRI connectivity pre-processing analysis

Prior to pre-processing, each subject fMRI data set was aligned to the AC-PC plane by using its own anatomical image. A total of 154 fMRI volumes corresponding to the trained condition were preprocessed and used in subsequent analysis. The volumes were concatenated as a function of session by using the stimulus' onset time.

For pre-processing the DPARSF Advanced software (Chao-Gan and Yu-Feng, 2010) was used. Standard pre-processing was conducted, which included the correction of the slice timing differences for interleaved ascending acquisitions (using the middle slice, which was the 29th, as the reference slice) and a two-pass procedure in realignment (first registration to the first image, then registration to the mean image) to correct head motion

through acquisition. No head motion with more than 2.0 mm of maximum displacement in any direction or 2.0° of any angular motion while the scan lasted was recorded. In order to control the movement effect throughout the experiment, the Root Mean Squared movement values (RMS, of translation and rotation parameters) were used to conduct a repeated measures 2x2 ANOVA with the Experimental Group (Trained group vs. Control group) as the between-subjects factor, and with Session (Pre-training session vs. Post-training session) as the within-subjects factor. No significant differences were yielded (RMS: $F(1,36) = 0.061$ $p = 0.806$). Then, within the nuisance regression step, and in order to reduce respiratory and cardiac effects on blood-oxygenation level-dependent (BOLD) signal, several sources of spurious variance were removed: the linear trend in the time series, six parameters from rigid body head motion (obtained from motion correction) and three parameters corresponding to the global mean signal, the white matter signal and the cerebrospinal fluid signal (Biswal et al., 1995). Spatial normalization to the Montreal Neurological Institute (MNI) space (3 mm³) using echo-planar image (EPI) templates was conducted. The temporal filtering step removed low and high frequency drift effects (0.01–0.08 Hz). Finally, data was down-sample from 3 mm to 6 mm voxel size for computational efficiency by means of SPM Image Calculator (ImCalc Toolbox, <http://robjellis.net/tools.html>).

2.5.3. Post-processing analysis: individual local and distant degree maps

Post-processing analyses were conducted with Matlab coding (v7.9, The Mathworks, Inc, Natick, MA). At the individual level, a whole-brain matrix Pearson Correlation Coefficient between each voxel pair was estimated for each participant and session. A mask of 6332 voxels that covered the entire brain was used. Each participant had a total of four matrices, two of them containing the r -values, and the other two containing the p -values. According to previous graph-based functional connectivity approaches (Sepulcre et al., 2010), the intrinsic functional connectivity (iFC) matrices of positive correlations represent the strength of the connectivity between every pair of voxels across the brain (i.e., the degree), and the pattern of these connections represents the functional connectivity network supporting task-performance in each time point. Therefore, we used the positive correlations in the following steps of the analysis, and

removed the negative r -values due to their controversial interpretation in fcMRI (Murphy, Birn, Handwerker, Jones, and Bandettini, 2009; Van Dijk, Hedden, Venkataraman, Evans, Lazar, and Buckner, 2010).

Degree analyses were used for studying the effects of training on brain connectivity, and its spatial distribution. Degree analyses make it possible to extract the spatial distance information of the connectivity patterns, differentiating between regional connections (local links) and interregional connections (distant links). This method was previously used for studying the connectivity patterns that are subjacent to the human information processing. To this aim, a novel whole-brain voxel-wise method to differentiate between spatial local ($<14\text{mm}$) and distant ($>14\text{mm}$) connectivity in rest and task-evoked BOLD fMRI data was used (Sepulcre, Liu, Talukdar, Martincorena, Yeo, and Buckner, 2010). In the present study, the neighborhood was set to the optimal threshold to segregate local and distant connectivity on each individual matrix [12 mm radius of a sphere; (Sepulcre et al., 2010)], and then group comparison analyses were conducted.

2.5.4. Post-processing analysis: training effects

We used the SPM8 software (Wellcome Department of Imaging Neuroscience, London, England) for group comparisons. First, a between-groups two-sample t -test was conducted with pre-training session data to verify that the brain responses yielded by the groups were equal (comparison: pre-training session *trained groups vs. control group*). This comparison was done separately for the local degree maps and for the distant degree maps. Then, an ANOVA 2x2 was conducted with the Experimental Group (Trained group vs. Control group) as the between-subjects factor, and Session (Pre-training session vs. Post-training session) as the within-subjects factor. The ANOVA analysis allowed studying the differences in degree connectivity between pre-training and post-training session. In this analysis we controlled for repetition effects using between-subjects controls (i.e., the data of the control group). The results of the ANOVA analysis represent the change in the number of local or distant links that a given voxel has from one session to the other. The results of all the analyses were $p < 0.05$ Family Wise Error (FWE)-voxel corrected.

2.5.5. Degree maps visualization and network layout

The Computerized Anatomical Reconstruction Toolkit (CARET, Van Essen and Dierker, 2007) was used to project the degree analysis results on the cerebral hemispheres of the PALS-B12 surface (Van Essen, 2005). The interpolated voxel algorithm and the multi-fiducial mapping of the metrics were used. The images were projected using the SPM's native space specification. A medial wall mask was also included in the projection. The data was projected using the 2% to 98% scale. This scale sorts all z -score voxel values, then the voxels with values corresponding to 2% of the lowest z -score value are set at the bottom of the scale (represented in purple), and the voxels with values corresponding to 98% of the highest z -score value are set at the top of the scale (represented in red).

With the aim of facilitating the visualization of the brain changes an overlap image of the local and the distant degree maps was created. The degree maps images were spatially smoothed with an isotropic Gaussian kernel of 6 mm full-width at half-maximum (FWHM) by means of SPM8. The projection of the data by means of the CARET software was done using the same aforementioned parameters, except for the use of a user defined scale for representing the data (70% to 98%). In the overlap image, the changes referring to local links are represented in red, in blue the distant links appear in blue, and in violet the regions showing changes in both local and distant links. Previous literature indicates that nodes displaying overlap in both local and distant links are assumed to present hybrid iFC (Sepulcre et al., 2010).

