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Research Report

Statistical learning of target and distractor spatial probability shape a common attentional priority computation

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ABSTRACT

Converging evidence recently put forward the notion that dedicated neurocognitive mechanisms do exist for the suppression of salient, but irrelevant distractors. Along this line, it is plausible to hypothesize that, in appropriate contexts, experience-dependent forms of attentional learning might selectively induce plastic changes within this dedicated circuitry, thus allowing an independent shaping of priorities at the service of attentional filtering. Conversely, previous work suggested that statistical learning (SL) of both target and distractor spatial probability distributions converge in adjusting only the *overall* attentional priority of locations: in fact, in the presence of an independent manipulation, either related to the target or to the distractor only, SL induces indirect effects (e.g., changes in filtering efficiency due to an uneven distribution of targets), suggesting that SL-induced plastic changes affect a shared neural substrate. Here we tested whether, when (conflicting) target- and distractor-related manipulations are concurrently applied to the very same locations, dedicated mechanisms might support the selective encoding of spatial priority in relation to the specific attentional operation involved. In three related experiments, human healthy participants discriminated the direction of a target arrow, while ignoring a salient distractor, if present; both target and distractor spatial probability distributions were concurrently manipulated in relation to each single location. Critically, the selection bias produced by the target-related SL was marginally reduced by an adverse distractor contingency, and the suppression bias generated by the distractor-related SL was erased, or even reversed, by an adverse target contingency. Our results suggest that even conflicting target- and distractor-related SL manipulations result in the adjustment of a *unique* spatial priority computation, likely because the process directly relies on direct plastic alterations of shared spatial priority map(s).

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Significance Statement

Here we investigated conflicting statistical learning processes in the attentional domain, as induced by prolonged exposure to concurrent imbalances in the spatial probability distributions of both the target and a task-irrelevant, salient distractor. Collected behavioral evidence ruled out the possibility that, when spatial probability manipulations for the target and distractor are pitted one against the other in relation to the very same location, dedicated mechanisms might be engaged to support the selective encoding of the priority of given locations in relation to the specific attentional operation involved (target selection vs. distractor filtering). Rather, plastic adjustments induced by the two SL processes collide on common spatial priority maps, such that the resulting priority for a given location corresponds to some kind of weighted average of the two contrasting SL processes, with imbalances of target spatial probability exerting a relatively stronger impact overall.

1. Introduction

Visual selective attention allows one to select and keep focused on relevant percepts, while ignoring potentially interfering information (Carrasco, 2011; Chelazzi et al., 2011; Egeth & Yantis, 1997; Theeuwes, 2010; Yantis & Jonides, 1990). It can be voluntarily deployed by the observer to one or more relevant features (e.g., specific colors or shapes), objects or locations, as guided by *top-down* or *goal-driven* attentional control mechanisms (Egeth & Yantis, 1997), resulting from extended modulations of neuronal activity within the visual system, both at the cortical (Corbetta & Shulman, 2002; Meehan et al., 2017; Reynolds & Chelazzi, 2004) and subcortical level (McAlonan et al., 2008; Schneider & Kastner, 2009). Attentional selection can also be determined by the intrinsic energy or salience of the visual input via a *bottom-up* or *stimulus-driven* attentional control mechanism (Theeuwes, 2010; Yantis & Egeth, 1999), that biases the competition for attentional resources towards the more salient visual stimuli at the expenses of the less salient ones following a winner-takes-all principle (Desimone & Duncan, 1995). While top-down attentional control guarantees an extremely flexible engagement of attentional resources at the service of current goals, bottom-up attentional guidance allows the individual to be alerted by unexpected, but potentially relevant events in the environment. Another important feature of visual selective attention rests on its ability to be shaped by previous interactions of the individual with the environment, through various forms of experience-dependent plasticity (e.g., Awh et al., 2012; Chelazzi et al., 2013; Chelazzi & Santandrea, 2018; Chun & Jiang, 1998, 2003; Jiang, 2018; Schapiro & Turk-Browne, 2015; Todd & Manaligod, 2018; Theeuwes, 2018, 2019; Wolfe, 2021). For example, attentional priority can be shaped by the positive or negative outcomes of previous attentional encounters (e.g., Anderson, 2019; Awh et al., 2012; Bourgeois et al., 2016; Chelazzi et al., 2013; Failing & Theeuwes, 2018) or be guided by the acquired knowledge of statistical regularities in the visual environment (e.g., Chelazzi et al., 2019; Jiang, 2018; Theeuwes, 2019).

