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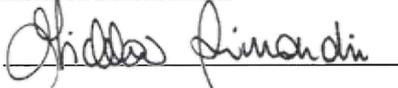
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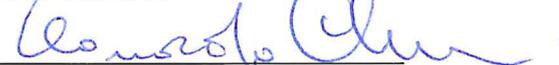
*The complex interaction between different attentional control mechanisms during
visual search*

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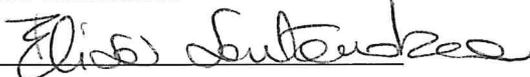
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*The complex interaction between different attentional control mechanisms
during visual search*

Carola Dolci

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RIASSUNTO

Il cervello elabora selettivamente le informazioni sensoriali in entrata e sviluppa un'adeguata programmazione motoria mirata ad oggetti con una rilevanza comportamentale nell'ambiente, sulla base di diversi meccanismi di controllo dell'attenzione (CA). Il contributo dei singoli meccanismi di CA all'attenzione visiva è stato indagato estensivamente; tuttavia, resta da chiarire come i diversi segnali di priorità interagiscano tra loro per giungere alla "scelta finale" riguardo alla posizione spaziale (o allo stimolo) che meriti attenzione. L'obiettivo principale del mio progetto di dottorato è stato quello di indagare se i diversi meccanismi agiscano congiuntamente per modificare la priorità di determinati stimoli o posizioni spaziali o se, in un dato momento, un meccanismo prevalga sugli altri, ottenendo la precedenza sulla rappresentazione neurale dello spazio visivo, nota come mappa di priorità spaziale. Utilizzando varianti dello stesso compito di ricerca visiva, abbiamo implementato una serie di esperimenti comportamentali ed EEG per testare l'effetto singolo e combinato di due meccanismi CA: controllo top-down, modulato tramite una cue endogena (valida vs. neutra), ed experience-dependent, modulato con un protocollo di apprendimento statistico (SL) (posizioni ad alta vs. bassa frequenza di comparsa del target). I risultati hanno rivelato che sia il controllo top-down che lo SL producevano prestazioni migliori rispettivamente per target preceduti da una cue valida (rispetto alla neutra) e per quelli presentati nella posizione alta-frequenza (rispetto a bassa-frequenza). Il vantaggio del controllo top-down è stato anche confermato da un'ampiezza maggiore di CNV e P1, i marcatori EEG rispettivamente ritenuti indici di preparazione generale e categorizzazione precoce per la selezione dello stimolo bersaglio. Aspetto importante, quando attivati insieme, il controllo top-down e lo SL mostrano un'interazione interessante, con l'effetto comportamentale dell'ultimo meccanismo che viene annullato dalla presenza del primo. Tuttavia, in termini di N2pc, un marker EEG di selezione, l'effetto della cue emergeva solo per target presentati nella posizione a bassa-frequenza, suggerendo che, anche se non visibile dal punto di vista comportamentale, l'effetto SL non era totalmente bloccato dal controllo top-down; piuttosto, poteva influenzare l'orientamento dell'attenzione, almeno ad un certo punto del processo di selezione del bersaglio.

Infine, nel nostro compito, abbiamo potuto rilevare indirettamente l'impatto di un distrattore saliente sulla prestazione dei partecipanti; questo segnale di controllo bottom-up effettivamente distraeva l'attenzione dal bersaglio e interferiva con il compito, indipendentemente dalla presenza o assenza degli altri meccanismi di CA.

SUMMARY

The brain selectively processes incoming sensory information and plans adequate motor output aimed at behaviourally relevant objects in the environment, based on different attentional control (AC) mechanisms. The contribution of single AC mechanisms to visual attention has been extensively investigated; still, it remains unclear how those different biasing signals interact with one another in order to reach the final choice of which spatial location (or stimulus) is worth of attention. The main goal of my PhD project was to investigate whether different AC mechanisms jointly act to shape priority of given stimuli and locations or whether, at any given moment, one mechanism prevails over the others, gaining precedence onto the neural representation of the visual space, known as spatial priority map. By using variants of the same visual search task, we implemented a series of behavioural and EEG experiments to test the unique and combined effect of two AC mechanisms: top-down control, modulated via endogenous cueing (valid vs. neutral cues), and experience-dependent control, implemented through a statistical learning (SL) protocol (high vs. low target frequency locations). Our results revealed that both cue validity and SL enhanced performance respectively for targets predicted by valid (vs. neutral) cue and for targets at high (vs. low) frequency locations. The benefit of top-down control was also confirmed by larger CNV and P1, i.e. EEG markers of general preparation and early categorization for target selection, respectively. Most importantly, when activated together, top-down control and SL display an interesting interaction, with the behavioural effect of the latter being overridden by the presence of the former. However, in terms of N2pc, an EEG index of selection, the cueing effect selectively emerged for targets in the low- (vs. high) frequency location, suggesting that, even if not behaviourally evident, the SL effect was not totally blocked by top-down guidance; rather, it could affect attentional deployment, at least at some point of the target selection process. Finally, in our tasks, we could also indirectly assess the impact of a salient distractor on individuals' performance; this irrelevant bottom-up AC signal indeed diverted attention from the target and interfered with the task, regardless of the presence or absence of the other AC mechanisms.

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1 GENERAL INTRODUCTION

1.1 Visual spatial attention

The external environment where we live is constituted by a large number of sensory inputs that greatly exceed our cognitive capacities. Our brain has indeed a fixed amount of overall available energy and, since neural activity has a high-energy cost, it is not able to manage detailed processing of all the available elements at once (Carrasco, 2011; Attwell & Laughlin, 2001). To perceive everything, without any type of selection, would lead to a form of paralysis, where our brain would be overwhelmed by a huge amount of information and we would be unable to focus and to achieve our objectives (Carrasco, 2011). It is therefore important to assign processing priority to only one or few stimuli that will become the actual targets in the planning of adequate behaviours to reach our goals, at the expense of other stimuli that are not relevant.

In the visual domain, *visual attention* is the cognitive function that acts as a filter allowing us to select relevant visual input and in the meanwhile to tune out the irrelevant one, by focusing on a certain spatial location or aspect of the surrounding environment (Desimone & Duncan, 1995; Reynolds & Chelazzi, 2004; Chelazzi et al., 2011; Carrasco, 2011). Visual attention can also be seen as a zoom lens, that highlights a specific region of space (Eriksen & St. James, 1986). The latter can have varying dimensions, but with an ensuing impact on the efficiency of attention: as a matter of fact, the larger is the portion of the visual field where attention is distributed, the greater is the loss in spatial resolution for the processing of each sub-region. Indeed, a reduction in neural activity elicited by each region has been shown within the visual cortex when attention is concentrated on a larger, compared with a smaller, spatial region (Müller et al., 2003; Carrasco, 2011). This evidence corroborates the notion that, regardless of the complexity of visual scene, it is not possible to increase cognitive resources (Castiello & Umiltà, 1992). The latter notion is also in line with the Biased-Competition model of Attention (Desimone & Duncan, 1995), in according to which, when multiple stimuli are presented simultaneously within a neuron's receptive field, the response of that neuron is smaller than the sum of the responses elicited by each stimulus taken

individually (Luck et al., 1997; Reynolds et al., 1999; Beck & Kastner, 2009), as due to competing interactions among the stimuli themselves for driving the neuronal response (Desimone & Duncan, 1995).

Therefore, in everyday life, even a simple action, such as going to a supermarket and getting some apples, sometimes, can be a difficult task since all available stimuli (e.g., a lot of people talking to each other, a huge variety of goods and foods among which to choose, music, noise) continuously compete with one another in order to gain access to further processing. This competition occurs automatically and it is at the basis of the target selection process, as it can be solved by a so called attentional control (AC) signal, i.e. a signal derived from neuronal mechanisms capable to orient and guide the attentional resources toward a specific spatial location and/or object.

Traditionally, two categories of AC signals have been identified: *top-down* and *bottom-up* (Posner, 1980; Corbetta & Shulman, 2002). The top-down mechanism is at play when our attention is voluntarily allocated to a given spatial location or object; this AC mechanism is based on previous knowledge, internal guidance, current goals or instructions (Egeth & Yantis, 1997; Reynolds & Heeger, 2009). In contrast, bottom-up signals are at play when our attention is automatically captured by a salient stimulus based on its physical properties, such as luminance, color or shape (Yantis & Egeth, 1999; Theeuwes, 2010). Nevertheless, in recent years, it has been suggested that this dichotomy is insufficient when trying to explain all selection biases. In fact, people can implicitly develop another type of bias through their past experience with the environment, which can also guide current and future target selection (Awh et al., 2012; Ferrante et al., 2018; Jiang, 2018). Therefore, a third category has been introduced, namely experience-dependent AC (Awh et al., 2012; Failing et al., 2018; Chelazzi & Santandrea, 2018), which refers to a series of factors, specifically linked to the individual's previous experience with a given context and/or stimuli, that also play a significant role in attentional deployment (Awh et al., 2012; Zelinsky & Bisley, 2015; Schapiro & Turk-Browne, 2015; Schapiro et al., 2017; Theeuwes, 2018; Chelazzi & Santandrea, 2018). In the current dissertation, we are going to focus onto a specific experience-dependent AC mechanism, known as statistical learning (SL), that

allows humans, but also animals, to implicitly extract regularities from the environment and plan future action based on these regularities (Geng & Behrmann, 2005; Walthew & Gilchrist, 2006; Druker & Anderson, 2010; Aslin & Newport, 2012; Jiang et al, 2013a,b; 2015; Ferrante et al., 2018; Rosa-Salva et al., 2018).

Directing attention toward a specific location in space to detect a relevant item, i.e. target, also requires to ignore all the surrounded stimuli which are irrelevant for the task. It has been traditionally shown that the attentional capture by a salient distractor in a visual search task can be reduced thanks to the top-down activation by the individual of a specific attentional set, based on the specific perceptual characteristics that define the target (Bacon & Egeth, 1994; Leber & Egeth, 2006; Chelazzi et al., 2019). Some researchers have also recently suggested that there may be an active mechanism dedicated to distractor filtering, whose intervention would be fundamental in the presence of irrelevant items with a high interfering power, e.g. a stimulus with a visual perceptual salience (Hickey et al., 2009; Noonan et al., 2016). This filtering mechanism could act differently according to the context and to the activity of the already mentioned AC mechanisms. For instance, beside the SL bias on target selection, evidence showed that people are able to also implicitly learn to suppress distractors. For instance, by manipulating the frequency distribution of a salient distractor across locations, Ferrante and colleagues (2018) found better performance when the distractor was presented in the location where it was more likely to occur, compared to the location where it appeared rarely. This suggests that SL allowed participants to learn to suppress the irrelevant item, which in turn resulted in a reduced interference with performance at the task.

The activity of all the AC signals, both in terms of target selection and distractor filtering, are thought to converge in the so-called *spatial priority map* (Bisley & Goldberg, 2010; Ptak, 2012), that is a neuronal representation of space wherein the highest peak of activation corresponds to the location in space where the attentional resources are/will be allocated, i.e. the actual target location. Differential activity within the map is thought to reflect different levels of priority across different portions of the visual space and/or different objects whereas, based

on more recent hypothesis (Chelazzi et al., 2019), negative peaks might represent regions that are actively ignored. (Figure 1)

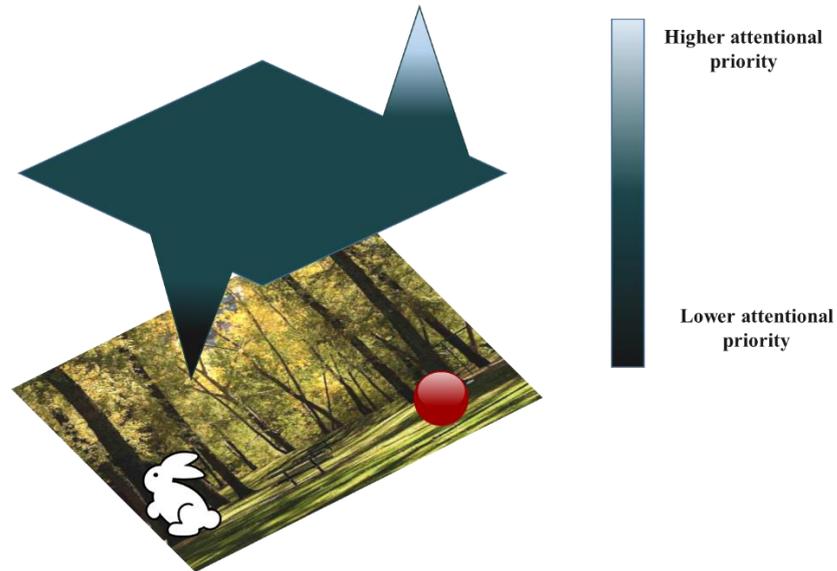


Figure 1: The picture is a cartoon example of a spatial priority map where each point in the map corresponds to a point in the visual scene, e.g. a park. The highest peak (on the right) in the map represents the spatial location where most of our attentional resources are/will be allocated, which in turn is the basis of target selection (e.g., the red ball), whereas the lower peak (on the left) might represent where specific resources might be allocated for an active distractor suppression process (e.g., the presence of a white rabbit in the park is a salient and interfering event and will capture our attention; if we want to keep looking for the ball we wanted, suppressing this stimulus might be beneficial).

Even if each of these AC signals is well described in the relevant literature both in relation to its functional prerogatives as well as to its neuro-cognitive substrates, it is far from clear how different AC signals might interact with one other, in turn leading to the emergence of a final, and by definition unique, “attentional choice”. One possibility is that, depending on the given context, a gating mechanism might be engaged, allowing only one biasing signal to determine the assignment of attentional priorities to available visual stimuli. Another

possibility is that, in any context and time, all available AC signals jointly contribute to establish attentional priorities.

The main purpose of my PhD project was to understand the degree of independence and/or synergy between the multiple potential sources of AC, in order to contribute to clarify the functional architecture of visual spatial attention.

In this Introduction, I will first describe in more details the three mentioned AC mechanisms (top-down, bottom-up, statistical learning) and then discuss about their interaction in the spatial priority map(s). Furthermore, I will present evidence coming from the implementation of a series of experimental paradigms that we developed to assess the unitary and combined influence of multiple sources for AC, considering both target selection and distractor filtering mechanisms. Specifically, by using variants of the same visual search paradigm, we implemented five behavioural experiments and one EEG study to investigate the integrated effect of top-down and statistical learning mechanisms over target selection and how a task-irrelevant, but salient, stimulus, interfered with the performance at the task.

1.2 Top-down control

Top-down (or goad-driven) AC is a mechanism referred to an internally induced process, driven by volitional selection of elements that are relevant with respect to an individual's goals (e.g. Folk et al., 1992; Bacon & Egeth, 1994; Egeth & Yantis, 1997; Folk & Remington, 1998; Corbetta & Shulman, 2002; Reynolds & Heeger, 2009; Carrasco, 2011). Posner (1980) firstly illustrated top-down selection using an experimental procedure called *endogenous cueing*, consisting in the presentation, before the onset of the visual search display, of a central visual cue (e.g., an arrow), which provides an indication about the upcoming target location. In the classical studies, following such experimental manipulation, better performance was found when the target appeared at the (validly) cued (vs. uncued/invalid) location, implying that under top-down control participants could early allocated their attentional resources in a specific spatial location, facilitating the subsequent processing of targets appearing therein (Posner, 1980). Furthermore, increasing the interval between the cue and the visual search display onset tends to amplify the facilitation in detecting the target stimulus, probably because it allows to better

encode the information derived from the cue and to consequently shift attention to the suggested location (Feng & Spence, 2017; Shepherd & Müller, 1989).

Top-down control is therefore able to unbalance stimulus competition in favour of the element presented in the expected spatial position at the expenses of the elements presented in unexpected regions (Luck et al., 1997; Recanzone & Wurtz, 2000).

The neural areas involved in top-down control include fronto-parietal regions, where an increase in neuronal activity has been observed during the interval period between a warning element (cue) and the subsequent stimuli (Beck & Kastner, 2009). Interestingly, EEG studies have identified many neural markers related to visual attention and, more precisely, some related to top-down AC, such as the *contingent negative variation* or CNV (e.g., Schevernels et al., 2014; van den Berg et al., 2014). The CNV is characterized by a slow, negative-going waveform normally detected in the central areas (fronto-parietal cortex) after the presentation of a warning stimulus, such as a cue (Walter et al., 1964). Available evidence in the literature revealed a larger CNV elicited after the presentation of a valid cue, as compared with a neutral one, suggesting that participants were getting more prepared to select the upcoming target when they received an instruction (cue) about the location where it would appear (e.g., Rashal et al., 2022; Dolci et al., *submitted*; Arjona et al., 2014; Eimer, 1993). This suggests that the fronto-parietal cortex plays an important role in attentional orienting towards a specific spatial location and for keeping the target representation active in working memory (Beck & Kastner, 2009).

Other EEG components that have been demonstrated to be significantly influenced by top-down signals are related to the activity of regions within the visual cortex. For example, the P1, i.e. the first positive-going ERP component observed in the contralateral occipital scalp, which usually starts around 90 ms after the presentation of a visual stimulus (Mangun & Hillyard, 1991; Baumgartner et al., 2018; Robinson & Rugg, 1988), has been shown to be affected by top-down guidance of attention. For instance, Luck and colleagues (1994) showed a decrement of the P1 component after attentional was first erroneously allocated to an incorrect area and then shifted toward the place where the actual target was

located (Luck et al., 1994; see also: Mangun & Hillyard, 1991; Van Voorhis & Hillyard, 1977).

1.3 Bottom-up control

Bottom-up (or stimulus-driven) AC is an externally induced process for which attention is automatically captured by stimuli with highly noticeable feature properties (e.g., Yantis & Jonides, 1990; Yantis & Egeth, 1999; Theeuwes, 1992, 2010, 2013). Saliency is not an absolute concept, but it depends on the relationship between a given object and the other objects present in the same visual scene (Treisman, 1988; Wolf, 1994). For instance, it would be easier to find a red apple among green apples, rather than to find a lemon among oranges, since in the first case our target (red apple) has a very distinctive colour feature which differentiates it from the other elements.

In literature the term *attentional capture*, referring to when objects gain processing priority, independently of the volitional goal of the observer. For instance, he demonstrated that the presence of a perceptually salient element is able to significantly impact behavioural performance. Specifically, in a visual search task, an item which differed from all the other stimuli for its colour interfered with target selection, since stimulus competition was solved by allocating attentional resources towards the element that “popped-out” from the surrounding objects (Yantis & Jonies, 1984; Theeuwes, 1992).

It is believed that simple stimulus features such as colour, luminance and orientation are represented in different regions within the cortical visual system, enabling attentional computation of pop-out stimuli to occur in parallel, without the need of examining every element in the visual scene (Duncan & Humphreys, 1989; Treisman & Gelade, 1980).

As a functional correlate of the individuals’ capacity to deal with attentional capture, Luck and colleagues proposed an inhibitory mechanism, which allows to suppress irrelevant but salient stimuli (that otherwise would automatically capture attention) to then shift attentional resources towards the actual target location (Gaspelin & Luck, 2018a; Gaspelin & Luck, 2018b; Sawaki & Luck, 2010).

The neural substrates of bottom-up attentional control are thought to reside within the so-called Ventral Attention Network, which includes the temporoparietal junction, TPJ, and the ventral frontal cortex, VFC (Corbetta & Shulman, 2002). However, as already mentioned for top-down control, electrophysiological evidence also revealed that bottom-up AC exerts a significant modulatory influence on the neural activity of occipital areas.

EEG studies have revealed that the presence of an additional singleton in a visual search display evokes a significant *distractor positivity* or Pd, then followed by an N2pc, or vice versa, the two ERP components in the opposite temporal order (an N2pc followed by a Pd). More specifically, the N2pc is a negative deflection at contralateral posterior electrodes, typically emerging around 200 ms after the appearance of an object that matches the target-defining features in a multi-stimulus display. The N2pc is commonly assumed to denote the allocation of attention towards the location where a task-relevant, or a salient stimulus is presented, although it is still open to debate if it underlines target selection or a filtering mechanism which inhibits all the irrelevant items (Luck & Hillyard 1994; Kiss et al., 2008; Luck et al., 2000; Eimer, 1996; Hickey et al., 2006). The Pd component is instead a posterior-contralateral positivity which is believed to reflect an active suppression of an elements that can occur before, after, or in the same time-window as the N2pc, implying different stages of distractor inhibition (Gaspelin & Luck, 2018b; Liesefeld et al., 2017; Berggren & Eimer, 2020). For instance, Liesefeld and colleagues (2017) developed a study where they compared the neural activity elicited by a target and salient distractor. They found that the N2pc evoked by the distractor was observed at an earlier time window compared with the target-related N2pc, and then followed by a Pd (Hickey et al., 2009; Liesefeld et al., 2017; Feldmann-Wustefeld et al., 2021). This suggests that attention was first captured by the salient element and then, while the distractor was actively suppressed, participants redirected their attention toward the target stimulus. It is however important to note that attentional capture, as indicated by the distractor-related N2pc, depends on task difficult and on the degree of similarity between the target and the distractor (Barras & Kerzel, 2017).

1.4 Statistical learning (SL) mechanism

Many everyday life activities, including music, dance, sport and social interactions, are characterized by a sequence of multiple elements and/or movements that follow a precise spatio-temporal order. Both humans and animals are able to implicitly extract these regularities in order to perceive the surrounded environment as an organized structure where planning future actions. One of the mechanisms that allow this process is *statistical learning* (Fiser & Aslin, 2001; Saffran, 1996; Jiang, 2018; Ferrante et al., 2018; Geng & Behrmann, 2005).

In behavioral and neuropsychological research, the first studies of this phenomenon on humans come from the acoustic domain, following the idea that SL is necessary for language and vocabulary acquisition (Saffran et al., 1999; Saffran, 2001; 2002; Horn, et al. 2004; Aslin & Newport, 2012). SL emerges already during the first month after birth (Bulf et al., 2011; Lewkowicz, 2004; Kirkham et al., 2007) and it is a spontaneous process that does not need to be guided by factors such as instructions, motivation, reward or punishment. Specifically, it has been shown that, after a short exposure to repeated observations, infants demonstrate to have developed an implicit knowledge about the internal structure of speeches or visual scenes, without someone who explicitly referred to or explained it (Fiser & Aslin, 2001; Saffran et al, 1996). This is of course a very important mechanism boosting adaptiveness to the environment. For instance, just imagine how difficult would be for a child to learn the rules necessary to live in a society, if his/her parents had to explicitly explain all of them.