3. RESULTS

3.1. Behavioral results

Descriptive statistics of the behavioral data appears in Table I. For each behavioral measure, a repeated measures 2x2x2 ANOVA, with the Experimental Group (Trained group vs. Control group) as the between-subjects factor, and Condition (Control vs. Trained) and Session (Pre-training session vs. Post-training session) as the within-subjects factors was computed (see **Table I** and **Figure 2**).

TABLE I. Descriptive statistics of the VST behavioral data. The percentage of correct responses and the averaged median RTs followed by their standard deviations are presented per each experimental group.

	PRE-TRAINING SESSION		POST-TRAINING SESSION	
	Control condition	Trained Condition	Control condition	Trained Condition
Trained group	99.58% 447±73 ms	87.75% 919±129 ms	98.25% 398±53 ms	92.58% 630±160 ms
Control group	100% 414±64 ms	90.75% 901±126 ms	99.58% 386±51 ms	93.83% 768±145 ms

In relation to RTs values, a main effect of Session ($F(1,36)=139.89$ $p<0.001$) and a main effect of Condition ($F(1,36)=545.75$ $p<0.001$) were found, indicating that, in general, the participants were faster during the post-training session than during the pre-training session, and when performing the control condition than the trained condition. These main effects were driven by significant Group x Session ($F(1,36)=17.20$ $p<0.001$) and Group x Condition interactions ($F(1,36)=6.04$ $p=0.019$), indicating that the trained participants were faster than the control participants in regard of the different conditions of the VST or in the post-training session. Also, a significant Condition x Session interaction was found ($F(1,36)=102.83$ $p<0.001$), indicating that, in general, the participants performed faster the VST in post-training session compared to pre-training session. As expected, the Condition x Session x Group interaction was significant ($F(1,36)=15.73$ $p=0.001$), indicating that the trained participants were faster than the control participants in the post-training session compared to the pre-training session, and when the performance of the trained condition was compared to that of the control condition.

In relation to the accuracy scores, main effects of Condition ($F(1,36) = 88.01$ $p < 0.001$) and Session ($F(1,36) = 6.95$ $p = 0.012$) were found, indicating that the participants performed better the control condition than the search task, and higher accuracy scores were found in the post-training session compared to the pre-training session. These main effects were driven by a significant Condition x Session interaction ($F(1,36) = 32.03$ $p < 0.001$), indicating that, in general, the participants performed better the task in post-training session compared to pre-training session. No other effects were found to be significant.

FIGURE 2. Results of the behavioral data analysis. (A) Results of the RTs analysis and (B) of the accuracy analysis. The trained participants, compared to the controls, were faster during the post-training session than during the pre-training session. Accuracy scores of both groups remained high throughout the experiment. Values in (A) express the averaged median RTs, and in (B) the averaged correct responses (maximum score = 12) per condition and session. Error bars express SD.

3.1.1. Cross-sectional analysis results

The Cross-sectional analysis was conducted to verify that the groups had no brain response differences while performing the visual search task during the pre-training session. The between-groups *t*-test yielded no significant differences ($p < 0.05$ FWE voxel-corrected). Therefore, the subsequent between-groups brain differences were due to training effects.

FIGURE 3. Functional connectivity changes after training in VST. (A) Local and distant connectivity changes were found in an extended brain cortical surface. The trained participants, compared to the controls, had increased connectivity in lateral and medial frontoparietal regions, as well as, in the inferior occipitotemporal cortex, and in the anterior temporal pole. (B) Representation of the VST learning network created with the distant degree maps. On the right the VST learning network itself, where the brain nodes have been represented in terms of the number of functional links that they had. The nodes with greatest number of links form the hubs, and are represented in red. On the left, the network formed by the hubs is represented, and also their links. It can be observed that connectivity within this network is high. The statistical contrast of these results corresponds to: *Trained group (post-training > pre-training session) > Control group (post-training > pre-training session)*. Results are $p < 0.05$ FWE voxel-corrected. [Next page]

Connectivity changes after training in VST

3.1.2. Degree maps results

The results of the degree analyses appear in **Figure 3**. An interaction analysis was conducted for studying the brain connectivity changes due to training effects. Therefore, an ANOVA 2x2 with the Experimental Group (Trained group *vs.* Control group) as the between-subjects factor, and Session (Pre-training session *vs.* Post-training session) as the within-subjects factors was computed. Repetition effects were controlled by introducing the control group data in the analysis.

When studying the local changes (contrast: *post-training > pre-training session*) (left part of the Figure 3A), increases in the number of links were found in the occipito-temporal cortex (BA 19, 21 and 37) including left fusiform gyrus; bilateral posterior parietal cortex (PPC), including superior parietal cortex (BA 7), supramarginal gyrus (BA 40), angular gyrus (BA 39) and medial portions like precuneus and posterior cingulate gyrus; bilateral anterior temporal lobe and right posterior insular cortex; bilateral dorsomedial (mPFC, BA 8/9) bilateral dorsolateral (DLPFC BA 9 / 46) and ventral (VLPFC BA 45 / 47) prefrontal cortex. That is, the number of short links on these regions increased due to training effects (i.e., nodes within the local neighborhood). This result was $p < 0.05$ FWE voxel-corrected (with a minimum t -score = 4.98). The reverse contrast yielded no significant differences.

The changes associated with distant links were found in similar regions (contrast: *post-training > pre-training session*) (right part of the Figure 3A). In this case, increases in the number of links were extended on a greater proportion of cortical surface than on the local degree maps. The distant degree maps represent the nodes whose connectivity beyond the specified neighbor changed due to training. These increases were found in the occipital cortex (more in medial than in lateral regions), inferior temporal gyrus, PPC (including the lateral surface of the superior parietal lobule, the intraparietal sulcus, the supramarginal gyrus, and the precuneus), posterior to anterior mPFC, including supplementary and pre-supplementary motor area, DLPFC (BA 9/46), and VLPFC along with the anterior insular cortex (BA 47/ 48). This result was $p < 0.05$ FWE voxel-corrected (with a minimum t -score = 4.98). The reverse contrast yielded no significant differences.