Several authors have proposed that the attentional priority of any given location (or object) is represented by the differential level of neural activity (or excitability) in the corresponding neuronal representations of the visual space, called *spatial priority maps* (Awh et al., 2012; Bisley & Goldberg, 2010; Fecteau & Munoz, 2006; Gottlieb, 2007; Itti & Koch, 2001; Ptak, 2012; Ptak & Fellrath, 2013; Thompson & Bichot, 2005). Neural activity within the topographically organized spatial priority maps reflects the combined influence of both perceptual salience and task-relevance (Awh et al., 2012; Bisley & Goldberg, 2010; Fecteau & Munoz, 2006; Gottlieb, 2007; Itti & Koch, 2001; Ptak, 2012; Ptak & Fellrath, 2013; Serences & Yantis, 2006; Thompson & Bichot, 2005), as well as of forms of experience-dependent attentional guidance (e.g., Chelazzi et al., 2014; Chun & Jiang, 1998; Jiang, Swallow, & Rosenbaum, 2013,Jiang, Swallow, Rosenbaum, et al., 2013; Stănişor et al., 2013). Over the years, various neurophysiological studies contributed to identifying critical hubs of the dorsal attentional network (DAN; Corbetta & Shulman, 2002), which are considered suitable substrate for the implementation of spatial priority maps, including the frontal eye fields (FEF; e.g., Moore & Zirnsak, 2017; Thompson et al., 1996), the cortex within the intraparietal sulcus (IPS; Thomas & Paré, 2007; Wardak et al., 2011) and the superior colliculus (e.g., Krauzlis et al., 2013; McPeek & Keller, 2002). Each of these regions is thought to host a similar spatial priority map for the control of attentional deployment to relevant visual inputs and to be part of a coordinated network which is shaped by the influence of multiple attentional control signals, albeit with some degree of specialization of specific hubs. For instance, in an electrophysiological recording study on monkeys, Buschman and Miller (2007) demonstrated an earlier activation of neurons within the lateral intraparietal area (LIP)—compared to neurons within the FEF—when a target stimulus was presented among homogenous irrelevant stimuli (pop-out condition), while the opposite pattern was observed when the target appeared among heterogeneous irrelevant stimuli (search condition). These findings support the idea that neural activity within FEF and IPS of the primate brain might be primarily sensitive to top-down and bottom-up attentional control, respectively (Buschman & Miller, 2007).

Visual selective attention has long been theorized as solely corresponding to forms of selective enhancement of relevant information at the service of target selection (Bundesen et al., 2005; Carrasco, 2011; Desimone & Duncan, 1995; Roe et al., 2012; Wolfe et al., 1989), in turn allowing the relative weakening of irrelevant input mainly through neuronal mechanisms of normalization (Chelazzi et al., 2011; Desimone & Duncan, 1995; Kastner & Ungerleider, 2001; Reynolds & Chelazzi, 2004; Reynolds & Heeger, 2009). However, recent studies have demonstrated that our ability to cope with distraction is also supported by *dedicated suppression mechanisms* (Chelazzi et al., 2019; Di Bello et al., 2022; Gaspelin & Luck, 2018a, 2019; Noonan et al., 2018), which directly allow to actively inhibit distracting visual inputs (Cosman et al., 2018; Ferrante et al., 2023; Gaspelin & Luck, 2018b; Ipata et al., 2006). The neural architecture that orchestrates filtering of distracting information has been identified as (partially) separated from the one governing attentional deployment towards relevant information (e.g., Chelazzi et al., 2019; Foxe & Snyder, 2011; Marini et al., 2016; Pascucci et al., 2018). In this respect, an important role has been attributed to regions within the ventral attention network (VAN, Corbetta & Shulman, 2002; see Chelazzi et al., 2019; Marini et al., 2016), including for example a causal involvement of the temporo-parietal junction (TPJ) in the dynamic adjustment of proactive distractor filtering mechanisms (Lega et al., 2020).

From a functional perspective, attentional capture by distracting inputs can be mediated by their intrinsic salience in bottom-up and/or in relation to the given observer attentional set (e.g., Luck et al., 2021). The role of other biasing signals in the control of such dedicated suppression mechanisms has also been explored (Chelazzi et al., 2019; Wöstmann et al., 2022). It is for instance disputed that individuals are able to intentionally suppress distractors via proactive, top-down mechanisms; rather, some exposure to distracting items seems to be needed to “learn” selective suppression (e.g., Cunningham & Egeth, 2016; but see Van Zoest et al., 2021). Critically to the purpose of the present study, experience-dependent attentional control has been demonstrated to have a significant influence on distractor suppression mechanisms (e.g., Chelazzi et al., 2013; Chelazzi et al., 2019; Theeuwes, 2019; Wöstmann et al., 2022). In particular, long-term modulations in the allocation of spatial attention may derive from statistical learning (SL) of the spatial probability distribution of the distractor (Di Caro et al., 2019; Failing & Theeuwes, 2020; Ferrante et al., 2018, 2023; Gao & Theeuwes, 2020; Goschy et al., 2014; Lin et al., 2021; Reder et al., 2003; Sauter et al., 2021; Wang & Theeuwes, 2018; Wang et al., 2019a, 2019b; Zhang et al., 2019), as they arise from SL of the target location (Ferrante et al., 2018; Geng & Behrmann, 2002, 2005; Jiang et al., 2013a, 2013b; Miller, 1988; Shaw & Shaw, 1977). More generally, statistical regularities experienced in the context of both attentional selections and rejections can be implicitly extracted and stored in order to optimize future performance.