One sources of information that allows statistical computations is *conditional probability*, i.e. the possibility to predict the occurrence of an element in the presence of another element. The element's predictability can be absolute, when an element always predicts, or appears, with another element (e.g., the element "bottle", that the mother gives to her son, always predict the element "food"); or probabilistic, when an element usually, but not always, predicts another element (e.g., when the mother feeds her son, the element "food" sometimes predicts the element "nap"; Marcovitch et. al., 2008).

The term conditional probability refers to two properties: the *frequency* whereby different elements appear together or following a certain order (lower

order statistics) and the *predictability* of the relationships between two or more elements (higher order statistics). Along this line, it is important to remember that co-occurrence and predictability do not necessary coincide: an element may be very frequent in the environment, but it can co-occur with many other elements; alternatively, an element may be quite infrequent, but it may co-occur with only one other element. An example could be the smile of the mother after her child's vocalization. If a mother always smiles when the child tries to talk, but she also smiles as often for other reasons, not related to the child's action, the probability of predicting the event "maternal smile" will be low (Frankenhuis et al. 2013).

In the visual attentional domain, SL is usually related to the frequency with which a given element, for example the target stimulus, appears at a given spatial location. This form of SL allows the individual to be more efficient in identifying a visual target when presented in a location where it appears more frequently (Ferrante et al., 2018; Geng & Behrmann, 2002; 2005; Jiang, 2018; Di Caro et al., 2019). For instance, in one experiment developed by Geng and Behrmann (2005) the target "T", presented among "L" signs, appeared in 75% of the trials in the one location (high-probability location) and in 25% of the trials in the remaining other locations (low-probability locations). As a result of this manipulation, the authors found that participants were faster and more accurate to detect the target when it appeared in the high- (vs. low-) probability location. Ferrante and colleagues (2018) confirmed the effects of SL and showed that this bias can emerge rapidly, even after a few dozens of trials (Ferrante et al., 2018). Several authors have also shown that the behavioral effects of SL of the target location persisted even after the target frequency was no longer manipulated, i.e., in an extinction regime (e.g., Jiang et al., 2013; Jiang et al., 2014; Ferrante et al., 2018).

Besides modulating target selection, SL is also able to affect the distractor filtering mechanism. Reder and colleagues (2003) used a variant of a visual search task where participants had to find a target stimulus presented with equal probability across locations. In some trials, they introduced a salient distractor, i.e. a stimulus with a different color from all the others in the visual search display, which was thus able to automatically capture attention under bottom-up control. However, the salient distractor was not equally likely to appear across locations,

with high-frequency (60%), intermediate-frequency (30%) and low-frequency (10%) locations. Collected results showed that the target was more easily detected in those trials when the distractor appeared in high- (vs low-) frequency location. This evidence suggested that participants had assigned different attentional priority to different spatial locations in the array, including by “de-prioritizing” the location where interference was more frequent (Reder et al., 2003): thus, after the SL process, when the salient, distracting stimulus appeared at the high-frequency location, it was actively suppressed and it could produce reduced interference with performance at the task (Reder et al., 2003; see also: Leber et al., 2016; Ferrante et al., 2018; Wang & Theeuwes, 2018; Di Caro et al., 2019).

In addition, it has been shown that target-related and distractor-related SL processes are interconnected such that, for example, SL allows people to better find a target when it occurs in the location where it is more likely to appear, but it also increases the interference of a salient distractor at the same location, as it gained high attentional priority (Ferrante et al., 2018).

Considering the overall evidence discussed so far, we might conclude that SL acts as a form of experience-dependent AC signal. Indeed, when SL is at play, the competition between multiple (visual) stimuli is solved in favor of the stimulus presented at the location that was selected more frequently, as that location gained higher attentional priority. Similarly, the region where interfering elements were more likely to occur, becomes more easily ignored, as that location was deprioritized, possibly becoming represented as a negative peak in the priority map(s) of space (see below). This hypothesis is supported by EEG studies that revealed how the exposure to statistical regularities in the occurrence of the target or of the salient distractor across location elicited a modulation of the N2pc and Pd components, respectively. A larger N2pc emerged when a target appeared in the high target frequency location (Dolci et al., *submitted*). Similarly, a larger Pd was evoked by stimuli presented in the high distractor frequency location (Wang et al., 2019). Additionally, it has been argued that a modulation of oscillatory activity in the alpha-band range (8-14 Hz) might also be an index of an active distractor filtering mechanism. For example, Worden and colleagues (2000) found an increase in alpha-band activity over the occipital cortex, contralateral to the to-be-ignored

location before the onset of the to-be-attended stimulus, predicted by an informative cue (Worned et al., 2000). Wang and colleagues (2019) also showed an enhancement of alpha oscillations in the hemisphere contralateral to the high-frequency distractor location, suggesting that SL can also proactively modulate attentional deployment, before the array onset location (Wang et al., 2019).

1.5 Priority map

As previously illustrated, the concept of *spatial priority map* refers to a topographic neural representation of space, where each point in the map corresponds to a specific location in space and has a specific neuronal activity. The level of the neuronal activity depends on the priority level of that spatial location, deriving from different AC signals (Thompson et al., 2005; Serences & Yantis, 2007; Ipata et al., 2009; Awh et al., 2012; Chelazzi et al., 2013), and in turn corresponds to the amount of attentional resources that are (or will be) allocated to that location. The highest peak of activation in the map corresponds to the spatial position where attention is deployed at the service of the actual target selection, following a winner-take-all mechanism (Bisley, 2011; Macaluso & Doricchi, 2013; Chelazzi et al., 2014). Along the same lines, it can be hypothesized that the lowest peak in the map might represent a location that is actively suppressed for distractor inhibition (e.g., Ferrante et al., 2018; Chelazzi et al., 2019).

As already mentioned above, all the stimuli in the visual environment continuously compete with one another in order to gain access to processing resources and to reach our perceptual awareness. The AC signals act to solve this stimulus competition by guiding attentional resources towards the single (or few) element(s) that will become the target of our overt behaviour. In particular, top-down control guides selection in favour of the stimulus that, for instance, appears in the location that was previously instructed by a cue stimulus, whereas bottom-up control guides selection towards the location containing a perceptually salient item. Finally, statistical learning privileges the spatial region where targets were more likely to appear in the past (or distractors appeared very rarely). Under the same circumstances, these AC mechanisms also play an important role in the distractor filtering in order to actively suppress elements that interfere with our goals.

Until now I have described how the various sources of AC individually influence and orient our attention. However, all of them coexist and affect target selection and distractor filtering together during everyday life: still it is yet unclear how they actually interact with one another in order to establish the final attentional choice. On the one hand, it is possible that signals elicited by different AC mechanisms sum up to jointly contribute to target selection (or distractor suppression). On the other hand, there is the possibility that, depending on the given context and time, signals elicited by one mechanism override the activity elicited by the others via some forms of gating, such that in the end target selection (or distractor filtering) will be the result of the activity of only one source of AC.

Some studies in the recent literature have tried to solve this issue, but results so far are contradictory. Considering the top-down and statistical learning, some argued that the final attentional choice is the outcome of the combined effects of both signals that independently modulate the priority map and jointly guide attention toward a specific spatial location (Geng & Behrmann 2005; Gao & Theeuwes, 2020; Duncan & Theeuwes, 2020). Others instead believe that the effect of implicit learning can be blocked by the presence of an explicit cue which gets precedence in guiding target selection (Jiang et al., 2013b; Geng & Behrmann 2005).

Also regarding the interaction between bottom-up and top-down there are some discrepancies. Some studies have shown that when attention is allocated in a certain spatial position under top-down control, the presence of a salient element that appears in another location does not interfere with the task, suggesting that goal-driven can shield from distraction coming from any region outside the focus of the attentional “zoom lens” (Yantis & Jonides, 1990; Theeuwes, 1991; Rashal et al., 2022). However, other evidence demonstrated that a salient singleton can automatically guide attention on itself, irrespective of top-down control settings, but that this saliency signal can then be overridden by an active suppression process to prevent the actual capture of attention (Sawaki & Luck, 2010).

The reasons why all these findings do not converge on a unique scenario may relate to the large variety of experimental paradigms used in different studies, which

make it difficult to reconcile collected evidence under the same theoretical framework.

1.6 Aim of the study

As already mentioned, the aim of my PhD thesis was to shed light onto the unique and integrated effect of different AC signals, namely top-down, bottom-up and statistical learning.

In particular, we developed a series of behavioural and EEG experiments by using the variants of the very same visual search task, in order to measure how the stimulus competition is solved under the influence of different control signals in the same experimental context.

Firstly, we performed five behavioural experiments where we focused on how target selection might be individually and jointly driven by top-down control, manipulated via an endogenous cueing protocol, and the experience-dependent mechanism of SL, manipulated by an imbalance in target frequency across locations. Within the same experiments, we assessed how the attentional capture due to a perceptually salient item might interfere with both the mentioned sources of AC. We then implemented electrophysiologically one of the behavioural studies in order to record the EEG activity in order to distinctively investigate the neural activity underlying top-down and statistical learning, when acting together.

2 OVERRIDDING THE IMPACT OF ATTENTIONAL PROBABILITY LEARNING BY TOP-DOWN CONTROL ¹

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¹ Chapter 2 is a manuscript under preparation, that describes a series of behavioural studies performed at the University of Verona (*Dolci Carola, Suliann Ben-Hamed, C. Nico Boehler, Emiliano Macaluso, Leonardo Chelazzi, Elisa Santandrea, Overriding the impact of attentional probability learning by top-down control in preparation*).

2.1 Introduction

In everyday life, we are constantly surrounded by a large number of visual inputs that compete with each other to reach our perceptual awareness. However, since our cognitive resources are intrinsically limited, only a small part of those inputs will be selected and will actually play a role in guiding our behavior. The competition among stimuli occurs automatically and has a substantial impact on visual processing and, consequently, on target selection (Desimone & Duncan, 1995). In accordance with the Biased-Competition model of Attention, when multiple stimuli are presented simultaneously within a neuron's receptive field (RF), the response of that neuron is smaller than the sum of the responses elicited by each stimulus when taken individually (Reynolds et al., 1999; Beck & Kastner, 2009), suggesting that the representation of a specific visual object might only occur at the expense of other objects' representations (Duncan, 1996; Beck & Kastner, 2009). However, different attentional control (AC) mechanisms exist that are able to unbalance the stimulus competition in favour of one (or a few) element(s), which will become the actual target(s) of selection. Following selection, the selected stimulus will be encoded by the neuron almost as the only element (albeit being presented among competing stimuli inside the RF), while all the other elements will be ignored (Desimone & Duncan, 1995) or even actively suppressed (Chelazzi et al., 2019).

Traditionally, attentional selection was described as governed by two main sources of AC (Posner, 1980; Corbetta & Shulman, 2002). On one side, the *top-down* (or *goal-directed*) AC is an active and endogenous mechanism that is at play when attention is voluntarily allocated to a given spatial location, or object, based on previous knowledge, internal guidance, or instructions (Egeth & Yantis, 1997; Leber & Egeth, 2006; Reynolds & Heeger, 2009). For instance, Posner (1980) showed that, following an informative cue which predicted the upcoming target location, the stimulus competition was solved in favour of the element presented at the attended (*cued*) vs. unattended (*uncued* or *invalidly cued*) spatial location, since people could allocate their attentional resources in advance (Posner, 1980). On the other side, the bottom-up AC mechanism is at play when attention is automatically captured by a perceptually salient stimulus, as based on its physical properties, such

as luminance, color or shape (Yantis & Egeth, 1999; Theeuwes, 2010). Indeed, a salient but irrelevant stimulus, that is presented among other homogeneous and non-salient stimuli, such as a red stimulus presented amongst a set of green stimuli, can be a powerful distractor which can strongly interfere with the ongoing task (Theeuwes, 1992).

Nevertheless, this dichotomy has more recently deemed to be reductive to explain how attentional deployment is guided. A third AC category, known as *experience-dependent*, has been introduced, referring to the attentional biases that individuals implicitly develop through their experience with the environment (Awh et al., 2012; Failing et al., 2018; Chelazzi & Santandrea, 2018). One of the mechanisms that belongs to this category is *statistical learning (SL)*, that allows us to implicitly extract regularities, such as the frequency with which an element appears at a given spatial location, to then plan future behaviour based on these regularities (Geng & Behrmann, 2005; Walthew & Gilchrist, 2006; Druker & Anderson, 2010; Aslin & Newport, 2012; Jiang et al., 2013; Ferrante et al., 2018; for evidence also in animals see e.g. Newport et al., 2004; Santolin et al., 2016; Rosa-Salva et al., 2018). In particular, individuals are more efficient in identifying a visual target, or in suppressing a visual distractor, when presented in a location where it is more likely to appear (Geng & Behrmann 2005; Ferrante et al., 2018; Di Caro et al., 2019).

All these AC mechanisms are involved in target selection and it is believed that their effects all affect what is termed the *spatial priority map* (Bisley & Goldberg, 2010; Ptak, 2012), i.e. a topographically-organized neural representation of space, where each point in the map corresponds to a specific spatial location. Shaped by the effect(s) elicited by one or more AC mechanisms, the level of the neuronal activity within the priority map represents the level of attentional priority of each spatial location and governs the amount of attentional resources that are allocated to it (Awh et al., 2012; Chelazzi et al., 2013). In fact, as a result of a winner-take-all competition, the highest peak of activation in the map corresponds to the location in space where the attentional resources are directed for actual target selection (Macaluso & Doricchi, 2013; Chelazzi et al., 2014).

The priority map can be therefore considered as a critical centre for attentional control, where all single AC signals have an *online* impact aimed at establishing the spatial position that should be prioritized. Crucially, albeit many studies already described the impact of each AC mechanism as taken individually, still not much is known about how these mechanisms interact with each other and how the final attentional choice is taken. One possibility is that, depending on the given context and time, a gating mechanism allows only one AC signal to assign attentional priorities to the current visual input. Another possibility is that, at any time, all different AC signals independently contribute to the computation of attentional priorities.

The purpose of the present research is to contribute to the characterization of the functional architecture of visual spatial attention, with particular emphasis on understanding how two different biasing signals, namely top-down attention and statistical learning, may interact in order to solve stimulus competition and to define the final and univocal attentional choice, essential to plan and guide actual behaviour.

Few recent studies in the literature already tried to investigate their combined effect, leading to controversial results. Specifically, some authors argued that these two mechanisms independently guide attentional resources toward a specific spatial location (Geng & Behrmann, 2005; Gao & Theeuwes, 2020), whereas others suggested that top-down AC and SL may interact, such that, depending on the specific context and epoch within the target selection process, when one mechanism is at a play, the effect of the other mechanism will actually be reduced (Dolci et al., *submitted*).

In order to clarify these contradictory results, here we developed a series of five coherent behavioural experiments entailing a unified version of a visual search task (see below) where, by introducing a central visual cue (valid vs. neutral) and an imbalance in target frequency distribution (high-frequency location vs. low-frequency location), we assessed the unitary influence of both top-down control (Experiment 1, 4) and statistical learning (Experiment 2), when presented in isolation, as well their combined effects (Experiments 3, 5). Furthermore, by also inserting a salient, but irrelevant distractor in the task, we could investigate the role

of these AC signals in relation to both target selection and distractor filtering attentional operations.

One of the strength of this study is that the SL effect was tested in the presence vs. absence of different type of endogenous cueing having different spatial resolution: a location-specific cue (Experiment 3) and a region-specific cue (Experiment 5). As in our previous study that also investigated the combined effect of top-down control and SL, the informative cue, when present, indicated the specific upcoming target location with 100% of validity (Dolci et al., submitted; see also Rashal et al., 2022; Beffara et al., 2022). However, here we also tested a “weaker” form of cueing which, albeit being still fully trustable (100% validity), indicated a region of the display encompassing two possible target locations (instead of a specific one), with the specific aim of testing whether the interaction between top-down AC and SL might be dependent of the relative strength of the cueing signal. As illustrated in details in what follows, thanks to the differential strength of the location-specific vs. region-specific cueing manipulations applied in the series of experiments implemented in the present paper, we could directly verify whether results collected in the combined experiments (Experiments 3 and 5) were dependent on the relative weight of the different AC engaged, or whether they truly reflected the functional architecture of attentional control.

In particular, if top-down control and SL interact with each other we should find either that the top-down AC leads to a gating effect, such that validly cueing the target location/region might eliminate any benefit following the statistical learning process, or that, analogously, statistical learning leads to a differential distribution of attention to the possible target locations that might override any top-down effect. Alternatively, if the two mechanisms independently act to guide attention towards a specific spatial location, better performance should be observed for targets in the high- vs. low- frequency locations, following both valid and neutral cues, and cueing effects may be measured in both frequency conditions.

Importantly, the paradigms we used in all the experiments were variants the same visual search task used by Dolci et al. (*submitted*) and other authors that investigated the interaction between different AC mechanisms (see Rashat et al., 2022; Beffara et al., 2022 for evidence regarding the combined effect of top-down

and bottom-up control). The reason for this choice was to create a unique and coherent scenario where collected evidence might be directly compared and unified to then shed light on the functional architecture of visual spatial attention.

2.2 EXPERIMENT 1

Experiment 1 aimed to assess the isolated influence of top-down control, i.e. the ability to voluntarily allocate the attentional resources toward a specific spatial location, following task instructions. Albeit top-down AC has already been extensively described, the importance of this experiment in the context of our current study was that of testing it in isolation within the identical task design in which we would then test interactions with other AC signals. Specifically, we focused on a specific manipulation known as endogenous cueing (EC), consisting in the presentation, before the search display onset, of a central visual cue which indicated the upcoming target location with absolute certainty (i.e. a validity of 100%). In some trials, however, a non-informative cue was provided and, participants had no hint about the upcoming target location. The impact of top-down control on attentional deployment was verified through the comparison between valid versus neutral cue conditions. We expected that the advance knowledge of target location following a valid cue would result in a behavioural benefit on subjects' performance, thanks to the possibility for them to pre-allocate attentional resources correctly towards the spatial region of the upcoming target in validly cued trials only.

Furthermore, we assessed the potential interference exerted by a task-relevant distractor, i.e. a second stimulus in the search array sharing the target-defining features, which could appear in a non-cued spatial location after a valid cue.

Finally, in order to also engage distractor suppression mechanisms (Chelazzi et al., 2019), in half of trials we introduced a perceptually salient stimulus, which differed from all other stimuli in terms of colour and therefore was able to automatically capture attention (Theeuwes, 1992). The attentional grabbing impact of this element was assessed by comparing performance between trials in which the salient distractor was present vs. absent.

2.2.1 Methods

This and all subsequent experiments in the present study were conducted in accordance with the Declaration of Helsinki and approved by the Institutional

Ethics Committee of the University of Verona. The study was not preregistered. All data supporting the findings of this research will be available in a public repository, soon after publication. To estimate the sample size for this and all subsequent experiments in the current study, we used in our previous study - Dolci et al., *submitted*, as a reference, since there the task and the main analyses we applied were the same as in the present study. We therefore run a power analysis using G*Power 3.1.9.7 (Faul et al., 2007) with a desired power of $1 - \beta = .95$ and an alpha error probability of $\alpha = .05$, and with $\eta^2_p = 0.29$ (effect size of the interaction between top-down control and statistical learning; Dolci et al., *submitted*) as the effect size. As a result, we obtained that our sample should comprise 27 participants in order to guarantee the same statistical power. However, given that, to counterbalance all of our conditions in Experiment 2, 3 and 5 (see below), we needed the sample size to be a multiple of 4, we decided to have 28 participants in this and all subsequent experiments.

Participants

Twenty-eight healthy volunteers (9 males; mean age \pm SD, 24.64 ± 3.52) with normal or corrected-to-normal visual acuity participated in Experiment 1. None of them had previously taken part in similar or related studies, and they were naive to the purpose of the present research; moreover, each participant was enrolled in only one experiment of the present study. All subjects gave their informed consent before participation. At the end of the experiment, they received a fixed monetary compensation for their participation (€10).

Two participants were excluded from subsequent analyses due to low accuracy (lower than -2SD from the average accuracy: mean - 2SD = 89.25 - 16.34).

Apparatus and stimuli

The experiment was conducted in a dimly lit and quiet room, where participants sat in front of a 17-in. CRT monitor. The viewing distance was held constant at 57 cm by using an adjustable chin rest. The experiment was run with the Open-Sesame software (Mathôt et al., 2012).

The paradigm we implemented was a modified version of an *additional singleton task* (Theeuwes, 1992), wherein participants had to perform a visual search in order to identify the target stimulus first and then to discriminate the location of a small gap within the target itself (see below). The stimuli used for the experiment were rectangular bars of size $1.9^\circ \times 0.5^\circ$, green (RGB coordinates: 0, 86, 0; luminance: 22.92 cd/m²) or red (RGB values: 170, 0, 0; luminance: 22.98 cd/m²), presented on grey background (RGB: 40, 40, 40; luminance: 10.32 cd/m²). Inside each stimulus on the display there was a small gap (diameter: 0.25 mm) of the same grey colour as the background and positioned in the upper or lower portion of the stimulus.

In each visual search display four stimuli were presented, one for each visual quadrant, equidistant from one another and from the centre of the screen, being placed along an imaginary circle with a radius of 7° centred on the fixation cross (centre of the screen). The target was the bar tilted $\pm 25^\circ$ with respect to the vertical axis, whereas the other, to-be-ignored stimuli (distractors) were bars tilted $\pm 25^\circ$ with respect to the horizontal axis.

In half of the trials, all the stimuli had the same colour (homogeneous display; e.g. red), while, in the other half, one of the stimuli had a different colour (non-homogeneous display; e.g., a green bar among red ones). The differently-coloured stimulus could be either a salient distractor or the target.

Before the search array onset, around the fixation cross, a visual cue appeared, which consisted of a square (dimension: $1.2^\circ \times 1.2^\circ$) made by four separate corners. In the case of a neutral cue, the square had all its parts coloured in pink (RGB: 120, 0, 90; luminance: 22.9 cd/m²), whereas, in the case of a valid cue, three corners were in pink and the fourth corner was coloured in cyan (RGB: 0, 56, 158; luminance: 22.93 cd/m²), indicating in which quadrant the target element would be presented.