The projection of the local and distant degree results on one overlap map, made it possible to visualize that some areas had hybrid changes (see **Figure 4**). That is, some areas had increases in short and long links, specifically the PPC (BA 7), supramarginal

gyrus (BA 40), precuneus and posterior cingulate cortex, left fusiform gyrus, posterior temporal cortex (delimited regions in superior and inferior temporal gyri), anterior temporal pole, bilateral mPFC (BA 8/9), bilateral DLPFC cortex (BA 9 / 46), a region at or near the inferior frontal gyrus pars triangularis and VLPFC (BA 47).

FIGURE 4. Overlap map of the local and distant connectivity changes. The aim of creating this projection is to assist in the visualization of brain regions showing preferentially local (projected in blue), distant (projected in red) or hybrid local and distant connectivity (projected in violet). Results are $p < 0.05$ FWE voxel-corrected. The projection has been made in the lateral and medial surfaces of left hemisphere.

4. DISCUSSION

Despite the advances made in behavioral and task-fMRI training studies, less research has been focused on exploring the effects that training has on functional connectivity. The present fMRI study focused on studying the training effects on the attention system. On the one hand, training on VST led to behavioral improvements since the trained group, compared to the control group, showed shorter RTs in post-training than in pre-training session. On the other hand, the imaging results showed increased local and distant connectivity in different frontoparietal areas.

4.1. Training effects in behavioral performance

According to previous studies, training on VST in consistent-mapping conditions might lead to developing automatic behavior, especially after completing a number of trials (i.e., 600 trials) (Shiffrin and Schneider, 1977). In the present study, the training

participants showed improved task performance after completing 840 search trials of training, and ~1200 trials in all the experiment. This improvement was observed in terms of reduced RTs, while the accuracy level kept high through the whole experiment. On the other hand, by the end of the experiment the control participants have improved a little because they have accumulated some trials (336 trials). The theoretical implications of these results are associated with controlled and automatic processing. Models of automaticity have linked the naïve performance of cognitive tasks to controlled processing, that is, when the task is performed under the supervisory and conscious attention of the subject. On the other hand, training is associated with less recruitment of the attentional control system because the performance improves, thus the behavior becomes automatic (LaBerge and Samuels, 1974; Shiffrin and Schneider, 1977; Logan, 1978; Schneider and Chein, 2003).

As aforementioned, training effects were observable on the speed response of the trained participants; in post-training session, they searched the targets significantly faster than the control participants. For instance, trained participants detected the targets ~600 ms after the search template was presented (with ~93% correct responses), which is significantly better than the control participants (~768 ms for target detection and ~94% of correct responses). In fact, trained participants reduced their response speed by 31% as a result of training. Therefore, trained participants achieved some degree of automation. Both groups obtained high accuracy scores through the experiment, and, in terms of accuracy, no significant differences were found between groups. This lack of difference could be due to the task characteristics since participants were asked to perform the task as fast as possible but without compromising their accuracy.

4.2. Training effects in brain connectivity

Our brain imaging results showed that, after training, trained participants had increased local and distant connectivity on an extended cortical surface. The changes were mostly found on brain areas that have been associated with the visual attention system (e.g., Kastner and Ungerleider, 2000). Indeed, the spatial distribution of the connectivity changes found here is similar to the ventral and dorsal visual processing streams (Deco and Rolls, 2005).

The local degree maps show the changes that each voxel has in relation to short connections. These are the changes in the connectivity within a neighborhood. On the other hand, distant degree maps reflect the changes in long connections. In our analysis, the distant degree maps show more prominent changes than the local degree maps. Whereas regions showing local changes were specific and discrete, distant changes were more spatially extended. The distinction between local and distant links make it possible to map that training effects on connectivity not only affect discrete regions but also involve long-distance connections. Areas showing both local and distant increased connectivity changes were found in: posterior parietal cortex, fusiform gyrus, posterior and anterior temporal gyrus, mPFC, DLPFC and VLPFC. Although some of these areas are part of known brain networks (Corbetta and Shulman, 2002; Dosenbach, Fair, Cohen, Schlaggar and Petersen, 2008; Power and Petersen, 2013), they do not exactly match any of them because are derived from task-data (Buckner et al., 2009). For instance, visual search tasks are usually related to the engagement of the dorsal attention and the executive control networks (Corbetta and Shulman, 2002; Shulman, McAvoy, Cowan, Astafiev, Tansy, d'Avossa et al., 2003; Cole and Schneider, 2007). However, different tasks generate slight differences in the recruitment of the task-dependent brain regions/networks (Cole, Reynolds, Power, Repovs, Anticevic, and Braver, 2013; Zanto and Gazzaley, 2013). Furthermore, individual differences in behavioral performance influence the engagement of the frontoparietal network (Wen, Yao, Liu and Ding, 2012).

The connectivity changes observed here might be associated with a specific VST functional network. Considering that the changes affected a wide variety of brain areas, the development of expertise performance had a complex effect on attention, control and task-specific systems. To note that working memory components are also involved during VST performance, and some areas have both attention and memory-related roles (Eimer, 2014). It is the case of the PPC and the DLPFC. On the one hand, the PPC has been widely associated with the control of attention by means of priority maps, where bottom-up and top-down information converge and the focus of attention is biased to complete the task goals (Deco and Rolls, 2005; Ipata, Gee, Bisley and Goldberg, 2009; Bisley and Goldberg, 2010). On the other hand, the PPC has also been related to the maintenance of task rules and the specific features of the visual objects (Ester, Sprague and Serences, 2015; Rasposo, Kaufman and Churchland, 2014). Meanwhile, the DLPFC transforms the representations of the visual stimuli in memory traces, which can be sustained over time

according to the task demands, and then in action representations for task performance (Cole and Schneider, 2007). But the DLPFC has also been related to target detection, it is a source of top-down attentional control because has cognitive information about the target, which is sent to PPC and other association areas (Bisley and Goldber, 2010; Noudoost, Chan, Steinmetz and Moore, 2010; Katsuki and Constantinidis, 2012). Thus, it could be said that training on the VST mainly affects the attentional control system, but other systems might change.