Although, as mentioned above, the neuronal mechanisms for target enhancement and distractor filtering have been shown to be at least partially separated, recent studies showed that the two forms of SL for selection and suppression do influence one another, perhaps reflecting some late stage of shared processing (Luck et al., 2021). In a previous work (Ferrante et al., 2018), we demonstrated that imbalances in the spatial probability of both target and distractor occurrence are extremely efficacious in biasing attentional deployment. Critically, we also found that these two forms of SL-induced attentional guidance are interconnected (Ferrante et al., 2018). Participants had to perform a variant of the additional singleton search task (Theeuwes, 1992) wherein the target, the salient distractor or both were unevenly presented across different locations. As a result, higher search efficiency was assessed for identifying targets presented at locations where they were more probable to occur and smaller interference followed distractors displayed at locations where distractors were more likely to occur (Ferrante et al., 2018). Critically, we also found substantial *indirect effects* following both SL processes (see also e.g., Lin et al., 2021; Kong et al., 2020; Wang & Theeuwes, 2018): in simple terms, besides strongly biasing target selection, the imbalanced probability of target occurrence across locations also affected the location-specific distractor filtering efficiency; similarly, the imbalanced probability of distractor occurrence, in addition to having a direct impact on filtering mechanisms, modulated the participants' ability to select targets at given locations (Ferrante et al., 2018). This pattern of results has been considered suggestive of the idea that the two forms of SL are implemented through plastic changes occurring within the same neural substrates for attentional control, likely within *shared* spatial priority maps at the service of both target selection and distractor suppression (Ferrante et al., 2018).

The described evidence aligns well with the general assumption in the recent literature (at least in relation to target selection) that a shared priority map circuitry is at play. However, this conceptualization reflects a complex scenario, in which parts of the mechanisms that build up the priority computation are indeed separate and independent: for example, priority assignment might be based on a reward-based learning process or a statistical learning process and the two processes might result in independent, additive effects (Kim & Anderson, 2021; Le Pelley et al., 2020, 2022). Similarly, as further discussed below, different feature dimensions may be prioritized and deprioritized at the same time, as suggested for example by Sauter et al. (2018) or Stilwell & Vecera (2023), or the same differential process might affect features vs. space (Stilwell et al., 2019; Luck et al., 2021). The mentioned studies can be taken as evidence for independent processes contributing to priority shaping, focusing on the fact that the level at which plastic changes (learning) occur to support priority assignments is not that of the shared priority map. The latter remains an unavoidable stage as, at any given time, each individual indeed performs a single, univocal attentional choice which should correspond to the final state of the priority map circuitry; however, the shared priority map might still contain segregated information that supports attributions of differential priorities for instance to the shape and color of the visual input, which might have a final independent impact on the processing of those features of given stimuli. Analogously, we might hypothesize that plastic adjustments of attentional priority might occur at segregated and independent levels for the two attentional operations of target selection and distractor suppression. This might result in segregated information that is then conveyed to the last (shared) stage of attentional control, which corresponds to holding on the results of independent computations at the service of actual behavior. If this were the case, then the actual selection and suppression of given items could be separately and independently influenced only by the specific, related learning process.

To further explain this reasoning in our empirical framework, since dedicated mechanisms are available for the filtering of distractors and SL of distractor probability distribution has been measured, it is very reasonable to hypothesize that the latter might occur within the critical neural substrates that selectively govern distractor suppression, at least in some critical (conflicting) contexts. Were this the case, one would expect a role-bound (i.e. bound to the “task role” –

target or distractor—held by the specific stimulus that was unevenly distributed across the visual space), operation-specific learning processes to be enacted in the brain, that might serve to selectively shape ongoing and future selection or suppression processes. In other words, this implies that the forms of plasticity required to support target- and distractor-related SL effects might occur at different levels in the attentional network. As mentioned above, this notion is plausible and not new to the field. For instance, it has been shown that plastic adjustments might occur at different levels depending on the degree of similarity in the target and distractor-defining features (Sauter et al., 2018, 2019, 2021). Sauter et al. (2018, 2019, 2021) demonstrated that an indirect effect (i.e. changes in target selection efficiency due to an uneven distribution of distractors across locations) was systematically produced when the distractor was defined in the same dimension as the target (e.g., both orientation-defined). However, the SL effect induced by a different-dimension distractor (e.g., color-singleton distractor) did not yield any significant transfer effect. These findings indicate that, at least under some circumstances, plasticity might be implemented at different neural levels, possibly reflecting the existence of distinct priority maps for selection and suppression, or at least the possibility that information resulting from different learning processes are kept functionally segregated also at the level of the final (shared) priority map.

Our previous SL studies seem instead to suggest that what is encoded in the brain is a *unique* attentional priority level for a given item or location, as informed by all past attentional experiences, being them linked to targets or distractors (Ferrante et al., 2018); if confirmed, this kind of evidence will confine the potential neural substrate of such SL processes to those brain areas that do serve both selection and suppression processes. Indeed, it is well established that specific nodes of the DAN, that are known for their role in attentional selection, do also host mechanisms for the suppression of distracting information, including the substrates of spatial priority maps, with a preeminent role of frontal regions (e.g., Chelazzi et al., 2019; de Fockert & Theeuwes, 2012; Lega et al., 2019; Marini et al., 2016; Suzuki & Gottlieb, 2013). In this view, such shared hubs will thus become the most likely neural substrates for SL-induced plasticity, as previously hypothesized.

Unfortunately, albeit suggestive, the evidence collected so far is still inconclusive. As a matter of fact, to date the main foundational evidence to sustain that location-specific SL effects do affect such *overall* attentional priority of given locations is the existence of indirect effects (Ferrante et al., 2018; Kong et al., 2020; Lin et al., 2021; Wang & Theeuwes, 2018). However, and critically to the purpose of the present study, the described transfer of SL effects has been demonstrated in the presence of a single probability manipulation associated with a given location, linked to either the target or the distractor (Ferrante et al., 2018). Still, it might be hypothesized that, in specific cases, when spatial probability manipulations for the target and the distractor are pitted one against the other in relation to the very same location, specific forms of plasticity will be engaged to support the role-bound, independent encoding of spatial priorities in relation to the specific attentional operation involved in the learning process.