Task and experimental design

The task required participants to discriminate the location of a small gap within the target item (up vs. down) by pressing the correspondent key: half of the participants had to press the "left arrow" if the gap was in the upper portion of the target bar and

the "right arrow" if it was in the lower portion; the other half of the participants had the opposite key assignment. In valid cue trials, the blue corner anticipated with absolute certainty (100% validity) the quadrant in which the target would appear in the upcoming search display, thus allowing the advanced allocation of attentional resources towards that specific location.

The experiment included a total of 768 experimental trials that we can classify into two distinct modules (Table 1): no-task-relevant-distractor and task-relevant-distractor (50% of the total trials in each block, i.e., 384 trials), in which the target could appear with the same probability in all the positions of the visual search display. In the no-task-relevant-distractor module, the cue could be either neutral or valid (50% each; 192 trials) and there was only one potential target. In the task-relevant-distractor module, the cue was always valid and there were two potential targets: the actual target appeared in the location previously indicated by the valid cue, whereas another stimulus in the search array, sharing the target-defining features (a tilt of $\pm 25^\circ$ around the vertical axis), defined as task-relevant distractor, appeared in one of the non-cued spatial locations. This element was therefore presented in the 50% of the total trials within the experimental session and, because of its features, it could potentially interfere with the performance of participants, unlike the other stimuli. The task-relevant distractor could have both the same orientation of the target (congruent) or the opposite orientation (incongruent).

As already mentioned, in half of the total experimental trials (384 trials), one of the non-target stimuli differed in terms of colour from all the other stimuli in the search display (e.g., a green stimulus among red ones). In the no-task-relevant-distractor module, the salient element was always one of the irrelevant stimuli and it could appear in 50% of the trials. In contrast, in the task-relevant-distractor module, the salient element corresponded to the task-relevant distractor in 50% of the trials (192 trials), it was the target in 25% of the trials (96 trials) and was absent in the remaining 25% of the trials (96 trials), wherein all stimuli in the search display had the same colour.

In Experiment 1 we can therefore identify three types of distractors: the salient distractor; the task-relevant distractor, and a salient and task-relevant distractor.

In the no-task-relevant-distractor module, half of the trials had a neutral cue and half a valid cue, whereas in the task-relevant-distractor module the cue was always valid. For what concerns all the other parameters (target orientation, filler orientation, target colour, target position, distractor position, and so on), the experiment was completely balanced.

The experimental trials belonging to the different conditions followed one another in completely random order during the course of the whole experimental session.

	Experimental modules	Trials number
Cue conditions	No-Task-relevant distractor module	
Neutral	Homogeneous display	96 trials
	Salient distractor	96 trials
Valid	Homogeneous display	96 trials
	Salient distractor	96 trials
	Task-relevant distractor module	
Valid	Salient task-relevant distractor	192 trials
	Non Salient task-relevant distractor	96 trials
	Salient target	96 trials

Table 1: The table represents the types and number of trials in each experimental module

Procedure

Each experimental trial (Figure 2a) started with a fixation cross, with a duration varying randomly between 750 and 1250ms, after which the cue appeared, lasting 500ms. The time interval between the cue offset and the onset of the stimulus

display (cue-target interval; CTI) was randomly chosen from trial to trial between the values of 500ms, 1000ms, 2000ms and 4000ms, each appearing with a frequency that followed a geometric distribution (CTI was 4000ms in 96 of trials; 2000ms in 144 trials; 1000ms in 216 trials; 500ms in 324 trials), in order to keep the participants' expectations about the search display onset constant for the entire time interval (Vangkilde et al., 2012). Afterwards, the search display remained visible for 300ms; then the fixation cross only remained on the screen until the participants' response, or for a maximum of 1500ms. After an inter-trial interval (ITI) of 500ms, a new trial sequence started automatically.

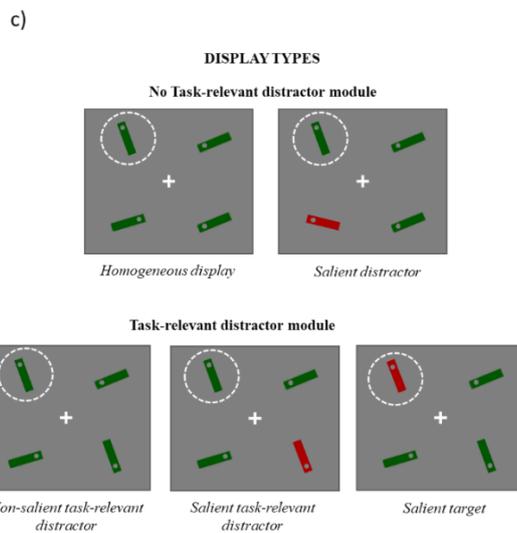
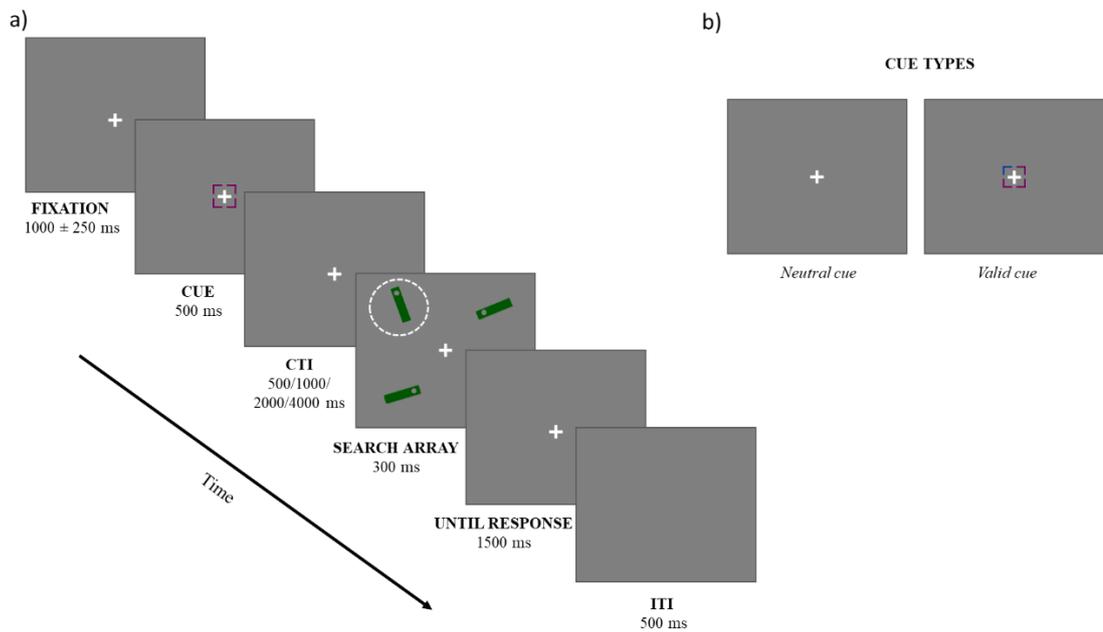


Figure 2: a) Example of the sequence of events in a typical trial. b) Different types of cue used in the experiment, i.e. neutral (left) and valid (right). c) Example search arrays for the various experimental conditions. Specifically, the upper row represents the two display conditions where no task-relevant distractor was present, i.e. homogeneous display (left) and salient distractor present (right), whereas the lower row represents the three conditions where there was a task-relevant distractor, i.e. non-salient task relevant distractor (left), salient task-relevant distractor (middle) and salient target (right). Importantly, the displays in the no-task-relevant distractor module (upper row) could be preceded both by a neutral and a valid cue. In contrast, the displays in the task-relevant distractor module (lower row) could be preceded by a valid cue only. The circled stimulus, inserted in each display for illustration purposes only, indicates the target.

Data analysis

Analyses were performed using R 3.6.2 (R Core Team, 2016) with ez (Lawrence, 2011/2015) and effectsize (Ben-Shacharet al., 2020) packages. Repeated-measures analyses of variance (ANOVAs) were performed both on accuracy and on reaction times (RTs) of correct trials. In cases of significant sphericity violation, p values were corrected by using the Greenhouse-Geisser epsilon correction.

2.2.2 Results

Top-down control

In order to evaluate the behavioural effects resulting from the top-down control on attentional resources, we considered only the trials in the no-task-relevant-distractor module and we performed a rANOVA with the within-subject factors Cue (neutral, valid) and Salient Distractor, both on accuracy and RT data. Results showed a significant facilitation in the valid (RTs: 659.63 ms; ACC: 95.2 %) vs. neutral (RTs: 918.06 ms; ACC: 81.60 %) cue trials both in accuracy [$F(1,25) = 41.46$, $p < 0.0001$, $\eta^2_p = 0.62$] and in RTs [$F(1,25) = 283.68$, $p < 0.0001$, $\eta^2_p = 0.91$]. Moreover, we assessed the typical attentional capture effect [ACC: $F(1,25) = 8.97$, $p = 0.006$, $\eta^2_p = 0.26$; RTs: $F(1,25) = 63.65$, $p < 0.0001$, $\eta^2_p = 0.71$], with worse performance in the presence (RTs: 946.59 ms; ACC: 80.70 %) vs. absence (RTs: 890.13 ms; ACC:

82.40 %) of a salient distractor. Interestingly, a significant interaction between the two factors emerged for RT data [ACC: $F(1,25) = 0.009$, $p = 0.921$; RTs: $F(1,25) = 33.76$, $p < 0.0001$, $\eta^2_p = 0.57$]. Paired post-hoc t-test (two-tailed) on RTs showed a significant distractor cost only when the cue was neutral [-56.46 ms; $t(26) = -7.81$, $p < 0.0001$, Cohen's $d = -0.43$] and not when it was valid [-4.57 ms; $t(26) = -1.11$, $p = 0.27$] (Figure 3). Overall, the collected pattern of results suggests that top-down control helped override the distracting impact of a perceptually salient, but irrelevant stimulus (see Discussion).

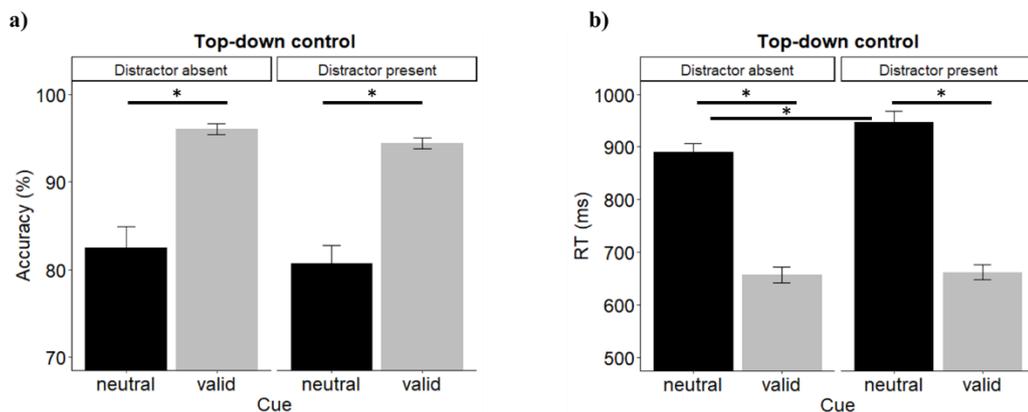


Figure 3: a) Cue validity effect in accuracy data. b) Cue validity effect in RTs data. The figures represent the cueing effects both when the salient distractor was absent (left part of each plot) and when it was present (right part of each plot). * $p < 0.05$

Saliency effect on target selection

We then assessed the possibility that a perceptual salience signal could enhance the efficiency of target selection, when the latter was guided by top-down mechanisms. Thus we conducted a rANOVA with the within-subject factor Salient Target (present, absent), considering only trials in the task-relevant-distractor module, but excluding trials in which the task-relevant distractor was salient (see Figure 2c, lower panels). In terms of RTs, we observed a marginally significant difference in favour of trials where the target was salient compared with trials where it had the same colour of all the other stimuli [RTs: ($F(1,25) = 4.40$, $p = 0.0461$, $\eta^2_p = 0.14$]. The effect was not confirmed in terms of accuracy [ACC: $F(1,25) = 0.67$, $p = 0.420$]. Overall, the presence of a salient target seemed to exert a marginal effect;

however, it is important to consider that, in this experiment, the salient target was always preceded by a valid cue (there was no a condition where it was preceded by a neutral cue), which likely produced an almost ceiling benefit through the early allocation of attentional resources towards the correct target location.

Salient and/or task-relevant distractor interference

Finally, to evaluate the influence exerted by the presence of a task-relevant and/or a salient distractor, we performed a rANOVA with the within-subject factor Distractor Type (absent, salient, task-relevant and salient-task-relevant). To make all the conditions equal, except for the presence of the distractor, we selected only valid cue trials (only valid cues were used in the task-relevant-distractor module; see above). Results showed a main effect only in term of accuracy [$F(3,75)= 4.77$, $p=0.004$, $\eta^2p = 0.16$], but not in RTs [$F(3,75)= 0.49$, $p=0.688$]. Two-tailed post-hoc t-tests on accuracy revealed that performance were significantly reduced by the presence (vs. absence) of both a salient [$t(25) = 2.87$, $p = 0.009$, Cohen's $d = 0.48$] and a salient-task-relevant distractor [$t(25) = 3.66$, $p = 0.001$, Cohen's $d = 0.59$], whereas the task-relevant distractor only marginally interfered with the task compared to trials where no distractor occurred [$t(25) = 1.99$, $p = 0.057$, Cohen's $d = 0.33$]. As pointed out in relation to the salient target (see above), also the marginal impact of the task-relevant distractor on performance might be due to the strong control exerted over attentional deployment by the top-down mechanism; only when it was also salient, it could interfere with the performance.

2.2.3 Discussion

Experiment 1 was designed with the primary objective to examine the top-down AC mechanism, in the context of the designed visual search task, focusing on a specific manipulation of spatial attention, known as endogenous cueing; the latter consists in the presentation of a central visual cue which provides an indication (in our case fully reliable; 100% validity) about the upcoming target location, before the onset of the visual search display. The analyses showed better performances, both in terms of accuracy and reaction times, in valid cue trials compared with

neutral cue trials, suggesting that a visual cue allowed to efficiently pre-allocate attentional resources at the location where the target would appear.

In the paradigm we implemented, the use of salient distractors, differing in terms of colour from all the other stimuli in the array, allowed us to also probe top-down control in trials where distractor filtering mechanisms were engaged. What we found is that the presence (vs. absence) of a salient distractor caused a worsening in the participants' performance only when top-down AC was not at a play, demonstrating that mechanism to be able to prevent attentional capture. The pattern of results measured in the presence of a salient target (again differing in colour from all other stimuli), can be interpreted along similar lines; as a matter of fact, target salience boosted selection of the critical stimulus only marginally, likely because of an already strong impact of the advanced allocation of attentional resources based on valid cueing. Unfortunately, for reasons related to the experimental design, the impact of target salience was not tested in neutral cue trials, where we hypothesize it could probably facilitate performance to a larger extent.

Finally, the occurrence of a task-relevant distractor allowed us to assess the potential interference given by an element with strong relevance for the task. Results showed that participants' performance was only slightly affected by the task-relevant distractor. Again, since all trials with this type of distractor presented a valid cue, these data can be interpreted as a proof of the ability of top-down mechanisms to reduce the interference exerted by any other element appearing on the screen.

Overall the collected evidence suggests that, when active, top-down attentional control exerts a strong gating over other sources of information (or biasing signals), such as salience or even task-relevance, in the guidance of attentional resources.

2.3 EXPERIMENT 2

In Experiment 2, we focused on a form of experience-dependent AC signals, by investigating the unique influence of the statistical learning (SL) process on attentional deployment, in the context of an identical visual search task as used in Experiment 1. We therefore introduced an imbalance in the frequency of target occurrence across locations in the visual search display; the manipulation was fully implicit, i.e. participants were not informed about the imbalance. Importantly, in this case, the visual cue was always neutral, such that participants received no explicit indication of the upcoming target location.

2.3.1 Methods

The methods were identical to those described for Experiment 1 (see above), with the following exceptions.

Participants

Twenty-eight healthy volunteers (8 males; mean age \pm SD, 22.50 \pm 4.50) took part in the Experiment 2. One participant was excluded from subsequent analyses due to low accuracy (lower than -2SD from the average accuracy: mean - 2SD = 85.02 - 21.35).

Apparatus and stimuli

The only difference with respect to the previous experiment is that only the neutral cue was used, such that participants had no explicit instruction regarding the upcoming target location.

Task and experimental design

Unlike the first experiment, Experiment 2 comprised 960 trials, divided into three different experimental epochs, which followed one another without any explicit indication to the participants, such that they were not aware of that subdivision. The first and last epochs, respectively the baseline and the test, included 192 trials each (50% of which with a salient distractor - 96 trials), where the target appeared with equal probability across the four spatial locations in the search display. Instead, the

training (epoch 2) consisted of 576 trials (again, 50% of each with a salient distractor - 288 trials) where, unbeknownst to participants, a frequency imbalance in target position was introduced. Specifically, in one location, the target appeared 42% of the total training trials (high probability location); in another, it appeared 8% of trials (low probability location); and, in each of the remaining two locations, the target appeared 25% of the trials (intermediate probability locations). Importantly, no frequency imbalance in the occurrence of the salient distractor across locations was introduced in none of the described epochs (Ferrante et al., 2018); thus, the SL process was selectively related to the target probability distribution.

Participants were randomly assigned to one of four different groups, each with a different spatial configuration relative to the spatial probability distribution of the target across locations (see Table 2).

Note that, in this experiment, since only the neutral cue was used, no task-relevant distractor was introduced.

Spatial Probabilities (%)					
	Item	Stimulus Location			
		Top L	Top R	Bottom R	Bottom L
Group1	Target	25	25	42	8
	S Distractor	25	25	25	25
Group2	Target	8	25	25	42
	S Distractor	25	25	25	25
Group3	Target	42	8	25	25
	S Distractor	25	25	25	25
Group4	Target	25	42	8	25
	S Distractor	25	25	25	25

Table 2: The table represents the spatial frequency distribution of target and salient distractor appearance across location, respectively for each subjects group.

Procedure

After the completion of the whole training session, participants were asked to complete an ad-hoc survey, developed to verify the implicit nature of the SL process: first, participants were asked to report whether they noticed anything odd

about the spatial distribution of the target stimuli and, in case they responded affirmatively, they also had to report (or guess) the locations where the target was presented most frequently (Ferrante et al., 2018).

2.3.2 Results

Statistical learning effect

In order to assess the statistical learning effect, we first performed a rANOVA with the within-subject factors Target-frequency (high, low), Epoch (baseline, training, test) and Salient distractor (present, absent).

Results revealed significant main effects of Epoch [ACC: $F(2,52) = 25.81$, $p < 0.0001$, $\eta^2p = 0.49$; RT: $F(2,52) = 21.22$, $p < 0.0001$, $\eta^2p = 0.44$] and Salient distractor [ACC: $F(1,26) = 5.74$, $p = 0.024$, $\eta^2p = 0.18$; RT: $F(1,26) = 8.83$, $p < 0.007$, $\eta^2p = 0.24$], respectively reflecting better responses in the training and test (vs. baseline) phases, likely due to practice, and a behavioural cost (attentional capture), when the salient element was present.

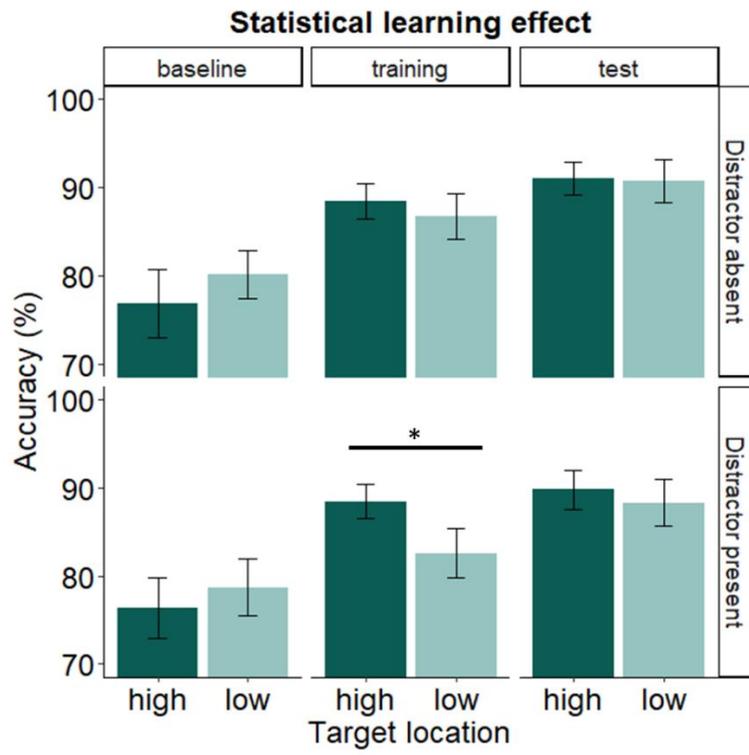
No significant main effect was found for Target-frequency [ACC: $F(1,26) = 0.15$, $p = 0.693$; RT: $F(1,26) = 0.68$, $p = 0.416$]. Crucially, however, a significant interaction emerged between Target Frequency and Epoch [ACC: $F(2,52) = 3.35$, $p = 0.042$, $\eta^2p = 0.11$; RT: $F(2,52) = 7.40$, $p = 0.001$, $\eta^2p = 0.22$]. Two-tailed post-hoc comparisons revealed better performance when the target appeared in the high- (vs. low) frequency location, only during the training epoch [ACC: $t(26) = 2.67$, $p = 0.009$, Cohen's $d = 0.29$; RT: $t(26) = -3.40$, $p = 0.001$, Cohen's $d = -0.40$].

In order to also look more closely to potential interactions also with bottom-up signals, we set out to further investigate differences between high- and low-frequency location in the presence vs. absence of the salient distractor. The SL effect was significant both when the salient distractor was present [ACC: 5.89%, $t(26) = 2.82$, $p = 0.008$, Cohen's $d = 0.43$; RT: -0.48 ms, $t(26) = -2.25$, $p = 0.032$, Cohen's $d = -0.38$] and absent, even if only on RTs in the latter condition [ACC: 1.75%, $t(26) = 0.92$, $p = 0.364$; RT: -0.50 ms, $t(26) = -2.53$, $p = 0.017$, Cohen's $d = -0.40$] (Figure 4).