Other studies have found increases in functional connectivity, most of them using resting-state data. For instance, intensive training on a visuomotor tracking task led to increased connectivity between the left frontoparietal areas (inferior and superior PPC, medial and lateral prefrontal cortex), crus II of the cerebellum, and left middle to inferior occipitotemporal regions (Albert, Robertson and Miall, 2009). Similarly, after training in a dynamic balancing motor task, it was found increased connectivity between some key brain regions for motor learning (i.e., pre-supplementary and supplementary motor areas and ventral premotor cortex), and between these regions and frontoparietal areas (e.g., orbitofrontal cortex, DLPFC, medial parietal cortex) (Taubert, Lohman, Margulies, Villringer and Ragert, 2011). A more complex pattern of connectivity changes was found after visual perceptual training. The trained area of the occipital cortex had increased negative correlation with cortical areas of the dorsal attention network, but decreased negative correlation with areas of the default mode network (Lewis, Baldassarre, Committeri, Romani and Corbetta, 2009). Functional connectivity changes in task-data have also been observed, for example, when studying the imaging data derived from the performance of the dual 2-back condition. In this case increased within-network and between-network connectivity were found in the executive control and the dorsal attention network after training (Thompson, Waksom and Gabrieli, 2016).

Overall, training effects on brain functioning are not only related to behavioral performance or enhanced connectivity between task-dependent regions. Improved cognitive efficiency have also been associated with decreased activation of frontoparietal areas whose role is related to the attentional control system (Chein and Schneider, 2005; Kübler et al., 2006; Bueichekú et al., 2016). Therefore, training on a cognitive leads to a general system improvement, that is, the automatic behavior entails increased connectivity between brain key regions for task performance but decreased brain activity on those regions.

5. CONCLUSIONS

In this study, task automaticity was achieved after the completion of an intensive training. Improved behavioral performance along with increased brain connectivity were observed in post-training session. The degree maps showed the distribution of the connectivity changes, which were mostly located in the brain areas associated with the performance of the VST. A general improvement on the efficiency of the attentional control system might explain the observed changes.

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Chapter 3. Discussion

The main objective of this thesis was to study the behavior and brain basis of the visual search processes. In order to accomplish this objective, we used the visual search task as the experimental paradigm and collected behavioral and brain data by means of fMRI. This thesis is composed of three experimental studies. The aim of the first study was to investigate the visual search task's underlying processes, including those associated with the categorization effect. The objective of the second study was to investigate the behavior and brain effects related to the development of automatic processing by training on a cognitive task, in our case, the visual search task. Finally, the objective of the third study was to investigate the changes in brain networks due to automaticity.

The visual search task has been widely used to study the visual attention system (Treisman and Gelade, 1980; Eckstein, 2011; Buschman and Kastner, 2015). Visual search has also been used to study the underlying brain processes that flow during visual information processing (Shiffrin and Schneider 1977; Kastner and Ungerleider, 2000) and the different selective attention processes (Eimer, 2014). Therefore, the visual search task seemed a suitable paradigm to accomplish our objectives and to study the visual attention system. This paradigm allowed us to contribute more empirical data to the visual attention theoretical models (e.g., Serences and Yantis, 2006; Deco and Rolls, 2005; Bisley and Goldberg 2010) and neuroplasticity theories (e.g., Kelly and Garavan, 2005; Chein and Schneider, 2012; Kelly and Castellanos, 2014). Lastly, our general objective was to contribute more empirical evidence to the attention field of knowledge. When we considered the studies in this thesis, we were thinking that a better understanding of the healthy human brain is needed. This could benefit the development of neuropsychological theories and neurorehabilitation programs in the future, thus improving the neuropsychological procedures.

1. The relationship between the visual search task, visual attention cerebral areas, the categorization effect, and the selective attention theories

In the first study presented in this thesis, we hypothesized that our visual search task would engage brain areas previously related to the visual attention system. The task involved an experimental method that allowed the study the categorization effect. Previous studies have found that the attention system is related to a variety of cortical areas, including the occipital cortex, PPC, FEF, aI/VLPFC, dACC and DLPFC; and, subcortically: the thalamus and the SC (Kastner and Ungerleider, 2000; Corbetta and Shulman, 2002; Cohen et al., 2009; Bisley and Goldberg, 2010; Eckstein, 2011; Saalmann and Kastner, 2011; Kim et al., 2012; Petersen and Posner, 2012; Zénon and Krauzlis, 2012; Krauzlis et al., 2013; Squire et al., 2013; Purcell et al., 2013; Eimer, 2014; Humphreys and Lambon Ralph, 2014; Peleen and Kastner, 2014; Buschman and Kastner, 2015; Cieslik et al., 2015; Katsuki and Constantinidis, 2015; Wimmer et al., 2015). Our fMRI data analysis results confirmed our hypothesis. We found that the visual search task is supported by a functional network that involves the occipital cortex, PPC (both inferior and superior parietal lobules), FEF, insular cortex, frontal areas like dACC, DLPFC and inferior frontal gyrus, and subcortically the thalamus and the SC.

The categorization effect is observed while performing a search in which both the target and the surrounding stimuli (i.e., distractors) belong to the same category of elements (Brand, 1971; Ingling, 1971). The similarity between targets and distractors is supposed to require greater attentional resources than searches where targets and distractors do not pertain to the same category. This assumption is made because worse performance is usually found in within-category searches than in between-category searches, as the former are more complex than the latter. Accordingly, we predicted that if the categorization effect has a behavioral component, it should also have a cerebral correlate. We predicted that it would give rise to greater activation in the frontoparietal attention areas associated with the performance of the visual search task under the within-category search condition.

We found that the categorization effect modifies the strength with which the PPC, FEF, aI/VLPFC, dACC and DLPFC are engaged. In within-category search conditions, lower correct hits and longer reaction times, along with greater brain activity, were found

in the aforementioned cortical areas. Both the worse performance and the increased brain activity support the hypothesis that more attentional resources are needed in complex visual scenes; for instance, when the targets and the distractors are visually similar as compared to when they are totally dissimilar. In turn, the “pop-out” effect was consistently found when the targets and the distractors did not belong to the same category. “Pop-out” or between-category searches were associated with better performance scores and less involvement of the attention-related brain areas.