Here we therefore asked directly whether target- and distractor-related SL processes might develop separately if the experimental context pushes towards a role-bound, operation-specific encoding of attentional priority, thanks to the possibility to engage plasticity within dedicated neurocognitive substrates. To this aim, we conducted three behavioral experiments wherein independent spatial probability schedules for the target and the salient distractor impinged onto the very same location, including with contrasting manipulations, thus maximally pushing the system towards keeping the adjustments of priorities as separate and operation-specific processes, if feasible. Collected results clearly reveal that the two processes greatly influence one another even in this context, supporting the notion that SL of the spatial probability distribution of both the target and the salient distractor engage plastic changes within the very same neural representation of attentional priority, i.e., a shared spatial priority map, which is in the end responsible to rule ongoing and future attentional operations of both selection and filtering. Or at least, albeit molding of priority at the service of selection and suppression might be handled at the level of separate substrates and as independent computations, the result of those separate computations are not kept segregated at the level of the final priority map, even in the case of conflicting situations, wherein that segregation could be advantageous.

2. Experiment 1

In Experiment 1, we wished to directly verify whether the role-bound encoding of priority in relation to distractor suppression and target selection processes is possible in the appropriate context, as hypothesized above. We therefore set out to probe the impact of concurrent SL protocols applied to the very same locations, either pushing towards the same (*synergistic condition*) or an opposite (*antagonistic condition*) direction in terms of priority assignment. This was obtained by frequently showing the target at a location where the distractor was rarely presented, and vice versa, in the case of the synergistic conditions (with both manipulations pushing towards a prioritization of the given location, or vice versa). Crucially, instead, the target was shown frequently at a location where also the distractor was shown frequently, and vice versa, in the case of the antagonistic conditions, such that one of the manipulations pushed towards a prioritization of the given location, while the other pushed towards its de-prioritization. Based on the rationale of our study, we could hypothesize two different scenarios:—were the role-bound, operation-specific encoding of priority possible, one should find identical SL effects for a given manipulation (e.g., the imbalance in distractor occurrence) independently of the nature of the concurrent manipulation (antagonistic or synergistic);—conversely, if SL-induced plastic changes of attentional priority might predominantly affect a shared neural substrate, one should expect a great influence of the concurrent manipulation on the observed SL results.

2.1. Material and methods

Experiment 1 and all subsequent experiments in the current study were conducted in accordance with the Declaration of Helsinki and approved by the institutional Ethics Committee at the University of Verona. No part of the study procedures or analysis plans was preregistered prior to the research being conducted. In the manuscript we explicitly report how we determined our sample size, all data exclusions, all inclusion/exclusion criteria applied prior to data analysis, all manipulations, and all measures applied in the study. Moreover, all data supporting the findings of this research are available at https://osf.io/q65vy/?view_only=eaebab2713de4e4795851b8ae562e2c0.

2.1.1. Participants

Twenty volunteers (thirteen females; mean age ± SD, 22.05 ± 2.95) took part in Experiment 1, one of whom was excluded from the analysis due to low accuracy (73%, more than two SDs below the average participants' accuracy).

All participants in this and subsequent experiments were right-handed and with normal or corrected-to-normal visual acuity. They were all naïve as to the purpose of the study, and each of them took part in only one of the described experiments. They gave their informed consent before participation, and received monetary compensation for their enrollment in the research at the end of the performed experiment (10 Euros).

2.1.2. Materials and stimuli

The participants sat in a dimly lit, quiet room, facing a 17-in. CRT monitor. A chin rest was used to keep the viewing distance constant at 57 cm during the whole session. The experiment was run in Open-Sesame 3.2.0 (Mathôt et al., 2012).

We adopted the same paradigm as implemented in our previous study (Ferrante et al., 2018), consisting in a modified version of the *additional singleton task* (Theeuwes, 1992). The visual search display comprised four stimuli, each composed of two green (RGB color coordinates: 134, 148, 0; luminance: 15.7 cd/m2) or red (246, 0, 0; 15.6 cd/m2) vertically-arranged triangles (1° × 1° each) presented on a light grey background (186, 186, 186; 32.7 cd/m2). In one half of the trials, all display items were of the same color, e.g., red, whereas in the other half of the trials three items were of one color, e.g., red, but the fourth item (the additional singleton) was of the alternative color, e.g., green. The target stimulus was designated as the sole item in the display with the two triangles pointing in the same direction (i.e., forming a double arrow-head), namely, upward or downward. The color-singleton distractor stimulus had the two triangles pointing outwardly, whilst the remaining stimuli (placeholders/fillers) had both triangles pointing inwardly. Within each visual search display, stimuli were presented equidistantly from one another–one per visual quadrant, along an imaginary circle with a radius of 4° and centered on the fixation point (Fig. 1).

2.1.3. Design and procedure

Each trial began with a fixation display lasting 300 ms, followed by a 700-ms display containing four placeholders, identical to the forthcoming fillers. At the end of this interval, one of the placeholders was immediately replaced by the target and, on half of the total trials, another one was concurrently replaced by the singleton distractor (Tommasi et al., 2015). The search display remained visible for 200 ms, and then a blank screen was presented. Participants had to discriminate the target orientation (i.e., whether it was pointing upward or downward) as quickly as possible, in any case within 2500 ms from target stimulus onset. One half of the participants pressed key 1 of the numerical keypad for 'up' responses and key 2 for 'down' responses, while the other half had the opposite key assignment. A new trial started after 1000 ms of inter-trial interval (Fig. 1).