Instead, no difference between high and low was observed neither during the baseline phase [salient distractor present ACC: -2.31%, $t(26) = -0.59$, $p = 0.554$;

RT: 0.006 ms, $t(26) = 0.0003$, $p = 0.999$; salient distractor absent ACC: -3.24%, $t(26) = -1.02$, $p = 0.312$; RT: 28.11 ms, $t(26) = 1.05$, $p = 0.299$], nor during the test phase [salient distractor present ACC: 1.54%, $t(26) = 0.79$, $p = 0.436$; RT: -7.22 ms, $t(26) = -0.39$, $p = 0.694$; salient distractor absent ACC: 0.30%, $t(26) = 0.19$, $p = 0.848$; RT: -3.22 ms, $t(26) = -0.19$, $p = 0.847$] (Figure 4). This finding suggests that, after an exposure to an imbalance in target frequency across locations, subjects developed an attentional bias for which they tended to allocate their attentional resources towards the location where the target appeared more frequently. Interestingly, this effect seems to act independently from the presence of a salient distractor. Furthermore, the absence of the acquired SL effect during the test epoch, i.e. when the target appeared again with equal frequency across locations, reflects a very rapid extinction of the learned attentional bias when the imbalance in target probability across locations was removed (Figure 4).

a)



b)

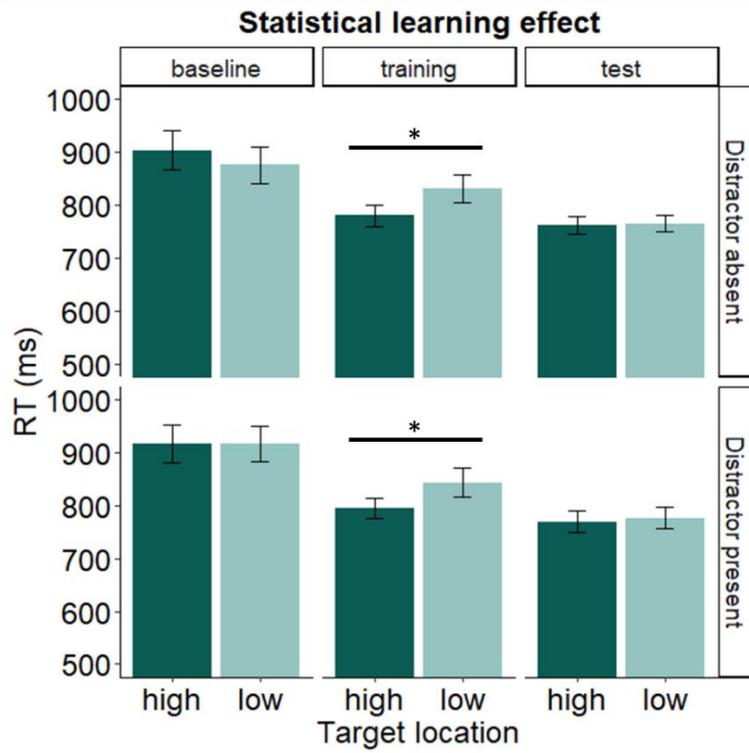


Figure 4: a) SL effect in accuracy as a function of Epoch (baseline, training and test) and Salient Distractor (absent, present). b) SL effect in RTs as a function of Epoch (baseline, training and test) and Salient Distractor (absent, present). * $p < 0.05$

At the end of the experimental session, eight participants reported to have noticed something peculiar regarding the target frequency distribution across locations and named the correct high-frequency spatial location as the location where the target was more likely to appear. However, repeating the analysis after excluding those participants fully confirmed collected results; in particular, the critical interaction Target Location by Epoch was confirmed, both in terms of accuracy and RTs [ACC: $F(2,36) = 5.38$, $p = 0.008$, $\eta^2p = 0.23$; RT: $F(2,36) = 8.55$, $p = 0.003$, $\eta^2p = 0.32$], corroborating the idea that the SL effect emerges through an implicit process.

We then assessed if the impact of this distractor was different when it appeared in the high or low target frequency location, possibly reflecting an indirect effect of statistical learning. Indeed, SL produced a change in attentional priority in favour of the location where the target was more likely to appear at the service of upcoming target selection and this prioritization process might in turn result in more difficulties in the engagement of distractor suppression mechanisms at that very same location: in simple words, we might expect a larger cost for salient distractors occurring at the location where the target appeared with high (vs. low) frequency. A rANOVA with the within-subject factor Salient Distractor Location (high target frequency location, low target frequency location) was thus performed considering only the training epoch. However, we did not find any significant effect neither in terms of accuracy [$F(1,26) = 1.10$, $p = 0.303$], nor in terms of RTs [$F(1,26) = 0.41$, $p = 0.525$]. These negative result suggest that, in the context of the present experiment, the prioritization process following SL of target location selectively affected subsequent target selection, but not distractor filtering (but see e.g., Ferrante et al., 2018 for contrasting evidence; see also Chelazzi et al., 2019 for review).

2.3.3 Discussion

Experiment 2 had the primary objective of studying the effects of one of the experience-dependent attentional control mechanisms, known as statistical learning. The analyses showed that, following the exposure to statistical regularities, such as a specific imbalance in the frequency of target occurrence across locations, a significant modulation of attentional priority emerged across locations in the visual space. Specifically, participants showed better performance for targets presented at a location associated with high-target probability compared with at a location associated with low-target probability. In the test phase, where the statistical manipulation was removed, a rapid extinction of the learned attentional bias was observed.

Furthermore, also in this experiment, the presence of a salient distractor produced a cost in the subjects' performance during the whole experimental session; critically, attentional capture was observed regardless of any imbalance in the target frequency distribution, suggesting that the two AC mechanisms might exert independent effects (see Discussion).

2.4 EXPERIMENT 3

Experiment 3 aimed to investigate the interaction between the two attentional control mechanisms studied in the previous experiments, namely top-down guidance, as tested via an endogenous cueing manipulation (Experiment 1), and statistical learning, following the introduction of an imbalance in the target frequency distribution across locations (Experiment 2).

Here, we directly tested whether these two sources of AC independently operate in assigning attentional priority to a specific spatial location, one regardless of the other, such that they might be both actively contributing to attentional guidance or to the final attentional choice; or, in contrast, if one of them might gain prevalence over the other in a given time and context, such that one mechanism (e.g., statistical learning) will not affect performance when the other (e.g., top-down) is at a play.

2.4.1 Methods

Again the methods were identical to those described for previous experiments (see above), with the following exceptions.

Participants

Twenty-eight healthy volunteers (8 males; mean age \pm SD, 22.53 \pm 2.50) took part in Experiment 3. Two participants were excluded from subsequent analyses due to low accuracy (lower than -2SD from the average accuracy: mean - 2SD = 87.28 - 17.05).

Apparatus and stimuli

Stimuli and procedure were identical to those used in the previous experiments. As in Experiment 2, no task-relevant distractor was introduced in this paradigm, while a salient distractor appeared in the visual search display in half of the total trials.

Task and experimental design

In order to investigate the interaction between the two previously described AC signals, we combined the experimental manipulations employed in Experiments 1

and 2: the use of a central visual cue, being either valid or neutral, supported the controlled implementation of the top-down mechanism (as in Experiment 1); the application of an imbalance in the target frequency distribution across locations in the visual search display instead elicited a statistical learning process (as in Experiment 2). Importantly, in order not to mix (and confound) the two AC manipulations, the valid cue, when present, indicated with equal frequency each of the four possible target locations. Therefore, the SL manipulation was only applied in neutral cue trials.

The experiment included two consecutive phases. The first epoch, defined as the baseline, consisted of 384 trials in which the target stimulus appeared with equal probability in all four locations of the visual display and was intended to evaluate the basal performance of the participants. In half of the trials, the cue was neutral and, in the other half, it was valid, indicating each of the four quadrants with the same probability. In the second epoch, defined as the training (1152 trials), we introduced the frequency imbalance in target occurrence across locations. As already mentioned, since the valid cue indicated the four quadrants with equal probability (192 trials, 16.6%: 48 trials per position), the statistical learning manipulation occurred only in the neutral cue trials (960 trials, 83.3%: specifically, in 48 trials the target appeared in the low-frequency location; in 432 trials the target appeared in the high-frequency location; in 240 trials the target appeared in each of the two intermediate-frequency locations).

In this experiment, we did not introduce any test phase in order to keep the length of the experiment more acceptable for the participants and in light of the rapid extinction of the statistical learning effect that emerged from the analyses of Experiment 2 (see above).

Furthermore, in half of the total experimental trials, a salient colour singleton (as in Experiments 1 and 2) appeared on the screen, probing the engagement of distractor suppression mechanisms. The salient distractor could appear with equal probability in all four locations across the search display.

Procedure

The trial sequence was identical to the previous experiments, with the only difference that the interval between the cue and the display onset (CTI) was chosen randomly in an interval between 750ms and 1250ms, to further simplify the experimental design.

2.4.2 Results

Interaction between top-down and statistical learning

To study the interaction between statistical learning and top-down mechanisms, a rANOVA was conducted with the within-subject factors Epoch (baseline, training), Cue (valid, neutral), Target Frequency (high, low) and Salient Distractor (absent, present). In line with the previous experiments, we found significant main effects of Epoch [ACC: $F(1, 25) = 30.57$, $p < 0.001$, $\eta^2p = 0.55$; RT: $F(1, 25) = 29.17$, $p < 0.001$, $\eta^2p = 0.53$], revealing a significant impact of practice at the task, and Salient Distractor [ACC: $F(1, 25) = 15.09$, $p < 0.001$, $\eta^2p = 0.37$; RT: $F(1, 25) = 24.31$, $p < 0.001$, $\eta^2p = 0.49$], confirming an attentional capture effect by the salient interfering stimulus. Moreover we also observed main effects of Cue [ACC: $F(1, 25) = 26.83$, $p < 0.001$, $\eta^2p = 0.51$; RT: $F(1, 25) = 97.97$, $p < 0.001$, $\eta^2p = 0.79$], in line with an enhancement of target selection following a valid (vs. neutral cue), and Target Frequency, even if only on RTs [ACC: $F(1, 25) = 2.67$, $p = 0.114$; RT: $F(1, 25) = 11.27$, $p = 0.002$, $\eta^2p = 0.31$], reflecting better performance at high (vs. low) frequency locations.

More importantly and of direct relevance for the aim of the present study, results revealed a significant interaction between Cue and Target Frequency [ACC: $F(1,25) = 6.63$, $p = 0.016$, $\eta^2p = 0.20$; RT: $F(1,25) = 20.43$, $p < 0.001$, $\eta^2p = 0.44$]. However, the pattern of results was quite complex to interpret here, due to the many significant interactions between the factor Epoch and other factors, including Cue [ACC: $F(1, 25) = 2.92$, $p = 0.099$, $\eta^2p = 0.10$; RT: $F(1, 25) = 14.99$, $p < 0.001$, $\eta^2p = 0.37$] and Target Frequency [ACC: $F(1, 25) = 10.71$, $p = 0.003$, $\eta^2p = 0.30$; RT: $F(1, 25) = 19.59$, $p < 0.001$, $\eta^2p = 0.43$], as well as the interactions Cue*Target Frequency [ACC: $F(1,25) = 5.84$, $p = 0.023$, $\eta^2p = 0.18$; RT: $F(1, 25) = 14.02$, $p < 0.001$, $\eta^2p = 0.35$] and Cue*Salient distractor [ACC: $F(1,25) = 0.003$, $p = 0.951$; RT: $F(1, 25) = 6.33$, $p = 0.018$, $\eta^2p = 0.35$]. Thus, we decided to perform other two

rANOVAs with Cue (valid, neutral), Target Frequency (high, low) and Salient Distractor (absent, present), separately for the baseline and training phases of the experiment.

Starting with the training, i.e. the epoch where we could actually test the interaction between top-down control and SL, results confirmed a main effect of Cue [ACC: $F(1,25) = 16.11$, $p < 0.001$, $\eta^2p = 0.39$; RT: $F(1, 25) = 78.52$, $p < 0.001$, $\eta^2p = 0.75$] Target Frequency [ACC: $F(1,25) = 14.97$, $p < 0.001$, $\eta^2p = 0.37$; RT: $F(1, 25) = 32.23$, $p < 0.001$, $\eta^2p = 0.56$] and Salient Distractor, on RTs [ACC: $F(1,25) = 1.96$, $p = 0.17$; RT: $F(1, 25) = 5.61$, $p = 0.025$, $\eta^2p = 0.18$]. Critically, also the interaction between Cue and Target Frequency was confirmed [ACC: $F(1,25) = 11.93$, $p = 0.001$, $\eta^2p = 0.32$; RT: $F(1, 25) = 27.04$, $p < 0.001$, $\eta^2p = 0.51$]. Two-tailed post-hoc paired t-tests revealed that participants were more accurate and faster to respond to targets presented at high- (compared to low-) frequency locations, but only when the cue was neutral [ACC: 7.30 %, $t(25) = 3.97$, $p < 0.001$, Cohen's $d = 0.62$; RT: -89.40 ms, $t(25) = -6.20$, $p < 0.001$, Cohen's $d = -0.57$], and not when it was valid [ACC: 0.88 %, $t(25) = 1.14$, $p = 0.262$; RT: -8.72 ms, $t(25) = -1.08$, $p = 0.288$]. In contrast, the benefit of a valid cue was evident when the target appeared both in the high- [ACC: -4.87 %, $t(25) = -2.65$, $p = 0.013$, Cohen's $d = -0.73$; RT: 122.55 ms, $t(25) = 7.54$, $p < 0.001$, Cohen's $d = 1.19$] and low-frequency location [ACC: -11.29 %, $t(25) = -4.44$, $p < 0.001$, Cohen's $d = -1.12$; RT: 203.23 ms, $t(25) = 8.85$, $p < 0.001$, Cohen's $d = 1.51$] (Figure 5). This pattern of results suggests that top-down control was able to exert a gating effect on the statistical learning mechanisms, with the latter emerging only when the cue was neutral, i.e. in the absence of a strong endogenous guidance. Whereas, the impact of the salient distractor was instead generally independent from top-down and probability learning.

Considering the baseline epoch we found, again, a main effect of both Cue [ACC: $F(1,25) = 27.12$, $p < 0.001$, $\eta^2p = 0.52$; RT: $F(1, 25) = 98.99$, $p < 0.001$, $\eta^2p = 0.79$] and Salient Distractor [ACC: $F(1,25) = 12.39$, $p = 0.001$, $\eta^2p = 0.33$; RT: $F(1, 25) = 19.90$, $p < 0.001$, $\eta^2p = 0.44$]. As expected, no main effect was found for Target Frequency [ACC: $F(1,25) = 0.58$, $p = 0.45$; RT: $F(1, 25) = 0.001$, $p = 0.96$], since no SL manipulation occurred during baseline. In addition, in term of RT a

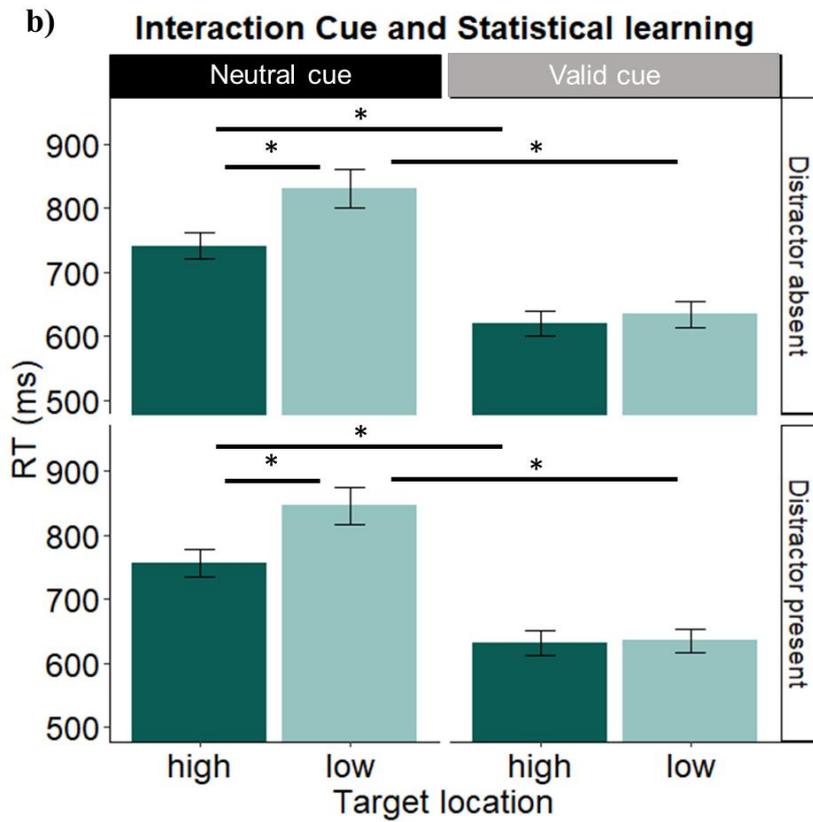
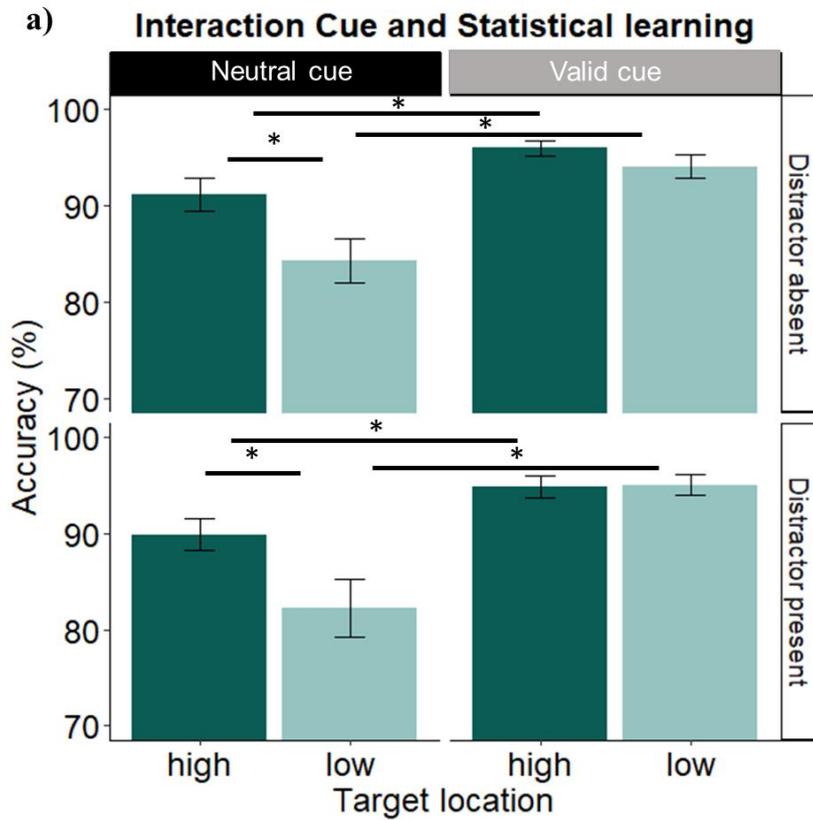
significant interaction emerged between Cue and Salient Distractor [ACC: $F(1,25) = 0.64$, $p = 0.42$; RT: $F(1, 25) = 10.52$, $p = 0.003$, $\eta^2_p = 0.29$]. Post-hoc t-tests on RTs revealed that the presence (vs. absence) of a salient distractor interfered with the performance only when the cue was neutral [RT: -48.32 ms, $t(25) = -4.87$, $p < 0.001$, Cohen's $d = -0.33$], but not when it was valid [RT: -6.82 ms, $t(25) = -0.90$, $p = 0.374$]. In contrast, the valid (vs. neutral) cue produced a benefit both when salient distractor was absent [RT: 188.31 ms, $t(25) = 9.39$, $p < 0.001$, Cohen's $d = 1.58$] and present [RT: -229.81 ms, $t(25) = 9.67$, $p < 0.001$, Cohen's $d = 1.76$]. Similarly to what we found in Experiment 1, these findings might index that at the beginning of the experiment the top-down control was able to prevent from the interference due to a salient distractor. This benefit was reduced during training (see above) maybe because participants learnt to inhibit the salient element with practice, thus efficiently doing so also in neutral trials.

Additionally, in terms of RTs, we also found a significant interaction between the factors Cue and Salient Distractor [ACC: $F(1,25) = 1.55$, $p = 0.224$; RT: $F(1,25) = 7.61$, $p = 0.010$, $\eta^2_p = 0.23$] and between Epoch, Cue and Salient Distractor [ACC: $F(1,25) = 0.003$, $p = 0.951$; RT: $F(1,25) = 6.33$, $p = 0.018$, $\eta^2_p = 0.20$]. Paired post-hoc t-test (two-tailed) on RTs revealed a significant distractor cost following a neutral cue [baseline RT: -47.48 ms, $t(25) = -5.27$, $p < 0.001$, Cohen's $d = 0.14$; training RT: -15.81 ms, $t(25) = -2.70$, $p = 0.009$, Cohen's $d = -0.09$], but not following a valid cue [baseline RT: -5.91 ms, $t(25) = -0.88$, $p = 0.38$; training RT: -7.54 ms, $t(25) = -1.21$, $p = 0.23$]. Similarly as with SL, top-down control was able to also block the information coming from a salient and irrelevant item.

Note that, in the survey that participants were required to fill in at the end of the experimental session, eight of them correctly identified the high-frequency spatial location as the location where the target was indeed more likely to appear. To control for the impact of participants' awareness, the rANOVA was repeated after excluding these eight participants. Previously collected evidence was fully confirmed, including the significant interaction between Epoch and Target Frequency [ACC: $F(1,17) = 6.07$, $p = 0.024$, $\eta^2_p = 0.26$; RT: $F(1,17) = 7.94$, $p = 0.011$, $\eta^2_p = 0.31$], corroborating the idea that SL is an implicit process.

Furthermore, also the interaction between Cue and Target Frequency was confirmed in terms on RTs and almost validated in terms of accuracy [ACC: $F(1,17) = 4.22$, $p = 0.055$, $\eta^2p = 0.19$; RT: $F(1,17) = 12.15$, $p = 0.002$, $\eta^2p = 0.41$].