In relation to visual attention, the PPC, FEF and DLPFC (BA 46) have been related to different attentional functions. Along with the SC, the PPC and FEF have been proposed as having priority maps that bias the focus of attention, moving it through the space (Serences and Yantis, 2006; Bisley and Goldberg, 2010; Krauzlis et al., 2013; Zelinsky and Bisley, 2015). The priority maps are convergence areas where bottom-up (e.g., objects features like color, shape, and orientation) and top-down information (e.g., the identity of the relevant stimuli and the saccadic information to locate it) about the context meet. Each and every point on a priority map represents the objects and locations of the space according to their relevance for completing the task (Bisley and Goldberg, 2010; Bisley, 2011). The DLPFC attention functions have been related to top-down control of behavior over the dorsal and ventral stream pathways (Noudoost et al., 2010). Recent investigations have linked the attentional control functions of the DLPFC to the priority map theory, as the DLPFC neurons respond like the PPC neurons when relevant stimuli are present (Katsuki and Constantinidis, 2012).

Early models of attention proposed that attention changed from a wide to a narrow focus with the aim of identifying the objects in specific spaces (e.g., Treisman and Gelade, 1980). The Feature Integration Model excelled in explaining how an object was identified. However, a better explanation was offered by models that took into account the changes in the attentional focus. Before a detection occurred, the focus of attention had to be moved through the visual scene, from one location to another, and then narrowed until identifying the target, thus overcoming the interferences of others signals. This idea is included in both the Posner and Petersen model (1990) and in priority map models (Feacteau and Munoz, 2006; Serences and Yantis, 2006; Bisley and Goldberg, 2010). Under the winner-take-all rule, the place on the map that has the greatest priority value gains the whole focus of attention (Fectau and Munoz, 2006; Serences and Yantis, 2006; Bisley and Goldberg, 2010), and if the object located at that place does not match the

target, the inhibition of return mechanism is used to suppress that location and lower its priority value, not visiting it again in that search (Koch and Ullman, 1985; Itti and Koch, 2000; Bisley and Golberg, 2010).

This process could explain why in within-category searches reaction times are longer and attention demands are higher than in between-category searches. Before the attention processes really start, and according to inherited early conceptions, all the stimuli features would be pre-attentively processed (Treisman, 1977; Treisman and Gelade, 1980). Then, bottom-up information and top-down information would be sent to the PPC, FEF and DLPFC, which have the priority values of each object/location (Fectau and Munoz, 2006; Serences and Yantis, 2006; Bisley and Goldberg, 2010). In within-category searches, the priority values assigned to each object must be quite similar because all the objects are alike. Therefore, various locations on the priority map could be selected and suppressed until a match between the cognitive target and the real object was found. Therefore, this process will result in the categorization effect (i.e., longer reaction times). On the other hand, on between-category searches, priority values from one object to another would be similar, except for one, which would probably correspond to an object from another category. This object from another category would be highly salient and would probably correspond to the cognitive target. Pre-attentively and from bottom-up processing, this object would have a different value (i.e. higher value) than the other objects. The focus of attention would be directed first toward this object, thus creating a “pop-out” effect (i.e., fast detection).

The only concern with priority map models is that recent findings claim that the focus of the attention can be sustained in one location processing one object, while still scanning the rest of the space (Busch and van Rullen, 2010; Buschman and Kastner, 2015). Neurocomputational models of selective attention, like the Biased Competition Model, argue that the multiple objects in the context can concurrently be processed by different populations of neurons (Deco and Rolls, 2005). Thus, a better explanation of how the visual information processing occurs is offered, but more integration between theories is needed.

2. Validity of rs-fcMRI in predicting behavioral differences in task performance and studying the top-down control of attention

Previous studies have successfully used rs-fcMRI techniques to predict individual differences related to performing cognitive tasks through cerebral measures (Hampson et al., 2006; Baldassarre et al., 2012; Sala-Llloch et al., 2012; Hamerlech and Malach, 2013; Ventura-Campos et al., 2013). In these studies, perception, memory, language or intelligence tasks were used to collect data that reflect how people differ. Along with behavioral data, measures of the brain activity in resting state conditions (i.e., unbiased by task stimulation and performance) were collected and then correlated with the behavioral data (Hampson et al., 2006; Baldassarre et al., 2012; Sala-Llloch et al., 2012; Hamerlech and Malach, 2013; Ventura-Campos et al., 2013).

Predictions about individual differences between rs-fcMRI data and behavioral data are usually formulated in relation to the effects studied. For instance, in Ventura-Campos and colleagues (2013), a group of healthy participants were trained on a phoneme identification task. Task-fMRI and rs-fMRI measures, along with behavioral learning rate measures, were collected. Participants were trained in identifying non-native phonemes from Hindi. The experimental paradigm compared the brain responses elicited when listening to native and non-native phonemes. Functional MRI served to localize the most relevant areas to perform the task, which were the left aI, left SPL, and left supramarginal gyrus. The rs-fcMRI data from the ROIs were correlated along with the learning rates, which were introduced in the analyses as regressors. Among other results, findings showed that connectivity between the left SPL and left aI in the pre-training session predicted the capacity for phonetic learning.

Similarly, we hypothesized that the study of the rs-fcMRI patterns of the visual occipital cortex, PPC (i.e., SPL), FEF, aI/VLPFC, dACC and DLPFC (BA 46) would predict the possible behavioral differences found in the data of the participants who completed the visual search task. Similar to previous research approaches, we used fMRI to locate the relevant brain areas involved in visual search task performance and then studied the connectivity of the SPL, which is a core region in visual attention tasks, with all the other brain regions. Our hypothesis was confirmed only by the pattern of connectivity found between the SPL and V1 when the response speed variable was

introduced in the regression analysis. Specifically, we found that the participants who gave faster responses during within-category searches, compared to between-category searches, had more correlated connectivity between SPL and V1. In turn, the slowest participants had more anticorrelated connectivity between these two areas (e.g., asynchronous activity). Rs-fcMRI data were obtained before the participants performed the visual search task. Therefore, the functional connectivity between the SPL and V1 at rest predicted the visual search efficiency.