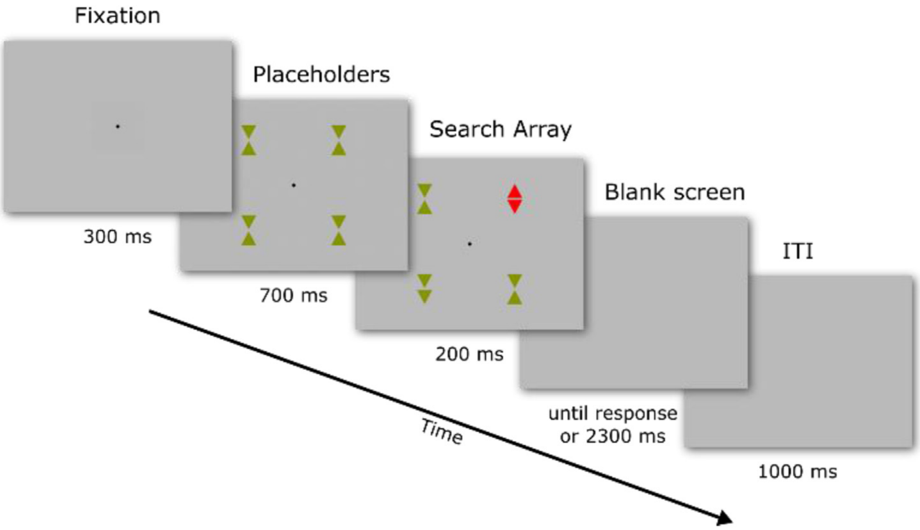

Fig. 1 – Experimental procedure for Experiments 1–3. Schematic representation of the temporal sequence of events in an example trial; a detailed description is provided in the text. The target corresponded to the only double arrow-head item. In the distractor-absent condition (50% of the trials), all stimuli in the array were either green or red. In the distractor-present condition (50% of the trials), one item (additional singleton or salient distractor) differed in color from all other items in the array.

Unbeknownst to the participants, the spatial location of both target and distractor followed a contingent probability distribution. Specifically, the target stimulus was presented with high probability at two locations (42% of the total trials; *high target probability location*, *HTPL*) and with low probability at the other two (8%; *low target probability location*, *LTPL*). Similarly, in distractor-present trials, the salient distractor was presented with high probability at two locations (42%; *high distractor probability location*, *HDPL*) and with low probability at the other two (8%; *low distractor probability location*, *LDPL*). By matching these probabilistic manipulations across locations in the search array, we generated two *synergistic conditions* (*sHTPL/sLDPL* and *sLTPL/sHDPL*) and two *antagonistic conditions* (*aHTPL/aHDPL* and *aLTPL/aLDPL*) (Table 1). In order to compensate for any unwanted form of prior spatial bias, participants were randomly assigned to one of four different groups, each with a different spatial arrangement of the four spatial probability conditions.

The experimental session was designed as follow. After receiving verbal instructions from the experimenter and completing a first practice block of 24 trials (in which target and distractor probabilities was equal across all display locations; *balanced practice phase*), participants started the SL epoch. The spatial probability manipulations were applied throughout this epoch, which comprised 6 blocks of 144 trials each, with a brief resting pause at the end of the third block. Once completed the SL epoch, the experimental session continued with an extinction epoch (3 blocks, 120 trials each), in which again both target and distractor probabilities were equal across all display locations (*balanced extinction epoch*), aimed at testing for any persisting effects from the preceding epoch. Finally, an explicit/implicit survey was conducted to evaluate whether participants were aware of the spatial contingency applied during the SL epoch (for details, see Ferrante et al., 2018).

2.1.4. *Data analysis*

All analyses were performed on reaction times (RTs) and accuracy data. RT analyses were performed after excluding trials with a wrong response or a RT below 200 ms (in total, less than 5% of the data were excluded). When appropriate, *p*-values for statistical significance were adjusted for multiple comparisons (Holm–Bonferroni correction). Along with significance levels, we also provided estimates of effect size (η_p^2 or Cohen's d). We ran a power analysis using G*Power 3.1.9.7 (Faul et al., 2007) to *a posteriori* estimate the smallest effect size that could be detected with our sample ($N = 20$ for all experiments). With a desired power of $1 - \beta = .95$ and an alpha error probability of $\alpha = .05$, the smallest detectable effect size was $\eta^2_p = .27$. When appropriate, non-significant contrasts were accompanied by Bayes Factors (BF) to establish whether the null hypothesis was statistically supported (Rouder et al., 2009; see also Dienes, 2014). Specifically, BF_{10} (for t-tests and main effects in ANOVAs) and $BF_{Inclusion}$ (for interactions in ANOVAs, with effects compared across matched models) were computed as the ratio of the likelihood of the alternative hypothesis (H1) to the likelihood of the null hypothesis (H0); values greater than 3 supported the alternative hypothesis, whereas values smaller than .33 supported the null hypothesis. All analyses were performed using R 3.5.1 (R Core Team, 2016) and Jamovi 2.2.5 (The jamovi project, 2021).