TRAINING EPOCH



*Figure 5 a) Interaction between cue validity and SL effects in accuracy, during the training phase of the experiment, i.e. when both these mechanisms were at a play. b) Interaction between cue validity and SL effects in RTs, during the training phase of the experiment, i.e. when both these mechanisms were at a play. The upper row of each plot represents the salient distractor absent condition, whereas the lower row of the plots represents the salient distractor present condition. * $p < 0.05$*

2.4.3 Discussion

The aim of Experiment 3 was to investigate the combined influence of the different AC signals studied in isolation in the previous experiments, i.e. top-down AC and SL. In line with what has been described in Experiment 1, the presence of a valid spatial cue improved participants' performance, suggesting an effective pre-allocation of attentional resources to the spatial location of the upcoming target through a top-down mechanism. Furthermore, the statistical manipulation of target frequency across locations optimized performance in trials where the target appeared in high- (vs. low-) target frequency locations, which acquired a higher level of attentional priority, in line with what reported for Experiment 2. Critically, here we also found a strong interaction between the two AC control mechanisms, likely corresponding to a sort of gating exerted by the top-down AC over the influence of the SL. The effects of the latter were indeed measurable only in the absence of a strong endogenous guidance, i.e. in trials with a neutral cue.

Albeit collected evidence was very interesting, the proposed interpretation is not the only possible one. As a matter of fact, the effects of the endogenous cueing manipulation, as taken individually, produced quantitatively larger behavioural effects as compared to the SL process. The cue validity effect (difference in performance between neutral- and valid-cue trials) during the baseline epoch, where no SL manipulation was present corresponded to +11.93% in accuracy and -199.26 ms in RTs; conversely, the SL effect (difference in performance for targets at high- vs. low-frequency locations), during the training phase, corresponded to -7.30 in accuracy and 89.40 ms in RTs, as measured in the neutral-cue condition, where no top-down effect was at a play. Therefore, on the one hand, the prevalence of the top-down control could reflect the ability to voluntarily allocate the attentional

resources in order to efficiently accomplish current goals and a concurrent active inhibition exerted by this AC signal on other biasing signals, such as those derived from the statistical learning process. However, on the other hand, another interpretation might be that all AC signals independently contributed to determine the attentional priority of the different spatial locations, each with its intensity, such that here the prevalence of the top-down bias could simply reflect its greater relative weight in the current context. The evidence collected in Experiment 3, albeit suggestive, was therefore inconclusive; to shed further light on the functional meaning of the observed interaction, the effect of the two AC signals, as measured in isolation, should be comparable to begin with. To this end, in Experiment 4 we tested the possibility to obtain a quantitatively smaller, but always reliable, top-down attentional modulation to then be able to combine again the effects of top-down AC and SL induced biases, but of comparable strength.

Although outside of the main goals of the current research, the experimental design we used also allowed to gain some insights on the interaction between top-down attentional guidance and the impact of a salient, interfering visual items, which was capable to capture attention in bottom-up. Collected evidence confirmed that the presence of a salient distractor in the visual search display produced substantial costs in the participants' performance, which were partially attenuated by practice at the task. Critically, participants were more efficient in the suppression of the described interfering signal under the top-down guidance, compatible with the idea that top-down AC might exert a gating effect also on bottom-up biasing signals. However, in line with the previous reasoning, results are difficult to interpret here because of the strong prevalence of the cue validity effect over the distractor cost, which was even weaker than the SL effect (performance in distractor- present vs. absent trials in the neutral cue condition, during the baseline epoch: ACC: 79.12 vs. 81.3%; RT: 903.03 vs. 863.32 ms). By implementing a somehow weaker form of top-down control, we might be able to gain further information also on the interaction of the latter signal with bottom-up AC.

2.5 EXPERIMENT 4

Experiment 4 was designed as a variant of Experiment 1 specifically aimed at implementing a form of top-down guidance with a quantitatively reduced impact on performance, with the ultimate goal of obtaining a biasing AC signal of comparable strength with respect to that of the statistical learning process.

In this version of the task, the valid cue indicated a wide region of the search display (top, bottom, left or right) encompassing two relevant spatial locations, instead of a specific location (as in Experiments 1 and 3). As illustrated below, thanks to this manipulation, the voluntary pre-allocation of attention resources in space following a valid cue generated a robust, but weaker modulation. Also in this paradigm, the impact of attentional control signals was studied in relation to both target selection and distractor filtering, the latter by introducing a salient distractor in half of the trials, which, due to the type of cue, when present, could either appear in a cued location or in one of the two remaining non cued ones.

2.5.1 Methods

All methodological choices were identical to those described for Experiment 1 (see above), with the following exceptions.

Participants

Twenty-eight healthy volunteers (11 males; mean age \pm SD, 23.10 \pm 3.01) took part in Experiment 4. One participant was excluded from subsequent analyses due low accuracy (lower than -2SD from the average accuracy: mean - 2SD = 86.25 - 18.56).

Apparatus and stimuli

The new visual cue was similar to the one used in previous experiments, with the only difference that, valid cues comprised two adjacent corners coloured in cyan, indicating the two possible locations where the target could appear in the upcoming search display (Figure 6). The neutral cue was instead identical to the one implemented before (four pink corners).

CUE CONDITIONS

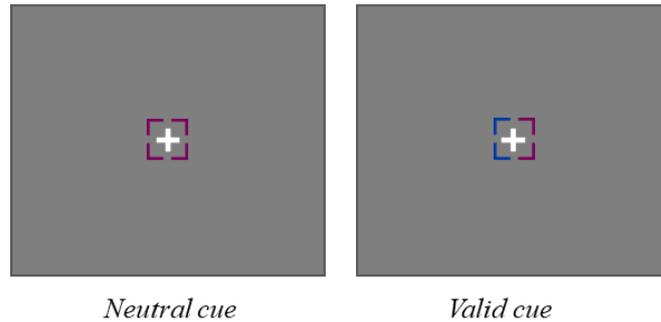


Figure 6: It represents the neutral (to the left) and an example of valid (to the right) cue used during Experiment 4. Here, the valid cue pointed to a region of the display (e.g. left side) instead of a specific spatial location, as in Experiment 1.

Task and experimental design

The task was the same as in Experiment 1. The cue could be either neutral (384 trials) or valid (384 trials), but, as stated above, unlike in the previous study, the valid cue indicated a region of the display, comprising two adjacent locations (i.e. top, bottom, right, left) where the upcoming target could appear, instead of a specific one.

Furthermore, in half of the total trials (192 trials with a neutral cue and 192 trials with a valid cue), there was a salient distractor. Because of the type of cue used in this experiment, the salient distractor location could also occur within the region indicated by the cyan corners of the cue, together with the target.

2.5.2 Results

Top-down control

Because the primary objective of this experiment was to obtain a top-down modulation of reduced size, first of all we compared the cue validity effects obtained in the current experiment with those of Experiment 1. A mixed rANOVA was performed with the within-subject factor Cue (valid, neutral) and the between-subject factor Experiment (Experiment 1, Experiment 4), after selecting the trials of the no-task-relevant-distractor module in Experiment 1 (see above). Results

showed a significant main effect of Cue [ACC: $F(1, 51) = 67.22$, $p < 0.001$, $\eta^2_p = 0.56$; RT: $F(1, 51) = 370.95$, $p < 0.001$, $\eta^2_p = 0.87$], and no effect of Experiment [ACC: $F(1, 51) = 0.25$, $p = 0.615$; RT: $F(1, 51) = 0.08$, $p = 0.767$]. The most important findings of this analysis was the significant interaction between Experiment and Cue [ACC: $F(1, 51) = 15.97$; $p = 0.001$, $\eta^2_p = 0.23$; RT: $F(1, 51) = 150.05$; $p < 0.001$, $\eta^2_p = 0.74$]. In line with our purpose, the benefit obtained here with a region-wide cue (ACC: valid minus neutral, 4.68 %; RT: neutral minus valid, 57.49 ms) was substantially reduced with respect to that obtained with a location-specific cue in Experiment 1 (ACC: valid minus neutral, 13.60 %; RT: neutral minus valid, 258.42 ms). This evidence confirmed that, albeit still fully reliable, the top-down modulation measured in Experiment 4 was significantly reduced as compared to that emerged in Experiment 1, leading the way to another combined experiment, similar to Experiment 3, but in which the attentional control signals involved could have comparable strength to begin with.

After verifying that our main goal was achieved, we proceeded with standard analyses. First, we performed a rANOVA with the within-factors Cue (valid, neutral) and Salient distractor (present, absent); here, we could also verify whether a weaker top-down guidance might still prevent from the attentional capture due to a salient and irrelevant item, as in Experiment 1. As stated above, because of the type of cue used in this experiment, in trials with a valid cue, the salient distractor could appear either in one of the two locations indicated by the valid cue (cued salient distractor condition) or in one of the locations outside the region indicated by the cue (uncued salient distractor condition). In order to select comparable conditions, in this analysis, we excluded trials with a cued salient distractor. The results show significantly better performance after a valid (vs. neutral) cue [ACC: $F(1, 26) = 36.95$; $p = 0.002$, $\eta^2_p = 0.58$; RT: $F(1, 26) = 79.76$, $p < 0.001$, $\eta^2_p = 0.75$]. Moreover, a significant capture effect was measured in the presence (vs. absence) of a salient distractor [ACC: $F(1, 26) = 10.76$; $p = 0.002$, $\eta^2_p = 0.29$; RT: $F(1, 26) = 26.79$, $p < 0.0001$, $\eta^2_p = 0.50$]. Finally, also in this experiment, a significant interaction between the two factors emerged [ACC: $F(1, 26) = 17.18$; $p = 0.001$, $\eta^2_p = 0.39$; RT: $F(1, 26) = 4.88$, $p = 0.036$, $\eta^2_p = 0.15$]. Paired post-hoc t-tests (two tailed) revealed that, at least in terms of reaction times,

the salient distractor interfered with performance after both a neutral cue [ACC: 3.41 %, $t(24) = 4.55$; $p = 0.001$, Cohen's $d = 0.36$; RT: -27.89 ms, $t(24) = -4.43$; $p = 0.001$, Cohen's $d = -0.27$] and a valid cue [ACC: -0.04 %, $t(24) = -0.08$; $p = 0.932$; RT: -13.56 ms, $t(24) = -3.67$; $p = 0.001$, Cohen's $d = -0.15$], even if in the latter case the cost was smaller (Figure 7).

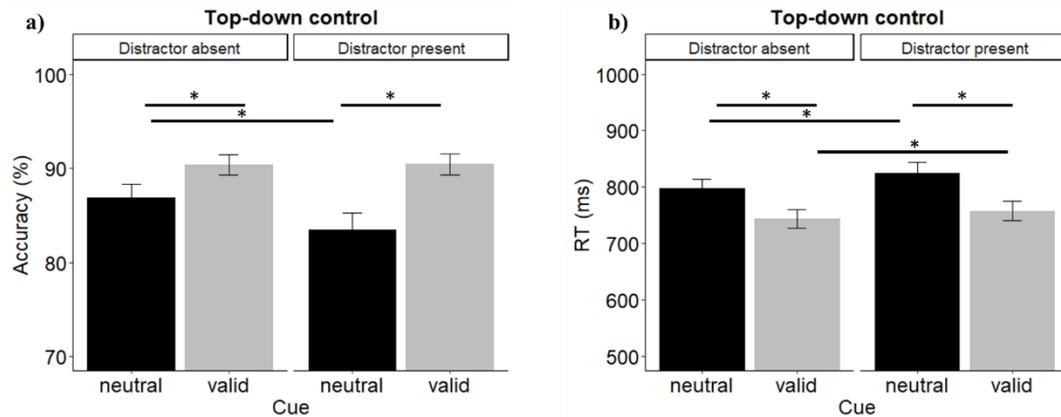


Figure 7: a) Cue validity effect in accuracy. b) Cue validity effect in RTs, as function of distractor presence. Performance as a function of the cue type (neutral in black vs. valid in grey) is shown as a function of distractor presence vs absence (right vs. left part of each plot). * $p < 0.05$.

Additionally, we assumed that the cued salient-distractors might produce greater interference on subjects' performance compared to uncued salient distractors. To directly verify this possibility, a rANOVA was performed with the within-subject factor Salient distractor (cued, uncued), selecting only the trials in which the cue was valid. Results confirmed our hypothesis, showing worst performance in the cued salient-distractor condition [ACC: $F(1,26) = 15.32$; $p < 0.001$, $\eta^2_p = 0.37$; RT: $F(1,26) = 7.73$, $p < 0.001$, $\eta^2_p = 0.22$].

2.5.3 Discussion

The aim of this experiment was to obtain a reliable, but weaker (reduced in size) effect of the top-down control signal by manipulating the amount of information

provided by the valid cue. Indeed, we tested the impact of a spatial cue with lesser spatial resolution, i.e. indicating a wider region on the screen (encompassing two adjacent locations in the visual search display), instead of a specific location (as in Experiments 1 and 3). The data confirmed that the valid cue used here improved performance, but the benefit on participants' performance was smaller in size with respect to that obtained in Experiment 1.

We also confirmed that the presence of a salient distractor interfered with participants' performance, especially when it appeared in one of the two locations indicated by the region-wide valid cue. However, in contrast with previous experiments, here, (even) the (uncued) distractor still captured attention even after a valid cue, likely thanks to the weaker impact of the top-down control.

In light of the collected results, we designed Experiment 5, a replication of Experiment 3 with the new cueing procedure tested here, with the aim of contrasting again statistical learning and top-down AC, in a context where the two biasing signals had comparable effects to begin with. This condition is in fact fundamental to obtain conclusive information about the putative prevalence of the top-down control over the experience-dependent one.

2.6 EXPERIMENT 5

Analogously to Experiment 3, Experiment 5 had the main purpose of studying the interaction between top-down and statistical learning attentional control mechanisms. The crucial difference from the previous experiment is that, in this case, the endogenous cueing manipulation consisted in the presentation of a visual cue that indicated a spatial region where the upcoming target would appear (as implemented in Experiment 4), instead of a specific location in the search display (as in Experiments 1 and 3). Thereby, since in Experiment 4 we demonstrated that a valid cue with lesser spatial resolution reduced the amplitude of the top-down modulation, Experiment 5 was optimized to investigate the interaction between two AC signals of comparable strength.

2.6.1 Methods

All methodological choices were identical to those described for Experiment 3 (see above), with the following exceptions.

Participants

Twenty-eight healthy volunteers (11 males; mean age \pm SD, 22.53 ± 2.47) took part in Experiment 5. Three participants were excluded from subsequent analyses due to low accuracy (lower than $-2SD$ from the average accuracy: mean $- 2SD = 82.79 - 28.42$).

Apparatus and stimuli

The valid cue used here was the same as the one used in Experiment 4, i.e. a cue that indicated a spatial region of the display. Furthermore, also in this study, in half of the trials a salient distractor was introduced and, when present, it could appear with equal probability in one of the two spatial locations indicated by the valid cue or in one of the remaining two locations.

Task and experimental design

The experimental design and procedure of this experiment were identical to those of Experiment 3. The only difference is that, as stated above, the visual cue, when

valid, indicated a spatial region of the upcoming search display (top, bottom, left, right) instead of a specific location. Importantly, the valid cue indicated with equal probability each of the four regions.

2.6.2 Results

Interaction between top-down and statistical learning

In order to reinvestigate the interaction between the statistical learning and top-down mechanisms, as tested here with signals of comparable strength (see above), we performed a rANOVA with the within-subject factors Cue (neutral, valid), Target frequency (high, low), Epoch (baseline, training) and Salient distractor (present, absent). In line with what emerged from the previous experiments, we found significant main effects of Epoch [ACC: $F(1, 24) = 21.82$; $p < 0.001$, $\eta^2p = 0.47$; RT: $F(1, 24) = 11.6$, $p = 0.002$, $\eta^2p = 0.32$], revealing a performance benefit due to the practice (i.e. in training epoch compared to the baseline), and Cue [ACC: $F(1, 24) = 14.38$; $p = 0.001$, $\eta^2p = 0.37$; RT: $F(1, 24) = 4.02$, $p < 0.0001$, $\eta^2p = 0.62$], with better performance following a valid (vs. neutral) cue. We also found a significant main effect of Salient distractor, even if only on RT [ACC: $F(1, 24) = 1.66$; $p = 0.209$; RT: $F(1, 24) = 5.84$, $p = 0.023$, $\eta^2p = 0.19$], corresponding to a performance cost when the salient distractor was present (vs. absent). Instead, only a marginally significant effect was found for Target frequency on RTs [ACC: $F(1, 24) = 2.88$; $p = 0.102$; RT: $F(1, 24) = 3.97$, $p = 0.057$, $\eta^2p = 0.14$].

Moreover, we found a significant interaction between Epoch and Target Frequency on RTs [ACC: $F(1, 24) = 0.95$; $p = 0.339$; RT: $F(1, 24) = 12.72$, $p = 0.001$, $\eta^2p = 0.34$], indexing that, during the training phase, participants acquired the SL bias. Finally, and most crucially for the purpose of the current experiment, especially in terms of RTs, here we confirmed the significant interaction between Cue and Target Frequency [ACC: $F(1, 24) = 0.78$; $p = 0.389$; RT: $F(1, 24) = 10.44$, $p = 0.003$, $\eta^2p = 0.30$] that we found in Experiment 3.

Given that there was also a significant interaction including Cue, Target Frequency and Epoch, at least in terms of RTs [ACC: $F(1, 24) = 3.88$; $p = 0.060$, $\eta^2p = 0.13$; RT: $F(1, 24) = 4.61$, $p = 0.042$, $\eta^2p = 0.16$], we decided to run an rANOVA separately for the baseline and training epochs in order to better

understand the interaction between top-down control and SL and, secondly, how they affected (or were affected by) the interference exerted by a salient distractor.

Results from training confirmed a significant benefit of having a valid (vs neutral) cue [ACC: $F(1, 24) = 1.03$; $p = 0.003$, $\eta^2p = 0.30$; RT: $F(1, 24) = 38.27$; $p < 0.001$, $\eta^2p = 0.61$] and a facilitation when target appeared in the high- (vs. low-) frequency location [ACC: $F(1, 24) = 7.46$; $p = 0.011$, $\eta^2p = 0.23$; RT: $F(1, 24) = 9.40$, $p = 0.005$, $\eta^2p = 0.28$]. However, also a significant interaction between the two factors emerged on RTs [ACC: $F(1, 24) = 3.28$; $p = 0.082$, $\eta^2p = 0.12$; RT: $F(1, 24) = 11.72$, $p = 0.002$, $\eta^2p = 0.32$]. Two-tailed paired post-hoc t-tests on RTs confirmed that Target Frequency had an impact on performance only after a neutral cue [-85.95 ms, $t(24) = -3.34$.; $p = 0.001$, Cohen's $d = -0.67$] and not when it was valid [-29.53 ms, $t(24) = -1.74$.; $p = 0.093$]. Instead, the cue validity effect was evident both for targets in the high- [27.26 ms, $t(24) = 2.99$; $p = 0.006$, Cohen's $d = 0.24$] and low-frequency locations [83.69 ms, $t(24) = 5.78$; $p < 0.001$, Cohen's $d = 0.61$] (Figure 8). Finally, the Salient Distractor interfered with the performance, especially in terms of RTs [ACC: $F(1, 24) = 4.22$; $p = 0.521$; RT: $F(1, 24) = 4.64$; $p = 0.041$, $\eta^2p = 0.16$]. During the training epoch, no significant interaction emerged between Cue and Salient Distractor [ACC: $F(1, 24) = 2.50$; $p = 0.621$; RT: $F(1, 24) = 0.15$; $p = 0.701$].

The analysis performed on baseline, instead, showed the well-established cueing effect [ACC: $F(1, 24) = 7.92$; $p = 0.009$, $\eta^2p = 0.24$; RT: $F(1, 24) = 21.49$; $p < 0.001$, $\eta^2p = 0.47$] and a marginal significant interference due to the presence (vs. absence) of a Salient Distractor [ACC: $F(1, 24) = 1.29$; $p = 0.266$; RT: $F(1, 24) = 3.63$; $p = 0.068$, $\eta^2p = 0.13$]. None of the other main effects or interactions were significant (all $ps > 0.1$).