According to the Biased Competition Model, during the visual processing of a scene, selective attention operates under top-down attentional control (Deco and Rolls, 2005). The model postulates that, although visual scenes are perceptually processed in the visual occipital cortex, some groups of neurons outside the occipital cortex are responsible for biasing the focus of attention. These neurons are located in the DLPFC and IT and communicate with the occipital cortex through the SPL. Two streams of top-down bias were specified: the dorsal stream, running from the DLPFC to SPL and V1; and the ventral stream, running from the IT to SPL and V1. Whereas the dorsal stream is engaged when the location of a target must be found, the ventral stream is related to the process of identifying an object in a specific space. In any case, both streams send information to each other because they converge in the early occipital cortex areas (Deco and Lee, 2004).

During search tasks where the target identity is known but not its location, the dorsal stream is engaged (Corbetta and Shulman, 2002; Deco and Rolls, 2005). It is important to note that the SPL is a key region during visual attention tasks because of its priority map, specifically, because it handles the top-down information coming from frontal areas (e.g., target identity) and the bottom-up information coming from early visual areas (e.g., visual stimuli features) (Fectau and Munoz, 2006; Serences and Yantis, 2006; Bisley and Goldberg, 2010; Noudoost et al., 2010). It is not surprising that the connectivity between the SPL and V1 predicts the performance on the search task: the SPL has the priority maps, and the dorsal stream is crucial for biasing the attention focus during the search for the target.

When studying the SPL connectivity with all the other areas of the brain, a broad cortical network of areas fluctuating synchronously was found. Either left or right SPL establishes connections with FG, IT, DLPFC, SMA and FEF. This network very much resembles the cerebral areas recruited during the performance of visual attention tasks.

However, bearing in mind the characteristics of the task (i.e., known identity but unknown location), it is understandable that we did not find any other pattern of connectivity that predicted the individual differences in task performance apart from the dorsal stream engagement, because the dorsal stream is the most related to the performance of the visual search task (Hopfinger et al., 2000; Corbetta and Shulman, 2002; Eimer, 2014).

3. Automaticity of the visual search task: behavioral and brain changes

In the second study presented in this thesis, we used a visual search task to longitudinally study the cerebral changes associated with developing automatic behavior. A pre-post fMRI study was completed by a group of healthy participants, who were randomly distributed in a trained group and a control group. An intensive training between the scanning sessions was completed by the trained group participants. According to previous literature, we hypothesized that intensive training in the visual search task would lead to automation of the task performance in terms of faster responses and better accuracy scores to trained stimuli than to untrained stimuli. We expected that the automatic processing would be observable in trained participants compared to control participants. Our hypothesis was confirmed because we found that trained participants improved their performance on the visual search task as a result of training. Specifically, when comparing the pre-training to the post-training session, trained participants produced faster responses than controls to trained stimuli. Moreover, the trained group's responses to trained stimuli were faster than those given to the untrained stimuli.

Two-process models of automaticity defend that a change from controlled to automatic information processing is achievable by practicing a task in constant conditions (Shiffrin and Schneider, 1977; Logan, 1978 and 1979; Schneider and Fisk, 1982). The change is noticeable when the performance improves on the visual search task. It usually involves a decrease in the reaction time values, and an improvement in the accuracy scores (Shiffrin and Schneider, 1977). In our study, both groups had high accuracy scores during the pre-training session and maintained their level of performance during the post-training session. However, after completing the intensive training session, the trained

participants produced faster responses to the trained stimuli in the post-training session, indicating that a certain degree of automaticity had been achieved. However, improvement of performance in the control group would imply a certain degree of automation.

These theoretical models of automaticity, predicted that automatic processing leads to less use of the attention system and no need for the subject's supervisory control (LaBerge and Samuels, 1974; Shiffrin and Schneider, 1977; Logan, 1978; Fisk and Schneider, 1982; Schneider and Chein, 2003). More recent fMRI studies are beginning to provide evidence for this prediction by studying the effects on training in cognitive tasks. Training has been found to lead to changes in the cerebral function (Kelly and Garavan, 2005). Accordingly, we hypothesized that changes in the functional organization of the brain's visual attention system should occur after training in the visual search task. We predicted that the brain processes underlying the behavioral automation of the task would show decreased activation after training.

In our study, we studied the effects of training with pre-post comparisons and included between-subjects controls (i.e., the control group data). We found an activation reduction solely in the PPC, but not in any frontal areas, partially confirming our prediction. Then, the post-training brain activations associated with the trained condition were studied with within-subjects conditions (i.e., the untrained condition data). Reductions in activation were found in the PPC and inferior occipital cortex areas, including bilateral FG (BA 19 and 37). That is, after training, these areas were less engaged than before training. Reduced activation in occipital areas has been linked to the repetition suppression process; that is, the neurons became adapted to the task rules, stimuli's features, and the stimulus-response relations (Wiggs and Martin, 1998; Grill-Spector and Malach, 2001; Larsson and Smith, 2012). These results could indicate that training on the visual search task led to an increase in the neural efficiency of the PPC, bilateral FG and inferior occipital cortex. These results agree with the early two-process models predictions, which foresee that training leads to improved information processing (Shiffrin and Schneider, 1977; Logan, 1978 and 1979; Schneider and Fisk, 1982).

In addition, we found similar results to previous visuo-spatial search task-fMRI training studies when we performed similar statical comparisons that did not include between-subjects controls (e.g., Kübler et al., 2006). The pre-post comparisons of the

trained condition data showed a general pattern of decreased activation in the areas commonly involved in the visual search task, specifically in frontal areas like the DLPFC, precentral gyrus, SMA/dACC, VLPFC/aI and posterior areas like PPC, superior and inferior occipital gyrus, and FG. Decreased activations in frontal and posterior areas were also found after analyzing the untrained condition data (SMA / dorsal ACC, IFC, precentral gyrus, VLPFC/aI, PPC). Therefore, without including control group data, the study of the training effects in pre-post comparisons is less clear. We found a general and broad decreased activation of the attention control system. Therefore, using the method of Kübler et al. (2006), we could be mixing effects that are related to repeating the task twice with true training effects. On the other hand, as we used between-subjects and within-subjects control measures, we were able to differentiate between repeating and training effects. Both repeating and training a task lead to a decrease in activation. However, training has specific effects. It changed the activity of the PPC, an area that is relevant for visual attention tasks, and in bilateral FG and inferior occipital gyrus (BA 19 and 37).