2.2. Results

2.2.1. *Statistical learning of target location in synergistic vs. antagonistic conditions*

We initially considered all experimental conditions together in relation to target probability assignments, with the specific aim of unveiling whether the SL effect of target location varied depending on the type of manipulation concurrently applied to the distractor at the very same location. We therefore performed a repeated-measures analysis of variance (ANOVA) on mean RTs with Target Location (*HTPL–High Target Probability Location* vs. *LTPL–Low Target Probability Location*), Concurrent Manipulation (synergistic vs. antagonistic) and Distractor Presence (absent vs. present) as within-subject factors. The results showed a significant main effect of Target Location ($F_{(1,\ 18)} = 24.26$, $p < .001$, $\eta^2_p = .57$) and Distractor Presence ($F_{(1,\ 18)} = 437.93$, $p < .001$, $\eta^2_p = .96$), as well as a significant Target Location by Distractor Presence interaction ($F_{(1,\ 18)} = 8.43$, $p = .009$, $\eta^2_p = .32$). Most crucially, we found a significant Target Location by Concurrent

Table 1 – Spatial probability distributions for the target and for the distractor in the various experiments (example configuration). Labels: a = antagonistic; p = pure; LTPL = low target probability location; HTPL = high target probability location; ITPL = intermediate target probability location; LDPL = low distractor probability location; HDPL = high distractor probability location; IDPL = intermediate distractor probability location.

		Spatial Probability (%)			
	Stimulus	Location			
		1	2	3	4
Exp 1		**aHTPL/aHDPL**	**aLTPL/aLDPL**	**sHTPL/sLDPL**	**sLTPL/sHDPL**
	Target	42	8	42	8
	Distractor	42	8	8	42
Exp 2		**aHTPL/aHDPL**	**aLTPL/aLDPL**	**pHTPL/(IDPL)**	**pLTPL/(IDPL)**
	Target	42	8	42	8
	Distractor	42	8	25	25
Exp 3		**aHTPL/aHDPL**	**aLTPL/aLDPL**	**(ITPL)/pHDPL**	**(ITPL)/pLDPL**
	Target	42	8	25	25
	Distractor	42	8	42	8

Manipulation interaction ($F_{(1, 18)} = 4.92$, $p = .04$, $\eta^2_p = .21$), demonstrating that the target-related SL effect varied depending on whether the concurrent distractor-related manipulation pushed in the same (synergistic; Fig. 2A) or different (antagonist; Fig. 2B) direction in terms of expected prioritization of the given location. Inspection of Fig. 2C directly represents how the SL effect for the Target Location (which was induced by an identical manipulation) was modulated by the concurrent (distractor-related) manipulation, by showing the SL effects calculated as the difference between the average RTs for the selection of targets presented at the LTPL *minus* the average RTs for the selection of targets presented at the HTPL, separately for the synergistic (69 ms ± 15) and antagonistic (33 ms ± 12) conditions.

The critical interaction between Target Location and Concurrent Manipulation was further modulated by the presence vs. absence of a salient distractor (Target Location by Concurrent Manipulation by Distractor Presence interaction: $F_{(1, 18)} = 5.03$, $p = .038$, $\eta^2_p = .22$). To further investigate this interaction, we performed two separate repeated-measured ANOVAs with the factor Target Location (*HTPL* vs. *LTPL*) and Concurrent Manipulation (synergistic vs. antagonistic), separately for the distractor-absent and distractor-present conditions. While the Target Location was significant in both conditions (distractor-absent: $F_{(1, 18)} = 20.60$, $p < .001$, $\eta^2_p = .53$; distractor-present: $F_{(1, 18)} = 19.645$, $p < .001$, $\eta^2_p = .52$), the interaction Target Location by Concurrent Manipulation was significant only in the presence of a salient distractor (distractor-absent: $F_{(1, 18)} = 1.67$, $p = .21$, $BF_{Inclusion} = .47$; distractor-present: $F_{(1, 18)} = 5.253$, $p = .034$, $\eta^2_p = .23$; Fig. 2D). The lack of an interaction in the distractor absent condition might be interpreted as suggesting that the impact of distractor-related weights on current attentional deployment might be context-specific, i.e. it might be evident only in a context where distractors are present and therefore previous experience with suppression is meaningful. Alternatively, it might be interpreted as reflecting the lack of proactive suppression of that location, in turn favoring the idea of an independent encoding of priority at the service of selection and suppression processes. However, the null result was not supported by the applied Bayesian approach (as stated above, $BF_{Inclusion} = .47$) and it was not confirmed in subsequent analyses and experiments (e.g., see Experiment 2). Albeit we recognize that the lack of a significant effect in the distractor absent condition for this first experiment might be considered a potential limitation of the study (see General Discussion), we also think that it would be unsafe to over-interpret its meaning. Still, for the sake of full transparency, we report data separately for the distractor-present and distractor-absent conditions (which reassuringly shows a qualitative pattern going in the expected direction; see Fig. 2D).

The same analysis on accuracy data revealed significant main effects of Target Location ($F_{(1,18)} = 8.53$, $p = .009$, $\eta^2_p = .32$) and Distractor Presence ($F_{(1, 18)} = 7.77$, $p = .01$, $\eta^2_p = .30$. Moreover, the critical interaction between Target Location and Concurrent Manipulation was close to significance ($F_{(1, 18)} = 4.40$, $p = .05$, $\eta^2_p = .20$). We also found a marginally significant interaction between Concurrent Manipulation and Distractor Presence ($F_{(1, 18)} = 4.40$, $p = .05$, $\eta^2_p = .20$), reflecting larger distractor costs in the synergistic (2% ± .7) than in the antagonistic (.6% ± .5) condition. All other interactions were non-significant (all ps > .08).