TRAINING EPOCH

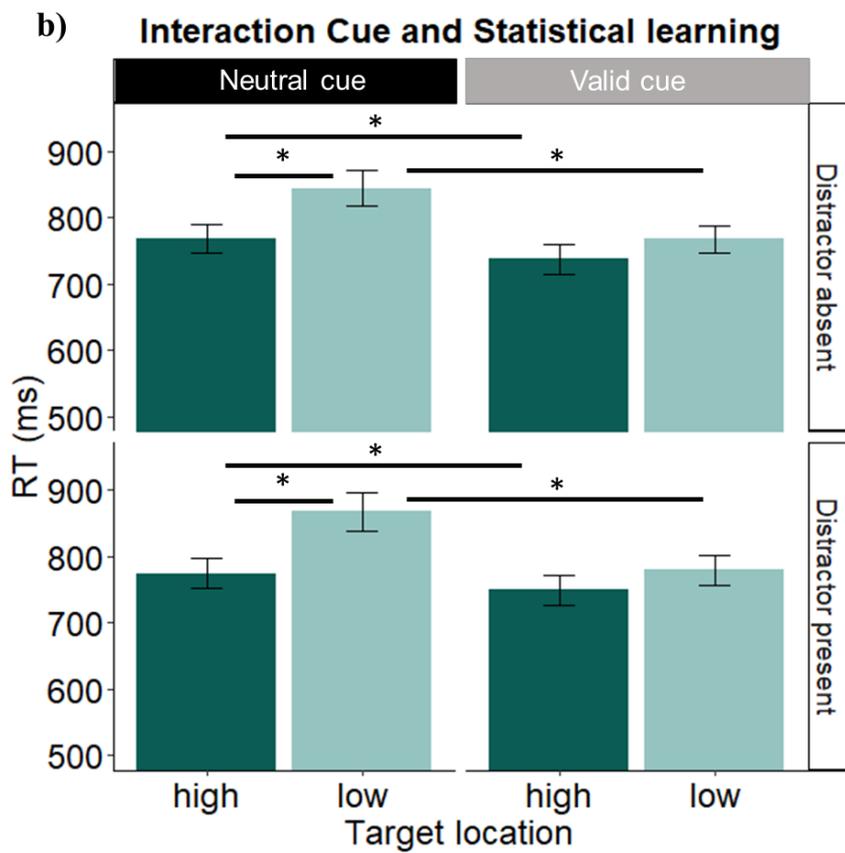
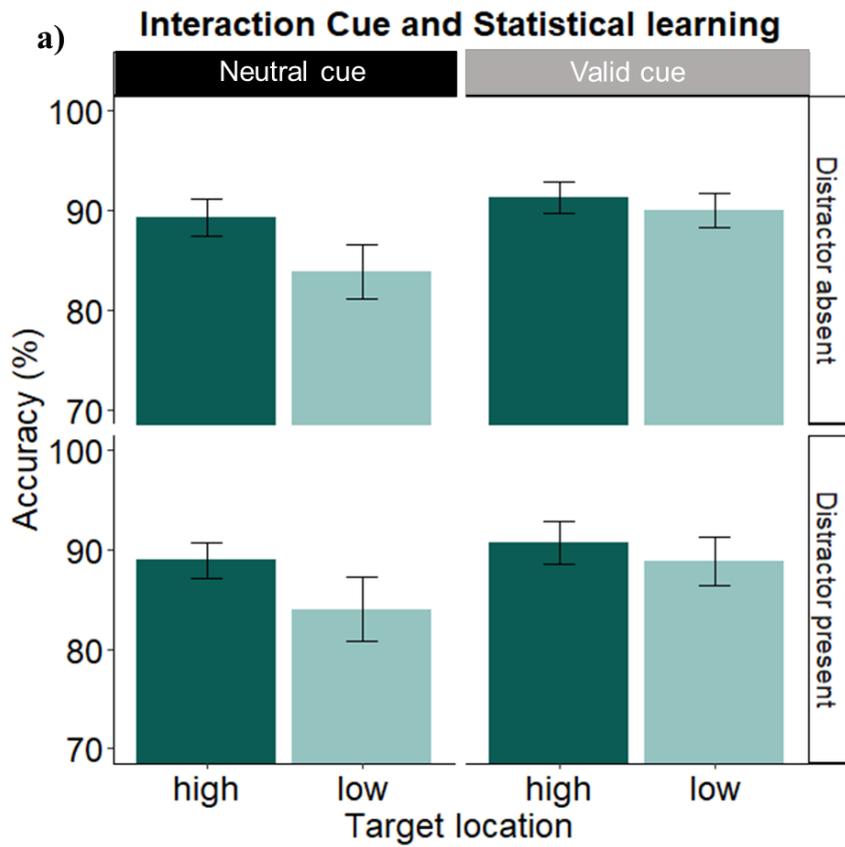


Figure 8: a) Interaction between cue validity effect and SL effect during training epoch (i.e. when both mechanisms were at a play) in terms of accuracy. b) Interaction between cue validity effect and SL effect during training epoch in terms of RTs. The upper row in each plot represents conditions in which the salient distractor was absent, whereas the lower row in each plot represents the salient distractor present condition. * $p < 0.05$

We then replicated this analysis, after excluding ten participants who reported the high-frequency location as the position where the target actually appeared more frequently, in the final survey administered at the end of the experimental session. The analysis confirmed the overall pattern of results assessed at the level of the entire group of participants, including a significant interaction between Target Frequency and Cue in terms of RTs [RT: $F(1,14) = 7.35$, $p = 0.016$, $\eta^2_p = 0.34$].

Overall, the collected evidence corroborates the results of Experiment 3, suggesting that top-down control was able to exert a strong guidance on attentional deployment, by gating the attentional biases induced by the statistical learning process, albeit the latter were clearly efficient in the absence of endogenous signals (neutral cue condition). Since in this experiment, the entity of the top-down modulation was even smaller in size with respect to the SL effect, we can argue that even the interaction we observed in Experiment 3 was not due to quantitative difference in the strength of the two mechanisms, but clearly reflects a qualitative (functional) prevalence of the top-down control, at least in the context of the current experimental setting.

None of the other main effects or interactions was significant, including the critical interaction between Cue and Salient Distractor (all p s > 0.1), suggesting that, in this experiment, top-down guidance was not able to prevent the interference from a salient irrelevant distractor.

2.6.3 Discussion

The main purpose of Experiment 5 was to investigate again the degree of independence between the different AC mechanisms under study, under more informative conditions. In the previous combined experiment (Experiment 3), we obtained evidence suggesting a gating effect exerted by top-down AC over the biasing signals derived from the statistical learning process. Unfortunately, given the relatively larger size of the top-down modulation as compared to the SL effect in that experiment, the, the observed results could either derive from a real inhibition/blocking effect exerted by the top-down signals over the SL, or be the result of an independent contribution of both mechanisms in shaping the attentional priority of given spatial locations, each contributing with its very different weight to the computation. In the latter case, the apparent prevalence of the top-down signals would merely reflect the greater entity of the effect, without being in any sense related to the functional organization of the attentional control circuitry.

Thus, we set out to test whether the results of Experiment 3 could be replicated by including modulations of comparable size to begin with. More specifically, in Experiment 4, we successfully validated a new type of cue, indicating a spatial region of the search display where the upcoming target could appear, instead of its specific location (as it was in Experiments 1 and 3), which was able to produce a robust, but smaller, behavioural effect due to engagement of top-down mechanisms. By using this new type of cue, in the current Experiment 5, we thus repeated the study of the interaction between top-down AC and SL. As a result, we replicate the findings of Experiment 3, i.e. a prevalence of the top-down effect over statistical learning, clearly supporting the idea that the former exerts a real, functional gating effect on the latter.

In contrast, we observed that, even in the presence of a weaker top-down control, the interfering impact of a salient distractor was still measurable, in line with the idea that pre-allocating attentional resources in the region of the display instructed by the region-wide valid cue was not enough to prevent the impact of bottom-up signals.

2.7 General discussion

The main purpose of the study was to investigate how stimulus competition is solved by the unique and combined effect of different AC mechanisms, namely top-down guidance, as modulated via an endogenous cueing protocol, and statistical learning, as introduced by using an imbalance in the target frequency distribution across locations. One possibility is that, in a given context, stimulus competition is biased and solved by the activity of a single source of attentional control that gets precedence over the other(s), whereas another possibility is that all priority signals independently act to assign priority to a certain spatial location, such that the resulting weighted average of modulations coming from all sources of AC will inform a general priority computation.

As a first step, we wanted to assess the effect of each AC mechanisms of interest taken separately. To this aim we created variants of a similar visual search paradigm in order to study the unique impact of those signals within the same experimental context (see also Rashal et al, 2022; Beffara et al., 2022; Dolci et al., *submitted*).

In Experiment 1 and 4, a central visual cue predicted in advance the forthcoming target location in some trials (valid cue condition), whereas, in some other trials no instruction was given (neutral cue). The cue, when valid, indicated a specific spatial location within the search array (Experiment 1) or a wider region of the display, which encompassed two possible target locations (Experiment 4). Independently of the higher or lower spatial resolution of the valid cue, we confirmed previous evidence in the literature, i.e. better performance was measured when participants could allocate their attentional resources to the instructed location/region in advance (e.g., Posner, 1980; Rashal et al., 2022).

Similarly, in Experiment 2, we also corroborated previous evidence suggesting that statistical learning processes might shape attentional deployment across space (e.g., Geng & Behrmann 2005; Ferrante et al., 2018), by assessing a benefit in favour of the location where the target was more likely to occur (high-frequency location) compared to the location where it occurred more rarely (low-frequency location), reflecting a strong prioritization of the former.

Crucially, we then set out to test the combined impact of the AC signals under investigation. Here, the critical finding is that, when active together, top-down control seems to override the influence of SL mechanisms, which can emerge only in the absence of a fully predictive, valid cue.

In two experiments, we tested different forms of endogenous cuing, which differed in terms of spatial resolution (specific spatial location vs. wider spatial region) and therefore resulted in modulations of larger or lower intensity, respectively.

In Experiment 3, where the valid cue precisely indicated the exact location of the upcoming target, we observed a strong prevalence of top-down control over SL, which however could be merely due to the relatively larger strength of former with respect to the latter. Based on this experiment, the absence of any SL effect in the valid cue condition could not be interpreted unequivocally, as it could either reflect the larger relative weight of the top-down signal in a shared computation of attentional priority or the fact that its intervention gated possible contribution from other sources of attentional control. Therefore, in Experiment 5, we tested again the interaction of interest, but after implementing the weaker, albeit still robust and reliable, endogenous cueing manipulation that we preliminary tested in Experiment 4. In Experiment 5, we replicated previous findings, with the top-down control abolishing the impact of SL; our interpretation is therefore unequivocally in favour of the idea that top-down guidance, when coming into play, is able to restrict/block any influence derived from the implicit learning of the target frequency distribution across locations. In simple words, when fully reliable instructions are available for where to orient our attention in order to find our target, information from past experience with the task is not taken into account.

In another study (Dolci et al., *submitted*), we found a similar gating effect of top-down over SL on performance during the same visual search task implemented here. However, in that research, we observed a significant modulation of the N2pc component of the EEG (which is believed to index the target selection process) due to the both top-down control and SL, resulting in an N2pc enhancement both for targets preceded by a valid (vs. neutral) cue and for targets presented in the high- (vs. low-) frequency location. However, the impact of top-

down control was blocked by the imbalance of target frequency distribution. In particular, a larger N2pc was elicited for validly cue targets presented in the low-, but not in the high- frequency location. This finding might suggest that information collected in past encounters with the task still has an influence at some level of the target selection process, albeit not influencing overt behaviour, likely because it is not allowed to enter the final attentional decision process. More precisely, it might be that what we observe behaviourally is the reflection of a “partial” gating exerted by the top-down control, with the more sensitive EEG measures revealing that SL-induced shaping of priority is still available at the brain level to be able to inform future attentional operations, as soon as a greater degree of uncertainty is sensed (as in the neutral cue condition). This interpretation might parallel what found in some recent studies where participants’ efficiently learn to suppress distracting stimuli, even if they were highly interfering due to their emotional content, thanks to extensive practice, with a sensible reduction of attentional capture effects; nonetheless, the emotional content of the interfering stimuli was still processed as reflected by a significant modulation of the LPP (late-positive potential) component of the EEG (Minucci et al., 2020): in other words, albeit not influencing behaviour, the biasing signal derived from emotional processing of those stimuli was still available in the brain, likely because it could turn to be useful to inform attentional deployment in future attentional decisions or, while being processed implicitly, it could have even be recognized as so relevant to change the current individual’s goals.

Nevertheless, our results are apparently in contradiction with other evidence in literature which, instead, supports the idea of an additive effect of top-down control and SL, which might jointly act to guide attention in space. For instance, Geng and Behrmann (2005) argued that these two AC mechanisms might be involved in two distinguishable and independent processes since in their experiment they found a facilitation to detect the target both in the valid cue condition and in the location where it was more likely to appear (Geng & Behrmann, 2005). However, in that study, it was difficult to really distinguish between top-down control and SL since the valid cue pointed to the high-frequency target location more often than to the other locations. Therefore, the SL effect they found also

when the cue was valid could be also partly due to the cue-frequency manipulation rather than to the target-frequency imbalance only. It is for this reason that, in our current study, we introduced the SL manipulation only in the neutral cue trials. This aspect allowed us to critically disentangle the specific benefit due to each AC mechanism, respectively, which revealed an interaction between top-down control and SL.

Indeed, as already mentioned above, 100% valid, explicit endogenous cueing was able to behaviourally override information coming from probability learning, thus being solely responsible for the actual attentional choice. In contrast, in experiments where the top-down control manipulation was not fully reliable, i.e. there were some invalid cue trials, such a gating effect over statistical learning did not occur (Geng & Behrmann, 2005; Gao & Theeuwes, 2020). One plausible explanation rests on the idea that there may be a fundamental difference in how fully-reliable and less-reliable explicit top-down AC biases are used, as participants will end up not fully trusting instructions, when invalid conditions are included, and therefore will stop fully relying on top-down guidance. Along this line of reasoning, our choice to decrease the spatial resolution of the endogenous cue (see Experiment 4), while maintaining 100% validity, critically allowed us to not compromise the reliability of top-down control. Indeed, to selectively evaluate the benefit of a valid cue it is necessary to compare conditions where participants know in advance the upcoming target location/region to conditions where they do not have any information, instead of conditions where the conveyed information is wrong (i.e. invalid conditions).

Additionally, in Experiment 1, top-down AC seemed to exert a partial gating effect also over bottom-up mechanisms. First of all, following a valid cue, the presence of a salient target (which differed in colour from the other stimuli) did not improve participants' performance with respect to when all the stimuli had the same colour. This might reflect a blockade of salience biases as implemented via top-down guidance or the result of a sub-additive contribution of both sources of AC, due to the strong impact of the latter (which exceed by far that of the salience signal), as also suspected in Experiment 3 in relation to the prevalence over the SL effect. Unfortunately, in this experiment we could not assess a baseline condition,

e.g., with neutral cueing, where a bottom-up effect could be measured in isolation, therefore any interpretation of the described negative result is to be taken with caution.

Interestingly, however, in a study by Rashal and colleagues (2022), that used the same visual search task of the present study (with some adjustment due to the EEG activity recording), they observed a diminished benefit derived from bottom-up AC mechanisms after a valid (vs. neutral) cue (Rashal et al., 2022). It is important to note that, since their paradigm was very similar to ours, also in their experiment the bottom-up effect was weaker than the top-down modulation. Therefore, future studies have to be developed to re-investigate this interaction with signals of comparable strength, with the same logic used here in developing Experiment 5.

Although outside the primary goal of our study, as a second pool of evidence related to the interaction between top-down and bottom-up signals, we could also examine the impact of a salient but irrelevant stimulus, i.e. a salient distractor. In Experiments 1 and 3, the salient distractor was indeed able to automatically capture attention and interfere with the task, in the absence of top-down guidance (neutral cue condition), while the distractor cost was mitigated by the presence of a strong top-down control, i.e. a valid (location-specific) cue. The latter finding might suggest that top-down control is able to prevent attentional capture, by blocking the impact of bottom-up signals. However, in Experiments 4 and 5, by using a weaker cueing manipulation, we found that the salient distractor still interfered with the task, even in the presence of a valid (region-wide) cue. Overall, our findings are therefore more in line with the idea that both top-down and bottom-up biasing signals contributed to the attentional choice, albeit with different strength or relative weight. In a recent study of fMRI which used a variant of the same visual search task of our study, Bertrand and colleagues (2022) tested how endogenous and exogenous AC signals modulate quadrant-specific activations in the occipital cortex. They found that under the top-down control the presence of a salient target produced an attentional enhancement, while a salient distractor reduced it, suggesting an independence between the considered attentional mechanisms which could jointly be responsible for attentional deployment (Bertrand et al., 2022).

Importantly, in this and other studies from our group (e.g., Dolci et al., *submitted*; Rashal et al., 2022; Beffara et al., 2022), we set out to investigate the unique and combined impact of different attentional control signals in a constant experimental setting, such that all collected results might be directly comparable and might be pulled together in order to contribute to shedding light on the functional architecture of visual spatial attention. So far, the collected results seem to be compatible with the idea that the allocation of attentional resources in space needed for both target selection and active distractor suppression, occurs at the level of a spatial priority map, where the neuronal activity related to each location reflects its level of attentional priority. Here we found that, when multiple AC signals are active together, stimulus competition seems to be preferentially solved by top-down mechanisms. As a matter of fact, independently of the strength of the cueing effects, top-down control do have a precedence over statistical learning effects, with the latter clearly emerging only in the absence of endogenous guidance.

Furthermore, under top-down control, also the impact of salience signals seems to be substantially reduced, as reflected by the absence of distractor costs in the presence of a valid, location-specific cue. However, in this case, no gating effect is at play, since the salient distractor is still able to interfere with the task, when attention is guided by the weaker, region-wide valid cue.

Thus, to recapitulate, it is plausible to hypothesize that any interaction between top-down and bottom-up signals is based on their relative weight with both independently contributing to the priority computation. At least in the context of the present experiment, the interaction between top-down AC and SL mechanisms was instead deemed to be functional, with the former overriding the influence of the latter, unrelated to their relative weights.

**INTEGRATED EFFECTS OF TOP-DOWN ATTENTION AND
STATISTICAL LEARNING DURING VISUAL SEARCH: AN EEG
STUDY**

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² Chapter 3 is a submitted manuscript, that describes an EEG study performed at the University of Ghent (Dolci Carola, C. Nico Boehler, Elisa Santandrea, Anneleen Dewulf, Suliann Ben-Hamed, Emiliano Macaluso, Leonardo Chelazzi, Einat Rashal. *Integrated effects of top-down attention and statistical learning during visual search: an EEG study, submitted*).

3.1 INTRODUCTION

In everyday life, the large number of visual inputs coming from the environment greatly exceeds our sensory and cognitive processing capacities. Looking for a book in a crowded library can be a difficult task since, at all times, all the available visual stimuli compete with each other in order to gain access to further processing. Visual attention is the cognitive function that acts as a filter, allowing us to select the relevant information and tune out what is irrelevant (Desimone & Duncan, 1995; Reynolds & Chelazzi, 2004). This process involves one or multiple attentional control mechanisms that assign processing attentional priority to a certain stimulus or location in the visual field. The activity of different AC mechanisms converges in the priority map, which is a topographically-organized neural representation of visual space (Bisley & Goldberg, 2010; Ptak, 2012), where, depending on the context and time, each location has a specific level of the neuronal activity determined by the amount of assigned attentional priority to that spatial location (Awh et al., 2012; Chelazzi et al., 2013; Ipata et al., 2009; Serences & Yantis, 2007). The highest activation peak triggers a winner-take-all process, leading to the target at that location being selected (Bisley, 2011; Chelazzi et al., 2014; Macaluso & Doricchi, 2013; Noudoost et al., 2010).

Traditionally, AC mechanisms have been separated into two main categories: top-down and bottom-up. Top-down (or goal-directed) AC is an endogenous process, driven by active volitional selection of items that are relevant to a person's goals or instructions (Carrasco, 2011; Egeth & Yantis, 1997; Leber & Egeth, 2006; Reynolds & Heeger, 2009). For instance, the competition between stimuli can be solved by the presence of a central visual cue which indicates the forthcoming target location and allows the pre-allocation of attentional resources to that position, facilitating target detection (Posner, 1980). In contrast, bottom-up attention is an exogenous AC mechanism by which attentional resources are automatically allocated toward a salient stimulus with highly noticeable feature properties, such as luminance, color, or shape (Theeuwes, 1991, 1994; Theeuwes & Godijn, 2004; Yantis & Egeth, 1999).

In recent years, it has been shown that people can implicitly develop another type of bias specifically linked to the individual's previous experience with a given

context and/or stimuli, which can also guide target selection (Awh et al., 2012; Ferrante et al., 2018; Jiang, 2018). Therefore, a third AC category has been introduced – experience-dependent AC (Awh et al., 2012; Chelazzi & Santandrea, 2018; Failing & Theeuwes, 2018). One of the experience-dependent mechanisms is statistical learning (SL) that allows humans, but also other animals, to implicitly extract regularities from the environment even without having explicit instructions (Aslin & Newport, 2012; Druker & Anderson, 2010; Ferrante et al., 2018; Geng & Behrmann, 2002; Duncan & Theeuwes, 2020; for evidence in non-human primates: Newport et al., 2004; and chicken: Santolin et al., 2016; Rosa-Salva et al., 2018). In particular, the probability with which a target element occurs in a specific location was found to induce an attentional bias toward the location where it is more likely to appear, without the participant being consciously aware of this.

As described above, a lot is known about how visual attention is guided by individual AC mechanisms. However, these studies, which are very useful in identifying different sources responsible for the deployment of attention, are limited to a certain context, where only one mechanism is at a play. In many aspects of everyday life, however, multiple AC mechanisms can act simultaneously, and it is still unclear how exactly they interact with one another in the prioritization process and how the final attentional choice is established. One alternative is that, when active simultaneously, the activity of all the AC mechanisms is added-up and they jointly contribute to solving the competition in favour of one stimulus. Alternatively, one mechanism prevails over the other and is responsible for target selection.

The aim of the present study is to study the combination of AC mechanisms, specifically, top-down AC and statistical learning, and test the hypotheses of a joint contribution or mechanism prevalence in solving the competition between stimuli over attentional resources. Previous studies are more in line with the first hypothesis, arguing that these two mechanisms operate independently from each other, since the activity of one mechanism is not affected by the activity of the other mechanism (Duncan & Theeuwes, 2020; Gao & Theeuwes, 2020; Geng & Behrmann, 2005). For instance, Gao and Theeuwes (2020) showed how SL biased the competition in favour of a target that appeared frequently in a certain location,

compared with a target that appeared in a rare location in the array, and that this effect was not contingent on the allocation of top-down attention to either location. At the same time, better performance was found when participants could benefit from valid (vs. invalid) information that was given to the top-down AC mechanism, both when the target was present in the high- and the low-frequency locations (Gao & Theeuwes, 2020). This suggests that both mechanisms can guide the attentional selection of specific spatial location on the priority map, which implies an additive effect of top-down control and SL activity.

However, in that study, top-down control was always present, as participants were instructed to attend to a location in the array that could be a match to the location of the upcoming target, but not with complete certainty; only on 50% of the trials the cue indicated the exact target location, whereas on the other trials it indicated a location nearby. Thus, it is possible that the cue validity led to the absence of an observable interaction between the two mechanisms. That is, the level of uncertainty introduced in the paradigm may have prevented a possible interaction between the mechanisms. For this reason, in the current study we provided participants with a fully predictive top-down control guidance, by using a 100% valid cue that pointed to the upcoming target location and compared it to a condition where top-down control was not at play, where participants were provided with an uninformative neutral cue.

EEG markers of visual selective attention

To further examine the prioritization process in visual search, in the present study, we investigated the neural mechanism underlying it. Specifically, we focused on three well-established ERP components related to attentional selection: the cue-related CNV, and the target-related P1 and N2pc. When investigating selective attention using visual-search paradigms, the principal EEG marker of interest is the N2pc, which is the negative deflection at posterior electrodes contralateral to the target, typically emerging around 200 ms from the onset of a lateralized target. Initially, the N2pc was commonly assumed to index the shift of covert attention toward a task-relevant, or salient stimulus (Eimer, 1996; Luck & Hillyard, 1994), but other findings suggest that the N2pc reflects various aspects of target processing

(Kiss et al., 2008; Theeuwes, 2010; Zivony et al., 2018). Importantly to the current study, in recent work using a very similar task to the one used here, Rashal and colleagues (2022; Experiment 2) observed an N2pc for targets preceded by a valid endogenous cue to the target location, suggesting that the N2pc reflected attentional processes also following top-down deployment of attention to that location.