The PPC has been related to numerous cognitive functions. Depending on the PPC region, this area supports attention, praxis, verbal or calculation functions (Humphreys and Lambon Ralph, 2014). The IPS and SPL constitute the dorsal parietal cortex and have been associated with the top-down attentional control. On the other hand, the supramarginal gyrus has been related to bottom-up control of attention and detection of relevant stimuli (Cabeza, Ciaramelli, Olson and Moscovitch, 2008; Humphreys and Lambon Ralph, 2014). In our visual search task training study, training was consistently found to affect the PPC (BA 7/40). This region extended from the SPL to the supramarginal gyrus, including IPS, not only implicating attention-related functions, but also, implicating working memory system or the mnemonic representations of the visual objects, especially the trained targets which became relevant after training (Cabeza, et al., 2008; Humphreys and Lambon Ralph, 2014; Sarma et al., 2016). In general, the PPC has been proposed as an area that supports the general processing system (Humphreys and Lambon Ralph, 2014).

It is interesting that we found the PPC to be related to the training effects. These results may give more strength to the view that the PPC is a central region during the performance of visual attention tasks, and support the importance of the priority map theory. Then, we also found changes in the inferior occipital gyrus that could be linked

to the PPC. On visual search tasks designed to investigate the priority map function, it has been observed that occipital gyrus neurons do not respond to task demands as the PPC does; the PPC responds more to targets than the occipital gyrus (Ipata et al., 2006; Buschman and Miller, 2007; Thomas and Paré, 2007; Mirpour et al., 2009). The decreased activation in occipital gyrus areas could be explained by repetition suppression mechanisms (Wiggs and Martin, 1998; Mukai et al., 2007). Repetition suppression may reflect neuronal adaptation. But, according to some theories, repetition suppression could be an effect of attention modulation (Guggenmos et al., 2015). As PPC can exert control over occipital gyrus areas, changes in occipital gyrus could be due to attentional modulation (Lee, Yang, Romero and Mumford, 2002; Deco and Rolls, 2005). In turn, attentional modulation might be an effect of training, which was consistently related to the PPC. The training could have led to a reduction in attentional control, which in turn could be related to improved neural efficiency or a more precise neural circuit (Garavan et al., 2000; Jonides, 2004; Kelly and Garavan, 2005).

4. Intrinsic functional connectivity brain changes after training in visual search task.

The aim of the third study was to investigate the changes in brain networks due to cognitive training. Based on previous literature we started from the hypothesis that training in visual search task leads to performing the task through automatic processing (Shiffrin and Schneider, 1977). Functional MRI studies have found that training in cognitive tasks leads to reduced brain activity, which should be accompanied by increased connectivity (Büchel, Coul and Friston, 1999). The brain changes after cognitive training are supposed to reflect increased neural efficiency (Kelly and Garavan, 2005).

At the behavioral level, as in the second study, we hypothesized that trained participants would improve their performance in terms of faster responses and better accuracy scores on trained stimuli. At the behavioral level, results were similar to those found in the second study as well as their discussion. Training effects were observable in the response speed, but not in the accuracy, as the latter remained high. Therefore, our hypothesis was partly confirmed. This effect may be due to both the instructions that the

participants received and their own behavior. Participants were asked to answer as fast as possible but without compromising their accuracy. Thus, they made sure they gave the correct answer on each trial, and therefore, yielded slow responses at the beginning of the experiment. During the post-training session, both groups continued to have high accuracy responses, but training made trained participants significantly faster than controls, who became slightly faster (e.g., were getting used to the task). Previous visual search training studies have found shorter reaction time values and associated this behavioral effect with automation (Shiffrin and Schneider, 1977). The theoretical implications of these behavioral results have already been discussed in the previous section; thus, the effects of training on the brain networks are now discussed.

In relation to brain connectivity, we predicted that the cerebral areas related to the attention-control system would exhibit an increased number of local and distant functional connections after training. As the visual search task is supported by this system, an enhancement of its functional connectivity was expected after training. Our results confirmed this hypothesis, as local and distant degree maps showed an increased number of connections in a diverse range of cortical areas. Moreover, local and distant degree maps were coherent. That is, connectivity changes were observed in areas that are central to the performance of the visual search task, as the mean global network depicted.

Contrary to the brain activation changes, connectivity changes were broad, even when including between-subjects control measures (i.e., control group data). Brain areas showing increased connectivity after training were located in the parietal, temporal and frontal cortices. Some of them have attention and control processes roles: PPC, DLFPC and VLPFC. These areas have been included as part of known brain networks, for instance, the DAN, CON or FPN (Corbetta and Shulman, 2002; Dosenbach et al., 2008; Power and Petersen, 2013). Thus, the observed changes (e.g., implying broad brain cortical surface) may support the notion that task-networks do not necessarily need to match resting-state connectivity networks (Buckner et al., 2009). The results we obtained seem to reflect the general change in the brain network that supports the performance of the visual search task. It seems that cognitive training leads to a general increased brain efficiency, at least in relation to attention and control processes, or in relation to a “visual search task network”.

Other fMRI studies have found increased connectivity in different brain regions after training. This is the case of both sensorimotor and cognitive tasks (Taubert, Lohman,

Margulies, Villinger and Ranger, 2011; Lewis, Baldassarre, Committeri, Romani and Corbetta, 2009; Thompson, Waskom and Gabrieli, 2016). The fact that different studies obtain results in the same direction could indicate that increased connectivity facilitates information processing (Lewis et al., 2009). Most of the areas that showed local and/or distant link changes have been related to visual processing, attention and control systems. In turn, all of them are found to be active during visual search task performance. In general, it seems that training leads to an increased coherence between the neural activity of the attention and control networks. In terms of connectivity, the general effect of training could be summarized as allowing that the different areas that compose the “visual search task network” to work better together because they had more connections between them and with the other cortical areas.