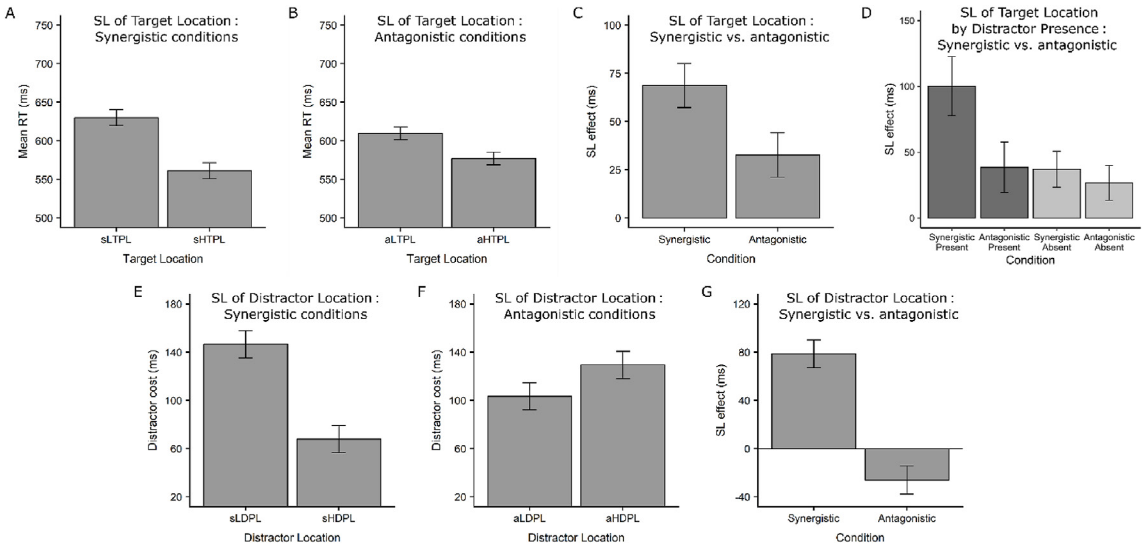

Fig. 2 – Statistical learning (SL) effects during the SL epoch in Experiment 1. (A–B) Average RTs are reported as a function of target location for synergistic (A) and antagonistic conditions (B). (C) Comparison between target-related SL effects measured in synergistic vs. antagonistic conditions. (D) Comparison between target-related SL effects measured in synergistic vs. antagonistic conditions, separately for distractor-present and distractor-absent conditions. (E–F) Average distractor costs are reported as a function of distractor location for synergistic (E) and antagonistic conditions (F). (G) Comparison between distractor-related SL effects measured in synergistic vs. antagonistic conditions. In all panels, error bars represent standard errors for within-subject designs (Cousineau & O'Brien, 2014). Labels: s = synergistic; a = antagonistic; LTPL = low target probability location; HTPL = high target probability location; LDPL = low distractor probability location; HDPL = high distractor probability location.

The results confirmed an overall impact of the target-related SL manipulation on performance at the task, with the efficiency of target selection varying as a function of spatial location or, better, of the associated probability schedule. Crucially, this effect was significantly affected by the concurrent distractor-related manipulation, suggesting that the two SL processes are not independently shaping a role-bound, operation specific computation of priority. Rather, it seems that the two processes are somehow interconnected, likely because the induced plastic changes do occur within a shared neural substrate and do not affect dedicated neural hubs responsible for selection and suppression only.

2.2.2. *Simple effects of target spatial probability in synergistic and antagonistic conditions*

Given that SL of Target Location was significantly modulated by the type of Concurrent Manipulation of the distractor probability, we further characterized the learning process in the two conditions separately. To begin with, in order to assess the impact of the synergistic SL manipulation, we directly compared the two locations where the target was shown frequently (*sHTPL*) vs. rarely (*sLTPL*), and the concurrent distractor probability manipulation was designed to push in the same direction in terms of expected prioritization of the given location (see Table 1).

A repeated-measures ANOVA on mean RTs with Target Location (*sHTPL* vs. *sLTPL*) and Distractor Presence (absent vs. present) as within-subject factors revealed a significant main effect of Target Location ($F_{(1,\ 18)} = 22.38$, $p < .001$, $\eta^2_p = .55$),[2] with faster responses for targets at the *sHTPL* (561 ms ± 20) compared to the *sLTPL* (630 ms ± 27) (Fig. 2A). Overall, this result was perfectly in line with previous findings, showing the expected performance imbalance following a SL process. There was also a significant main effect of Distractor Presence ($F_{(1,\ 18)} = 511.52$, $p < .001$, $\eta^2_p = .97$) with slower performance in the presence (656 ms ± 24) vs. absence (536 ms ± 17) of a salient distractor. Finally, a significant interaction between the two factors ($F_{(1,\ 18)} = 12.82$, $p = .002$, $\eta^2_p = .42$) indicated larger SL effects (*sLTPL minus sHTPL*) in the presence (100 ms ± 22) than in the absence of the distractor (37 ms ± 9), albeit the SL effects were significant in both conditions, as assessed by post-hoc analyses (distractor-present condition: $t_{(18)} = 4.48$, $p < .001$, d = 1.07; distractor-absent condition: $t_{(18)} = 4.28$, $p < .001$, d = .98).