As SL induces a change of attentional priority in favour of the high-frequency target location, it would be expected that a facilitation of target selection (Ferrante et al., 2018; Geng & Behrmann, 2002) would be accompanied by a larger N2pc elicited by that target. Still, a recent study by van Moorselaar and Slagter (2019) found instead a reduction of N2pc amplitudes when the target appeared frequently in a certain location. In their study, however, the target competed with only one other stimulus (i.e., distractor), making the task easier as attentional selection was quickly accomplished (see also Rashal et al., 2022, for evidence that the N2pc is modulated in amplitude by difficulty-related factors). Furthermore, statistical learning in that study was constrained to target repetitions, with the target appearing at the same location for a number of consecutive trials (4 trials) within a sequence, but that location varied across the duration of the experiment. However, in classic SL paradigms, target location frequency is associated to just one (or a few) spatial location or region across the entire experiment, allowing SL to be reinforced continuously and inducing an attentional enhancement in favour of that location. Critically, the modulation of the N2pc reported by van Moorselaar and Slagter (2019) revealed that the N2pc amplitude, and thus the deployment of attentional resources needed for target selection, was diminished for repeating target location in consecutive trials. That is, the N2pc was larger in the first trial than in the last trial of the repetition sequence. However, this result may be attributed to inter-trial priming and may not apply to a situation where SL is established across the entire experiment.

Other components related to attentional control, specifically for top-down control, are post-cue CNV and post-target P1 (Mangun, 1995; Schevernels et al., 2014; Van Den Berg et al., 2014). The CNV is characterized by a slow, negative-going waveform normally detected in central areas after the presentation of a warning stimulus such as a cue (Walter et al., 1964), likely reflecting a general

preparatory attention during the cue-target interval of attentional tasks (e.g., Grent-‘t-Jong & Woldorff, 2007). The P1 is the first positive-going ERP component, starting around 90 ms after target-array onset, and displays increased amplitudes over the occipital scalp contralateral to the precued location (Baumgartner et al., 2018; Mangun & Hillyard, 1991). P1 amplitudes have been demonstrated to be enhanced when the corresponding visual stimuli appeared on the cued compared with the non-cued side of the array, suggesting that they are an early manifestation of top-down attentional control (Mangun & Hillyard, 1991; Van Voorhis & Hillyard, 1977; Eimer, 1994).

Aim of the study

We devised a visual search task to investigate both isolated and integrated effects of different sources of AC during the target selection process. In particular, we focused on top-down attention control, which we manipulated via endogenous cueing, and statistical learning, which was manipulated by an imbalance of target frequency across locations. By comparing performance in trials where targets appeared in the high- (HFTL) versus low- frequency target location (LFTL) and preceded by an informative (valid) or non-informative (neutral) cue, we tested whether top-down control and SL, when active together, both contribute to assigning attentional priority to a specific spatial location (hypothesis 1) or if one mechanism is blocked by the presence of the other mechanism (hypothesis 2). Specifically, in the first case, if the two mechanisms operate largely independently, better performance and a larger N2pc should be observed for targets in the HFTL, compared with LFTL condition irrespective of the cueing condition. At the same time, cueing effects should emerge regardless of the target location frequency condition, and better performance and a larger N2pc should emerge following a valid cue both when the target appears in the HFTL and LFTL. Alternatively, if the two mechanisms interact with each other, we should find that one mechanism affects the other in some way. For example, it is possible that top-down control blocks the effect of SL mechanism, such that its effect can be reduced or even gated by pre-cueing the target location, resulting in a smaller difference in performance and N2pc mean amplitude between targets in the HFTL and LFTL following a valid

cue compared with the same difference in performance and N2pc amplitudes for targets following a neutral cue. Similarly, it can be that SL blocks top-down control. In this case, we should find that the benefit of validly cueing the target location is reduced by the presence of target-location frequency imbalance, resulting in a smaller cueing effect on behaviour and N2pc amplitude in the HFTL compared with the LFTL conditions.

Additionally, we focused on a set of other EEG components mostly related to the top-down control; the P1 during visual search, and the CNV during the cue-target interval. By looking at the CNV and P1 components, we can investigate modulations to top-down attentional orienting pre- and post-stimulus array onset. A larger CNV should emerge following a valid compared with a neutral cue, reflecting advance preparation for selecting the target stimulus (Rashal et al., 2022; Schevernels et al., 2014; Van Den Berg et al., 2014). Furthermore, the P1 could also be modulated by the presence or absence of a valid cue. Specifically, we expected a larger P1 following a valid compared with a neutral cue, indicating an early stimulus categorization when a stimulus is presented in the expected spatial location (Mangun, 1995; Heinze et al., 1994). Indeed, Livingstone and colleagues (2017) demonstrated that P1 indexes an enhanced processing for the search item pointed by a valid cue at a stage of vision that precedes attentional selection.

Lastly, even if a modulation of the CNV and P1 have been most clearly associated with cueing, here we tested if SL was able to affect the general preparation and attentional orienting pre- and post-stimulus array onset. If so, as for N2pc, we would expect a larger CNV and P1 for targets in the HFTL, compared with the LFTL condition, and this effect could interact with the cueing manipulation.

3.2 Materials and Methods

Participants

Twenty-four healthy volunteers (4 males; mean age 23.62, $SD \pm 3.4$) with normal or corrected-to-normal visual acuity participated in this experiment. None of them had previously taken part in similar or related studies, and they were naive to the purpose of the present study. At the end of the experiment, they received a fixed

monetary compensation for their participation (€32.5). All subjects gave their written informed consent before participation. The present study was approved by the ethical committee of the Faculty of Psychology and Educational Sciences of Ghent University (code 2021/09).

Apparatus and stimuli

The experiment was conducted in a dimly lit and quiet room, where participants sat in front of a 24" Benq XL2411Z LED monitor controlled by a Dell Optiplex 9020 tower with Intel Core i5-4590 processor, at 60-Hz refresh-rate. The viewing distance was held constant at 60 cm by using an adjustable chin rest. The experiment was run with the PsychoPy (v1.84.2) software (Peirce, 2007). Good central fixation by the participants was monitored using the camera of an Eyelink 1000 plus (SR Research, Canada). The experimenter was sitting in a different room and warned the participants during breaks in case eye-movements were observed in the preceding block, to allow correction.

The stimuli were rectangular bars of $2.0^\circ \times 0.5^\circ$ in size, either green (RGB coordinates: 0, 86, 0; luminance: 138.5 cd/m²) or red (RGB values: 170, 0, 0; luminance: 64.8 cd/m²), presented on grey background (RGB: 128, 128, 128; luminance: 85.5 cd/m²). Colours were randomly chosen on a given trial, with all stimuli being drawn in the same colour. The choice for two colours, which was not essential to the present task, and which were fully counterbalanced across conditions, largely relates to earlier work of ours using the same global approach (Rashal et al., 2022). Within each stimulus, there was a small gap (diameter of 0.25°) of the same grey colour as the background and positioned at the upper or lower part. The target was the bar tilted $\pm 25^\circ$ across the vertical axis, whereas all the other stimuli, that had to be ignored (distractors), were bars tilted $\pm 25^\circ$ across the horizontal axis. Two stimuli were presented in the upper visual field, two on the horizontal midline and two in the lower visual field (Figure 9, panel a). Since evidence indicates that the N2pc is usually larger in the lower visual field and on the horizontal meridian than in the upper visual field (Bacigalupo & Luck, 2019; Luck et al., 1997), the target never appeared in the two upper locations, which hence just contained filler items. In each visual search display, six stimuli were presented,

centred equidistantly 7° away from a white fixation cross ($0.5^\circ \times 0.5^\circ$; RGB: 255, 255, 255; luminance 190.2 cd/m²).

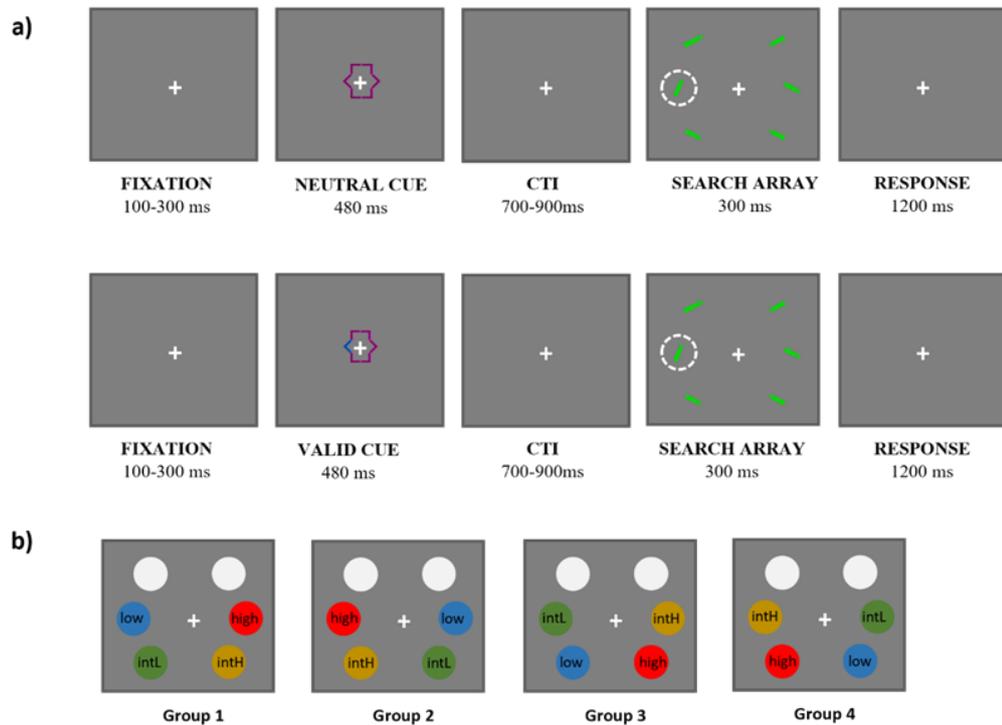


Figure 9. (a) Examples of the trial sequence. Top row: a neutral cue preceded target array onset. Bottom row: target location was predicted by a valid cue. The target is indicated in the figure by the dashed circle (for illustration purposes; no such circle was present during the task) and was the bar tilted $\pm 25^\circ$ from its vertical axis, while the non-targets were tilted $\pm 25^\circ$ from their horizontal axis. (b) Target frequency distribution across groups (during neutral cue trials only). Note that the target never appeared in the two upper locations.

Before the onset of the stimulus array, a cue stimulus was presented around the fixation cross (Figure 9, panel a). The cue consisted of a geometric shape (dimension: $1.5^\circ \times 1.5^\circ$) made up of six separate corners, each pointing at one of the stimulus locations. In the case of the neutral cue, all the corners were coloured with the same pink (RGB: 120, 0, 90; luminance: 89.5 cd/m²), whereas in the case of the valid cue, five corners were pink and one was cyan blue (RGB: 0, 56, 158; luminance: 81.1 cd/m²), indicating in which spatial position the target element would be presented (Figure 9, panel a).

Experimental design

A central cue presented prior to the target array onset was either valid or neutral. In the valid cue condition, the location of the upcoming target was predicted with a validity of 100%. In the neutral cue condition, the cue did not include information about the target location. Importantly, in order to not mix the two AC manipulations SL was manipulated exclusively following neutral cues, by introducing, unbeknown to the participants, an imbalance of target frequency appearance across the four possible target locations: high, low and two intermediate location frequencies (Ferrante et al., 2018). The valid cue, when present, indicated with equal frequency each of the four possible target locations (96 trials each location). The neutral cue trials (1216 trials; 76% of all trials), provided a baseline where the SL effect could be assessed in the absence of top-down guidance. Here the target appeared in the high-frequency location 50% of the trials (608 trials), in the low-frequency location for 7.9% (96 trials), and in each of the intermediate-frequency locations for 21% of these trials (256 trials each). We did not introduce an imbalance of target frequency appearance in the valid cue condition because doing so would mean introducing an imbalance of valid cues. This, in turn, would complicate the interpretation of the results, as it would be impossible to disentangle the benefit in target detection due to SL of the target location, or SL of the valid cue, or both. Participants were randomly assigned to one of four groups (Figure 1, panel b), each with a different spatial configuration of target-location probabilities, but with the constraint that the high-probability and low-probability conditions were always in opposite locations in the left vs. right visual field.

Procedure

Each experimental trial (Figure 9, panel a) started with a fixation cross, which remained on the screen for the whole duration of the experiment. After a random interval jittered between 100 and 300 ms, the cue appeared for 480 ms. After a cue-target interval (CTI), jittered between 700 and 900 ms, the search display appeared and remained visible for 300 ms. Responses were recorded from the onset of the search display until 1200 ms after display offset, for a total of 1500 ms. Afterwards,

a new trial sequence started automatically. The task was to discriminate the position of the gap within the target item (top vs. bottom) by pressing the letter “M” on the keyboard with their right index finger if the gap was in the lower part, or the letter “Z” if their left index finger if it was in the upper part. The experiment included a total of 1600 trials, divided into 8 blocks. Before starting the actual experiment, a practice phase of 64 trials was used to allow participants to familiarise themselves with the task. All the conditions previously described were presented in a fully randomized order. Participants were instructed to maintain their eyes on the fixation cross and fixation quality was monitored by the experimenter by means of the online eye-position display of the eye-tracker.

In order to evaluate if participants were aware of the frequency manipulation, a survey was conducted at the end of the experiment (see Ferrante et al., 2018). Participants were first asked to report whether they noticed something about the spatial distribution of target stimuli, and in case they responded “yes” they had to report (or guess) the locations where the target was presented most frequently.

Electrophysiological recording and analysis

EEG data were recorded using a Brain Products actiCHamp 64-channel system (Brain Products, Gilching, Germany) with 64 active scalp electrodes positioned according to the standard international 10–10 system. Signals were recorded at a 500-Hz sampling rate, using Fz as the online reference and then re-referenced offline to the average of TP9 and TP10, corresponding to the left and right mastoids. Fz was then restored to the dataset. A high-pass filter of 0.1 Hz was applied to the raw data and segments of the continuous data with clearly identifiable, large artefacts (not including blinks and eye movements) were excluded by manual inspection. Successively, independent component analysis (ICA) was used to remove components related to eye blinks and (residual) eye movements. We then segmented the data into epochs from –200 ms to 2900 ms relative to cue onset and from –200 ms to 800 ms relative to the stimuli array onset. We then baseline-corrected with regard to the 200-ms pre-cue or pre-stimuli period, respectively. Then, a second artifact rejection (AR) was performed to flag and remove epochs

contained artifacts in the analyzed channels (PO7/8; absolute amplitude exceeding $\pm 100 \mu\text{V}$). On average this led to exclusion less than 5% of the total trials.

In order to study the temporal dynamics of attentional orienting and subsequent visual search, we focused on three components, namely the cue-evoked CNV, and the P1 and N2pc elicited by the search array. The CNV was examined at Cz using the cue-locked epochs (Ribeiro & Castelo-Branco, 2021; Macar et al., 1999; Pfeuty et al., 1997; Praamstra et al., 2006), whereas for the N2pc and P1 we used the average of two electrodes capturing activity at PO7/PO8, where the N2pc and P1 are usually the largest (e.g., Liebrand et al., 2017; Rashal et al., 2022). To determine the analysis time-windows for each of these EEG markers, we took the canonical values used in the literature: for the CNV, we selected a time-range from 700 ms after cue onset until approximately the earliest point in the CTI in which the search display could appear (plus 70 ms, accounting for transduction delay into visual cortex), i.e., 700-1250 ms (e.g., Liebrand et al., 2017; Rashal et al., 2022). For the N2pc and P1 the respective time-ranges were set to 200-300 ms (N2pc) and 90-140 ms (P1) after the search-display onset, in line with the existing literature (e.g., Eimer, 1996; Luck et al., 2000; Mangun & Hillyard, 1991). Note that counter to most of the earlier N2pc and P1 literature, the target location frequency imbalance led to the fact that for a given participant, the contralateral and ipsilateral locations were either PO7 or PO8, and could not be collapsed across those locations for different conditions, with corresponding targets on the left and right (e.g., Wu et al., 2011). Therefore, in this study, the average across locations was possible only across groups (Wang et al., 2019).

Analyses were performed using R 3.6.2 (R Core Team, 2016) with *ez* (Lawrence, 2011/2015) and *effectsize* (Ben-Shacharet al., 2020) packages. For CNV we used rm-ANOVAs to compare the mean amplitude in the different conditions, whereas for N2pc and P1 we first calculated the mean amplitude of the ipsi and contra location of interest, and then performed rm-ANOVAs to compare the difference waves (DW) resulting from the subtraction contra-minus-ipsi between different conditions. All these analyses were performed only using trials with correct responses. *p* values were corrected with Greenhouse-Geisser epsilon in cases of significant sphericity violation.

3.3 Results

Behaviour

In order to assess the effects of and interaction between statistical learning and top-down mechanisms, 2x2 rm-ANOVAs were conducted with Target Location Frequency (high, low) and Cue (valid, neutral) for accuracy and RT. These analyses showed significant main effects of Cue for accuracy and RT [ACC: $F(1, 23) = 15.32, p = 0.0006, \eta^2p = 0.39$; RT: $F(1, 23) = 134.41, p < 0.0001, \eta^2p = 0.85$], and Target Location Frequency for RT [ACC: $F(1, 23) = 0.46, p = 0.50, \eta^2p = 0.01$; RT: $F(1, 23) = 6.10, p = 0.02, \eta^2p = 0.20$]. Importantly, a significant interaction between the two factors was observed for RT [ACC: $F(1, 23) = 0.71, p = 0.40, \eta^2p = 0.03$; RT: $F(1, 23) = 9.32, p = 0.005, \eta^2p = 0.29$]. Post-hoc paired t-tests (two-tailed), revealed that participants were significantly faster to detect the target in the HFTL, compared with the LFTL but only when the cue was neutral [$t(23) = -2.84; p = 0.009, \text{Cohen's } d = -0.34, -30 \text{ ms}$], and not when the cue was valid [$t(23) = -0.73; p = 0.47, \text{Cohen's } d = -0.04, -3 \text{ ms}$], suggesting that top-down control is able to exert a gating effect over SL mechanisms. Furthermore, the benefit of the valid cue was observed in both the HFTL [$t(23) = 12.25; p < 0.0001, \text{Cohen's } d = 1.02, 100 \text{ ms}$] and LFTL [$t(23) = 9.75; p < 0.0001, \text{Cohen's } d = 1.49, 130 \text{ ms}$] conditions (Figure 10), but with a larger benefit for the cue in the latter (130 vs 100 ms).

At the end of the experimental session, four participants reported to have noticed something peculiar regarding the target frequency and named the correct high-frequency spatial location as the location where the target was more likely to appear. However, excluding these participants from the analysis did not change the main results, corroborating the effect of an implicit learning.

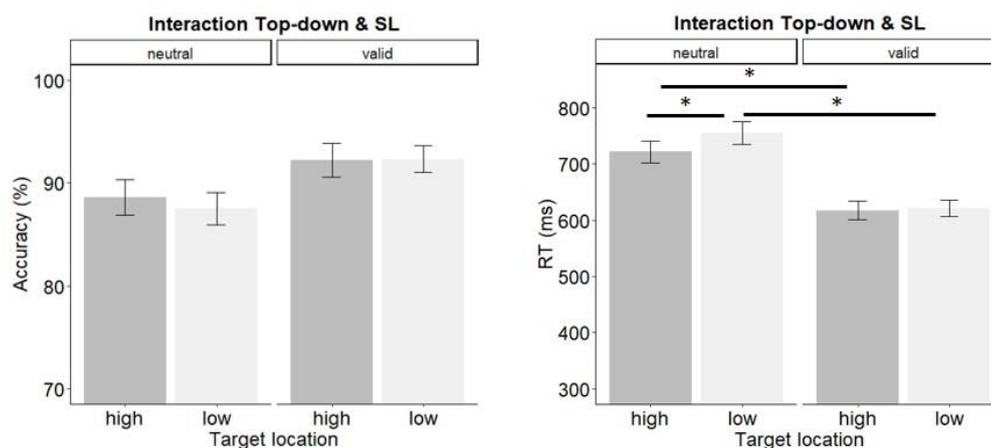


Figure 10. Mean accuracies (left) and reaction times (right) as a function of cue and target frequency conditions.

CNV

To assess whether a valid endogenous cue elicited a preparatory effect, a one-way rANOVA was performed with Cue (valid, neutral). This analysis showed a significant difference between the two conditions [$F(1,23) = 33.46$, $p < 0.001$, $\eta^2p = 0.59$]. Specifically, a larger CNV was evoked by valid cues, indicating that the participants could prepare to orient their attentional resources before the search array onset following an informative cue. Furthermore, we explored whether SL proactively modulates top-down control, such that a preparatory effect would emerge according to the target location frequencies. To this end, another rANOVA was conducted on the data from trials following a valid cue in the HTLF and LTLF conditions. No significant difference was found between these two conditions [$F(1,23) = 0.70$, $p = 0.41$, $\eta^2p = 0.02$] (Figure 11).