5. General conclusions

After the studies presented in this thesis, the conclusions are:

1. Visual search task performance engages the visual, attention and control brain systems. The cortical areas supporting the performance of this task are: the occipital cortex, PPC, FEF, aI/VLPFC, dACC and DLPFC, and subcortically, the thalamus and the SC.
2. Processing of complex visual scenes requires increases in the brain activity and affects the behavioral performance. The categorization effect is an example of a visual complex scene. The visual search task allows us to study this effect.
 - A) Searching for a target among similar objects (i.e., within-category search) generates greater brain activity than searching among dissimilar objects (i.e., between-category search). This is the categorization effect. Increased brain activity of the attention and control systems is observable during this effect (i.e., frontoparietal areas: PPC, FEF, aI/VLPFC, dACC and DLPFC).

- B) Within-category search leads to slower responses than between-category search. Individual differences in task performance are predictable through the study of rs-fcMRI patterns. The PPC-V1 connectivity pattern predicts individual differences (e.g., faster participants during complex search have more correlated PPC-V1 connectivity than slower participants). The PPC exerts top-down control over early occipital areas, biasing the focus of attention during the visual search task performance.
3. Training on the visual search task leads to behavioral improvement. After a short but intensive training (840 trials in 30 minutes approximately), cognitive training allows a person to be able to perform a task faster. Importantly, the person is able to perform the task correctly (not worse). The effects of training are not transferable; even though the untrained condition was an identical visual search task that only differed on the targets.
4. Training on the visual search task also leads to brain changes. Cognitive training leads to improvement in neural efficiency. Training effects are different from repetition effects, although both move in the same direction. After training, key areas for task performance show decreased neural activity. The underlying network supporting the visual search task shows increased connectivity, in terms of number of connections.
- A) In terms of brain activation, both training and repeating a task lead to decreased brain activity. However, the effect of training is consistently related to the PPC; which has a key role during the performance of visual attention tasks. The PPC is an association area that supports the formation of priority maps. It controls the flow of information by combining bottom-up and top-down information. The focus of attention is biased, using the priority maps and both sensorial and cognitive information.

- B) After training, decreased brain activity is also found in some areas of the inferior occipital cortex. This change seems to be related to repetition suppression and/or attentional modulation processes. The PPC could actually be modulating the inferior occipital cortex. Therefore, the specific brain activation changes could be indicating less recruitment of the attentional control system.

- C) After training, the PPC, middle prefrontal cortex, VLPFC and DLPFC show an increased number of short and long functional connections, as the local and distant degree maps depicted. These areas are related to attentional control processes and seem to form a specific visual search task network.

Chapter 4. Future lines of research

The studies included in this thesis have allowed us to study the behavioral and brain basis associated with the performance of the visual search task. We have studied the categorization effect, the development of automaticity, and the brain activation and network correlates associated with this task. We have used a controlled experimental setting, but incorporating realistic stimuli by using alphanumeric stimuli instead of arbitrary forms. The main challenge for visual search related researches is definitely to incorporate real-world scenes into the search paradigm, as some authors have started to investigate (Peleen and Kastner, 2014).

Some experimental issues related to the visual attention system have yet to be explored. In addition, the relationship between visual search, working memory and other high-order cognitive functions could be further studied by means of fMRI. Some of the experimental questions that could be answered are listed below.

- 1) To adapt the visual search task to a mixed block/event-related fMRI design. Block designs have the advantage of enhancing the neural response associated with the performance of a task. Due to averaging across trials, block designs provide adequate signal-to-noise ratio data. However, mixed block/event-related designs make it possible to separate the different task signals: start/cue signal, task signal and self-monitoring signal. Therefore, this type of design clarifies the different processes involved in a specific task (Dosenbach et al., 2006; Petersen et al., 2012).
- A) On the one hand, a mixed block/event-related design would be useful to study the processes that have been related to the performance of the visual search task (Eimer, 2014). The visual search task is thought to involve four stages: 1) a preparation stage 2) a guidance stage; 3) a selection stage and; 4) an identification stage. This approach is based on segregation principles, as the response of each brain region could be related to the process that supports it.

- B) On the other hand, applying trending analysis techniques (e.g., graph theory) could add more empirical data to the information processing models of attention (Deco and Rolls, 2005; Bisley and Goldberg, 2010). For instance, the exact flow of information during a visual search task could be mapped by means of step-wise connectivity methods (Sepulcre, Sabuncu, Yeo, Liu and Johnson, 2012). Thus, analysis based on integration principles would make it possible to verify theoretical models that make predictions about visual attention information processing.
- 2) To use the methodology presented in this thesis to study other high-order cognitive functions such as the working memory system and the control system.
- A) Some neuroimaging studies have explored the changes in the working memory system due to training. Most of these studies use long-term training programs and pure working memory tasks (i.e., n-back task). This approach has made it possible to elucidate the effects that training in working memory has in the brain. For instance, Thompson et al. (2016) were able to dissociate the role of the FPN and DAN in executive control; only the DAN is related to the working memory load. In addition, they studied the connectivity changes in these networks in relation to n-back load and training. However, working memory becomes involved during the performance of cognitive tasks (i.e., visual search task, Eimer, 2014). There are fewer or no training studies that have explored the changes and implications of the working memory system during the performance of other high-order cognitive tasks.
- B) On the other hand, the number of studies that have combined multiple tasks and studied the training effects in the brain remains low. For instance, Garner and Dux (2015) studied the effects of training in the frontoparietal and subcortical systems. Multitask paradigms allow us to study the control system while involving different sensorimotor or cognitive systems. Usually, simple tasks are used in these paradigms. However, it is also important to know what happens in the brain activity and networks when high-order cognitive functions are involved, and in turn, whether complex tasks need to be

automatized in order to be performed simultaneously with simple tasks. How this process occurs and how the brain changes are relevant questions to understand the brain's functioning in complex situations.

- 3) To increase the translation from basic to applied neuroimaging investigations. Cognitive training effects are usually studied with healthy population. It is a good point of departure as models of brain functioning can be developed by studying the intact brain. However, preventive and neurorehabilitation studies with elderly and clinical population are still scarce. For instance, the benefits of visual search and visuo-spatial training for the attention system could be explored. Thus, the results from this kind of research could improve cognitive training and rehabilitation programs.

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