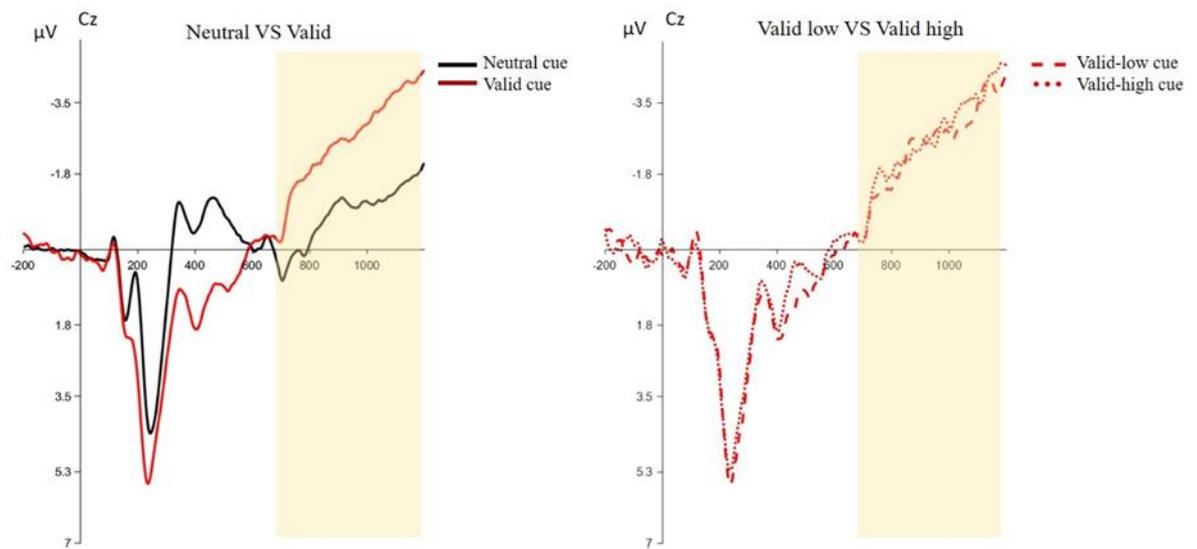


Figure 11. The plot on the left shows the CNV elicited by neutral (black line) and valid (red line) cues, whereas the plot on the right shows the CNV elicited by valid cue pointing to the LTLF (dashed line) and HTLF (dotted line). Time-point zero indicates cue onset. The yellow area represents the time-window where the mean amplitude of the CNV was quantified.

P1

A two-way rm-ANOVA with Cue (valid, neutral) and Target Location Frequency (high, low) was performed to investigate the effects of top-down AC and SL on the early stage of target selection. Importantly, this was done on the contra-minus-ipsi difference waves, hence characterizing lateralization effects. Similar to the CNV, this analysis revealed a significant main effect of Cue [$F(1,23) = 23.20$, $p < 0.001$, $\eta^2_p = 0.50$], that elicited a larger P1 lateralization for valid (vs. neutral) cues, but not of Target Location Frequency [$F(1,23) = 0.65$, $p = 0.424$, $\eta^2_p = 0.02$]. Furthermore, no significant interaction emerged between the two factors [$F(1,23) = 0.58$, $p = 0.451$, $\eta^2_p = 0.02$] (Figure 12).

N2pc

To investigate the effect of top-down AC and SL on the N2pc, a rm-ANOVA was conducted with Cue (valid, neutral) and Target Location Frequency (high, low). Similar to the analysis of P1, this analysis considered the contra-minus-ipsi

difference waves, again directly focusing on attentional lateralization effects. This analysis showed a significant main effect of Cue [$F(1,23) = 5.84, p = 0.023, \eta^2p = 0.20$], but not of Target Location Frequency [$F(1,23) = 0.57, p = 0.497, \eta^2p = 0.02$]. Importantly, a significant interaction emerged between the two factors [$F(1,23) = 4.28, p = 0.049, \eta^2p = 0.15$]. Post-hoc paired t-tests (two-tailed) revealed that targets in the LFTL condition following a valid cue elicited a larger N2pc compared with targets at that location following a neutral cue [$t(23) = 2.85, p = 0.009$, Cohen's $d = 0.22$; $0.74 \mu\text{V}$]. In contrast, this effect was not present for targets in the HFTL condition [$t(23) = -0.10, p = 0.918$, Cohen's $d = -0.006$; $-0.02 \mu\text{V}$]. Furthermore, no significant difference in N2pc amplitudes was found between HFTL and LFTL, neither in the neutral [$t(23) = -0.94, p = 0.355$, Cohen's $d = -0.37$; $-1.28 \mu\text{V}$], nor in the valid cue condition [$t(23) = -0.40, p = 0.688$, Cohen's $d = -0.16$; $-0.51 \mu\text{V}$] (Figure 12).

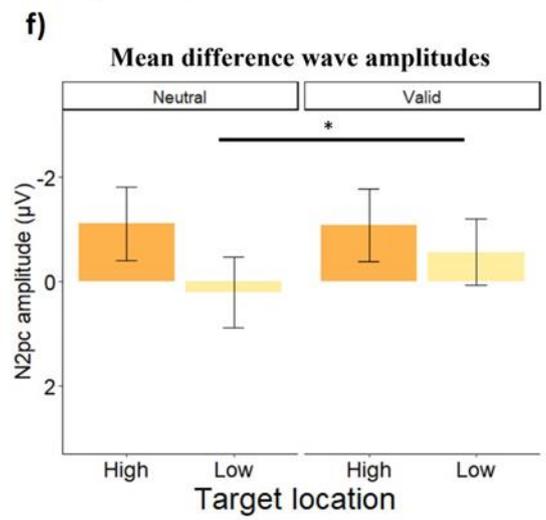
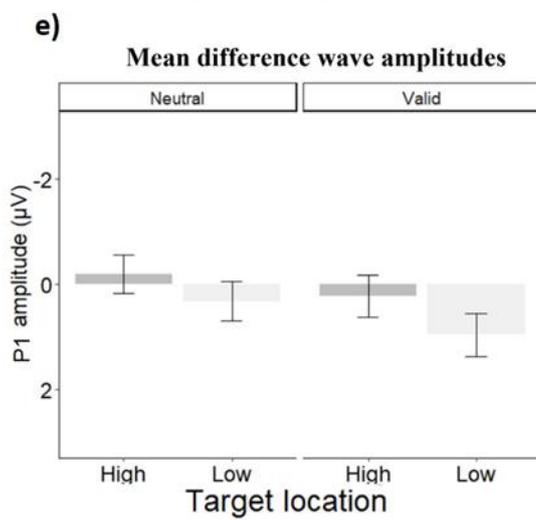
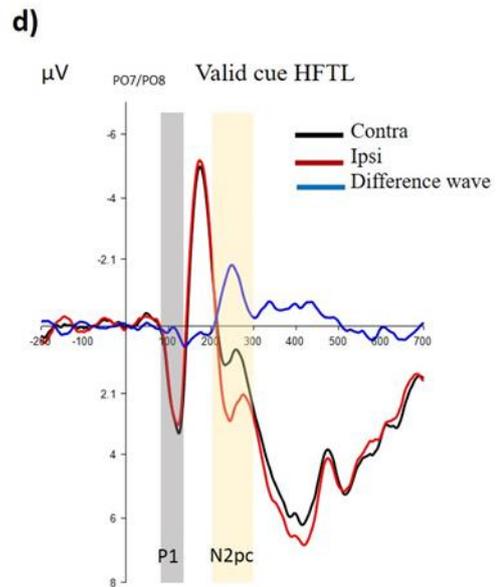
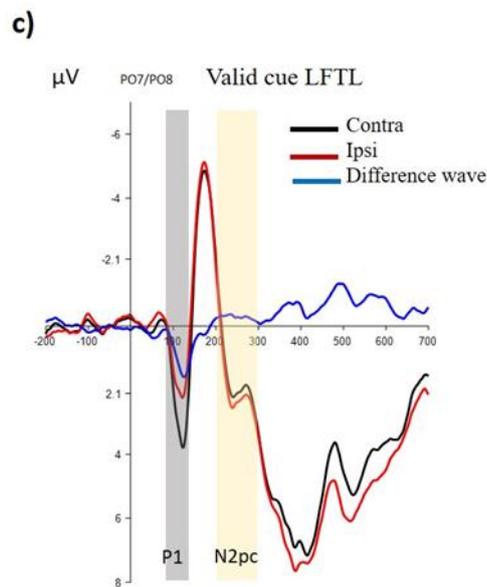
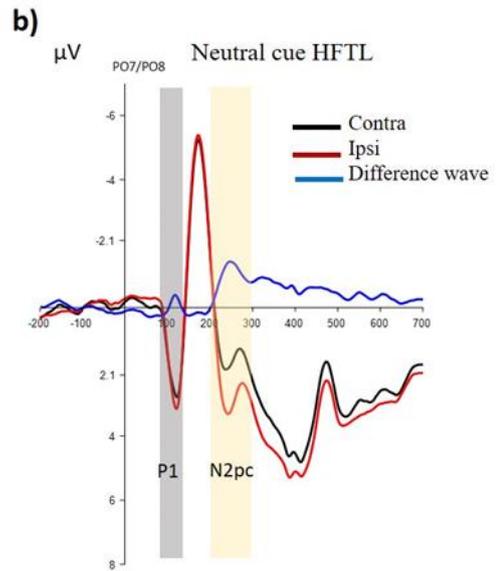
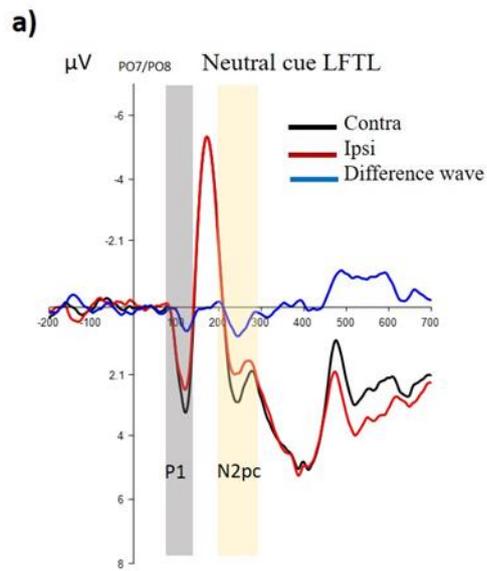


Figure 12. Sensor plots showing contra (black line), ipsi (red line) and the difference waves (contra-minus-ipsi; blue line) activity following a neutral cue (a, b), or a valid cue (c, d). Panels a and c depict activity in the LTLF condition, and Panels b and d depict activity in the HTLF condition. Time-point zero indicates the search-display onset. The grey area is the time-window where mean amplitude of the P1 was calculated, whereas the yellow area refers to the N2pc time-range. Panels e and f show the mean amplitude of P1 (e) and N2pc (f), calculated by subtracting the contra-minus-ipsi channel, in the two Target Location Frequency conditions as a function of the cue.

3.4 Discussion

In the current study, we aimed to assess the combined effects and neural correlates of top-down AC and SL when both are present. To that end, we introduced an imbalance of target frequency across locations, and manipulated top-down AC via an endogenous cue in the same visual search task. Critically, we implemented the target location imbalance only for non-cued trials in order to fully dissociate target location frequency and cue validity in our task, and utilized a neutral rather than an invalid cue as a baseline. Additionally, we used the same visual search task (with some adjustments due to methodological reasons) already implemented and adapted for the study of the integrated effect of other AC signals, namely top-down control via endogenous cueing and bottom-up allocation of attention due to salience (Beffara et al., 2022; Rashal et al., 2022).

Combined effect of top-down control and SL on behaviour and their underlying neural activity

The behavioural results separately concerning SL and top-down control confirmed our hypotheses and were in line with the literature, showing an overall effect of both mechanisms of facilitation of target identification following valid, compared to neutral, cues (e.g., Folk et al., 1992; Posner, 1980; Rashal et al., 2022), as well as targets presented in the high- (vs low-) frequency location (Ferrante et al., 2018; Geng & Behrmann, 2005). Participants could indeed benefit from the available information and prepare for the onset of the array, and then efficiently identify the

relevant item (i.e., target). Furthermore, participants' performance indicated that they had learnt the bias induced by the statistical imbalance of target frequency across locations, which could facilitate target detection in the location where it was more likely to appear. During the debriefing at the end of the experimental session, only four subjects reported to have noticed the manipulation (and excluding their data did not significantly change the results). This supports the idea that people can implicitly extract regularities from their external environment even without explicit instructions (Ferrante et al., 2018; Fiser & Aslin, 2001; Jiang, 2018; Saffran, 1996). Most importantly, in this study we directly examined whether, when active together, these AC signals act independently during the attentional deployment or, in contrast, the effect of one signal interferes with the other. Our results were more in line with the latter hypothesis, revealing an interaction between the two sources of AC. In particular, on the behavioural level we observed a gating effect of top-down control over SL, as the effect of SL clearly emerged only in the absence of top-down guidance; responses were faster for targets in the HFTL compared with the LFTL following a neutral but not a valid cue. The prevalence of top-down control could represent an important feature of the functional architecture of visual spatial attention, and it could reflect the ability of voluntary control to actively inhibit the contribution of other signals, e.g., SL, through a gating mechanism in order to fully and efficiently guide attention to current objectives. Previous studies, however, are more in line with the idea that top-down control and SL are independent mechanisms and, when active together, whose activity is summed-up to bias the competition over attentional resources (Gao & Theeuwes, 2020; Geng & Behrmann, 2005). Gao and Theeuwes (2020) argued that at the level of neural activity, statistical learning creates an implicit landscape where multiple spatial locations have a certain level of activations and inhibitions, and top-down control may then operate to orient the attentional spotlight from one location to another (Gao & Theeuwes, 2020). Their theory seems to be in line with our evidence coming from EEG data. Indeed, even if in our study the final attentional choice seems to be guided by top-down control that prevails over SL in terms of RTs, our EEG results showed that the latter mechanism is not completely overridden by top-down AC, since the N2pc modulation indicates that the two mechanisms interact.

Indeed, in terms of the N2pc, the benefit of cueing the target location was associated with a larger N2pc that was elicited by targets following a valid, compared to a neutral cue. In addition, this effect interacted with SL, showing an increased N2pc amplitude for validly cued targets (compared with neutrally cued targets) but only in the low-frequency location. This appears to be in line with the priority map theory, whereby the low-frequency target location in general should be associated to less neuronal activation due to the statistical learning mechanism, and thus, can benefit from the allocation of attention due to the cue. In contrast, when the target appeared in the high-frequency location, the benefit from the preceding cue was eliminated. This might suggest that the gating effect exerted by top-down AC over SL that we observed on behaviour was not a full gating, but, at least in some stage of target selection the SL could also exerts an effect which prevent top-down control to emerge (as in the high-frequency location).

One of the main differences between this study and the previous is that here there is no invalid cue condition and, when informative, the cue predicted the target location with 100% validity, and thus participants could fully trust the information coming from top-down control. Therefore, when these AC mechanisms act the interaction between SL and top-down control could depend on the degree of validity of the latter, which can guide attentional selection, bypassing the information coming from SL. Together, our findings might suggest a close and complex interaction between top-down control and SL, where when one mechanism is acting (and has enough strength to optimize selection), the effect of the other is reduced.

Neural activity underlying the preparatory effect of top-down control

The CNV reflects processes involved in the preparation of anticipatory attention for the upcoming stimulus and motor preparation needed to respond (Tecca, 1972; Brunia & van Boxtel, 2001). It has been shown that the CNV mean amplitude was modulated by the presentation of a warning stimulus, such as a cue, demonstrating its link to strong attentional engagement (e.g., Rashal et al., 2022; Schevernels et al., 2014; van den Berg et al., 2014). During the CTI, a larger CNV was indeed elicited by a valid (vs. neutral) cue, in accordance with the idea that under top-down control participants could orient their attention in advance toward a certain position.

In addition, as a consequence of the preparatory effect exerted by top-down control, we found that the valid cue could affect also the early components of target selection, such as the P1 (e.g., Mangun & Hillyard, 1991). Knowing the upcoming target location enables an early allocation of attentional resources toward a specific region of that display. Indeed, targets following a valid cue produced a general contralateral enhancement of P1 amplitudes.

In contrast, we did not find any preparatory advantage due to statistical regularities neither for what concern CNV nor P1. Indeed, no difference emerged between the CNV elicited by valid cues pointing at the high-frequency location and valid cues pointing at the low-frequency location. As well no (lateralization of the) P1 was not modulated by statistical learning.

The priority map is modulated by combined effects of different attention control signals

Most studies of attention use experimental paradigms that are testing only one specific AC mechanism, which makes it extremely difficult to compare their results in order to assess the interaction of different attentional mechanisms for assigning priority and generating the final attentional choice which must, by definition, be univocal. Here we used a visual search paradigm previously implemented in its general form in another study that examined the combined effect of attention-control sources with behaviour and EEG, as an attempt to develop a unified account. Rashal and colleagues (2022) demonstrated that top-down guidance of attention via an endogenous cue diminished the benefit of target salience and the interference from a salient distractor. Similarly, top-down control seems to prevail over the other AC signal, i.e., SL, in this experiment. However, our EEG data showed that SL could block the benefit of a valid cue in the high-frequency location, as if in that location the neural activity already reached the highest possible peak due to the probability distribution of target frequency.

As mentioned above, since the present work and the work of Rashal and colleagues (2022) used the same experimental task, it is possible to make hypotheses on the functional architecture of visual spatial attention. In particular, together these findings seem to suggest that there is a general dominance of the

mechanism underlying top-down allocation of attention, since the effects of both bottom-up capture by salience and SL on performance were diminished, or even absent, following a valid cue. In this scenario, one could argue that the final attentional choice is the result of the activity of only one mechanism, i.e., top-down control, that prevents the influence of all the others. Still, since in our experiment the cue was 100% valid and predicted the target location well in advance, participants could ignore the information coming from the target probability distribution when they already had a certain and explicit information where to find the target. As a consequence, the lack of effect of SL in the valid cue condition was likely not the result of a general gating effect of top-down control but might simply index that the SL became a condition-dependent mechanism, in this case, following the neutral cue. However, this hypothesis can be excluded given the presence of an interaction between top-down control and SL on the N2pc, which suggests an intervention of SL in assigning different attentional priorities to different locations on the priority map, which can lead to the reduction of the benefit of top-down control during the early stage of target selection.

One critical aspect is that the ability of top-down control to modulate attention and bypass the information of all the other AC mechanisms can depend on its strength and its relevance in the given experimental context. Indeed, a fully reliable informative cue, as the one used in this experiment, can strongly guide attention toward the instructed location without additional information from other AC signals. Counter to that, when the informative cue is partially predictive (such as the case where some invalid cue trials occurred), the gating effect of top-down control is weaker since it is needed to consider also information coming from other AC signals, in this case, SL.

Conclusion

In conclusion, this study seems to indicate a close interaction between top-down control and SL, where one mechanism is at a play, the influence of the other is reduced or even absent. Specifically, the fully reliable valid cue allowed participants to prepare to allocate their attentional resources for target selection before the stimuli array onset. Moreover, the behavioural results suggest that when

top-down attention control is available SL could not emerge, as if the information coming from the cue bypasses the information coming from the implicit learning when visual attention is guided toward the indicated spatial location. Nevertheless, our EEG results suggest that SL was not totally overridden, at least at some stage of target selection.

4 CONCLUSION

In this study we aimed to contribute to unveiling the functional architecture of visual spatial attention and, in particular, to investigate how different AC mechanisms interact to solve stimulus -competition in favour of a relevant visual element towards which the individual will plan adequate behaviour in order to reach his/her goals. More specifically, in this study, in a series of behavioural studies, we systematically addressed the impact of top-down guidance ((Egeth & Yantis, 1997; Reynolds & Heeger, 2009), i.e. the ability to endogenously and voluntarily guide attention on the basis of current knowledge, instructions and goals, and biasing signals induced by statistical learning process (Geng & Behrmann, 2005; Walthew & Gilchrist, 2006; Aslin & Newport, 2012; Jiang et al, 2015; Ferrante et al., 2018), i.e. experience-dependent attentional control signals derived by the assessment of specific statistical regularities in the spatial distribution of relevant items in the visual world. Albeit outside the primary goals of our research, we also collected some information concerning interactions of those AC signal with bottom-up AC (Yantis & Egeth, 1999; Theeuwes, 2010), i.e. the intrinsic ability of perceptually salient visual inputs to attract attention automatically.

Altogether, our results showed a prevalence of top-down control over both statistical learning and bottom-up mechanism. Specifically, following a valid cue, participants could allocate their attentional resources towards the specific location of the upcoming target in advance, which in turn strongly facilitated target selection and processing. In this condition, all information coming from other AC mechanisms seemed not to affect target selection, likely because the stimulus competition was already solved in favour of the stimulus presented at the location instructed by the cue. Only when an uninformative (neutral) cue was delivered, attention was successfully guided by statistical learning towards the location where the target was more likely to appear (vs. where it was appeared less frequently). This held true both with a very efficient cueing manipulation (location-specific valid cue) that largely modulated performance, as well as with a less efficient cueing manipulation (region-wide valid cue) that caused a weaker modulation, fully comparable with the SL effect. This suggests that the top-down AC exerts a gating effect of the tested experience-dependent signals.

In order to investigate the neural mechanisms underlying this critical interaction, we in one additional study, we also recorded the EEG activity of participants during the visual search task. Here we found a significant modulation of the CNV component as an index of the early allocation of attention following a valid vs. neutral cue, a specific correlate of the pre-allocation of attentional resources in space. Moreover, we also observed an N2pc enhancement reflecting a facilitation in target processing when participants knew the upcoming location of the relevant stimulus in advance. However, this modulation was only evident when targets appeared at the low- (vs. high-) frequency location, i.e. at the location that, due to statistical learning, had gained less priority in the spatial priority map. This implies that, at least at some stages, the SL was not completely overwritten by the top-down. The latter mechanism could indeed compensate for the lower resources allocated to the spatial region where the target appeared rarely as a result of the SL process. Instead, in the presence of top guidance, the benefit derived from SL at the high-frequency target location could not emerge, likely due to the already ceiling benefit of the cueing manipulation. . This is an important evidence demonstrating that, even in the presence of a form of gating effect exerted by the top-down AC over statistical learning, the differential priority assignment across locations induced by the latter is still encoded in the brain, as reflected by the N2pc modulation, and may have an influence at some level of the visual and attentional processing of the relevant stimuli.

Furthermore, in our behavioural experiments, we observed that, in the absence of valid cueing, participants' performance was affected by the presence of a salient distractor in the search display which was able to automatically capture attention through bottom-up control. Nevertheless, top-down guidance abolished attentional capture only following a high-resolution cue, which unequivocally indicated the upcoming location of the target, while it was still measured in the presence of the less efficient cueing manipulation (region-wide cueing). This hints to the idea of a full independence between top-down and bottom-up AC mechanisms, with both signals contributing to the shaping of attentional priority within spatial priority maps, albeit each with its specific weight depending on the specific experimental settings.

In conclusion, our results suggest that top-down and statistical learning mechanisms do interact in the guidance of attentional resources, with the former exerting a (at least partial) gating effect on the latter. Conversely, endogenous guidance and bottom-up control seem to act as fully independent sources of AC, each contributing to priority assignment based on its relative weight.

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