We then applied the very same approach focusing on antagonistic conditions, by directly comparing the two locations where the target was shown frequently (*aHTPL*) vs. rarely (*aLTPL*), and the concurrent distractor probability manipulation was designed to push in the opposite direction in terms of expected prioritization of the given location (see Table 1).

A repeated-measures ANOVA on mean RTs with Target Location (*aHTPL* vs. *aLTPL*) and Distractor Presence (absent vs. present) as within-subject factors revealed a significant main effect of Target Location ($F_{(1,\ 18)} = 8.05$, $p = .01$, $\eta^2_p = .31$),[3] with faster responses for targets at the *aHTPL* (577 ms ± 21) compared to the *aLTPL* (610 ms ± 25) (Fig. 2B). We also obtained a significant main effect of Distractor Presence (distractor-absent: 536 ms ± 17; distractor-present: 656 ms ± 24; $F_{(1,\ 18)} = 281.87$, $p < .001$, $\eta^2_p = .94$). The two-way interaction was instead not significant ($F_{(1,\ 18)} = .49$, $p = .49$, $BF_{Inclusion} = .37$).

2.2.3. *Excluding spurious qualitative differences between synergistic and antagonistic conditions*

Previous analyses confirmed that the SL effect of Target Location occurred in both synergistic vs. antagonistic conditions (and in both cases the SL effect was not to be primarily ascribed to inter-trial priming effects; see relevant footnotes), albeit being significantly different in quantitative terms (synergistic SL effect: 69 ms ± 15, antagonistic SL effect: 33 ms ± 12; Fig. 2C).

In order to test whether the observed differential effects for synergistic and antagonistic conditions might reflect some spurious qualitative differences between the two conditions, here we applied further control analyses related to participants' awareness of the applied manipulations and to the duration of the effects in the extinction phase (see below).

First of all, based on our final assessment (see Methods), ten participants (out of nineteen) reported the impression of an uneven target distribution and correctly indicated at least one of the HTPLs and one of the LTPLs. A mixed ANOVA on the SL effect with Type of Manipulation (synergistic vs. antagonistic), as a within-subject factor, and Awareness (aware vs. unaware), as a between factor, did not yield any significant effect—nor interaction—of Awareness on either RTs (all ps > .24) or accuracy data (all ps > .43). This pattern of results indicates that the level of awareness had no relevant role in the observed discrepancy in the SL effects detected for the synergistic vs. antagonist conditions.

To test for potential differences in the lingering effects of the two experimental manipulations, we analyzed the balanced extinction phase of the experiment. Specifically, a repeated-measures ANOVA on SL effects on RTs was performed with Type of Manipulation (synergistic vs. antagonistic) and Epoch (SL vs. extinction) as within-subject factors. The analysis revealed a significant main effect of Epoch ($F_{(1,\ 18)} = 14.34$, $p = .001$, $\eta^2_p = .44$), as well as a significant interaction between the two factors ($F_{(1,\ 18)} = 10.46$, $p = .005$, $\eta^2_p = .37$). Post-hoc analysis indicated that the synergistic SL effect was significantly reduced in the balanced extinction epoch (SL epoch: 67 ms ± 15; extinction epoch: 9 ms ± 9; $t_{(18)} = 4.28$, $p < .001$, d = .98), while the antagonistic SL effect did not change significantly across epochs ($t_{(18)} = 1.06$, $p = .30$, $BF_{10} = .38$). However, neither the synergistic nor the antagonistic SL effect was significant during the balanced extinction epoch (all ps > .11).

To sum up, the SL effect of target location, i.e., the difference in performance (specifically, in response time) when selecting targets presented at high vs. low probability

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[2] Note that the described SL effect on RTs was still detectable after excluding all instances in which target location repeated across subsequent trials ($F_{(1,\ 18)} = 17.18$, $p < .001$, $\eta^2_p = .49$), confirming that it was not to be merely ascribed to inter-trial priming effects (see also Ferrante et al., 2018). Still, the overall inter-trial repetition priming effect for target location was highly significant in Experiment 1 ($t_{(18)} = 8.51$, $p < .001$, d = 1.95), with faster RTs in repeat (571 ms ± 28) vs. no-repeat (621 ms ± 33) trials.

[3] Note that again the described SL effect was essentially confirmed after excluding all instances in which target location repeated across subsequent trials ($F_{(1,\ 18)} = 3.69$, $p = .07$, $\eta^2_p = .28$), such that it is not to be primarily ascribed to inter-trial priming effects (see Ferrante et al., 2018 and footnote 1).

locations, resulted to be much larger for the *synergistic conditions* than for the *antagonistic conditions*, in line with the idea that SL of target location is strongly affected by the concomitant distractor probability manipulation at a given location (see below for further discussion). No qualitative differences between the conditions emerged that could account for the described quantitative difference.

2.2.4. *Statistical learning of distractor location in synergistic vs. antagonistic conditions*

The same rationale in the analytical approach was applied to investigate distractor-related SL effects. First, we performed a repeated-measures ANOVA on mean RTs with Distractor Location (*HDPL—High Distractor Probability Location* vs. *LDPL—Low Distractor Probability Location*) and Concurrent Manipulation (synergistic vs. antagonistic) as within-subject factors, which revealed a trend for a main effect of Distractor Location ($F_{(1,\ 18)} = 3.81$, $p = .067$, $\eta^2_p = .17$, $BF_{10} = 2.43$) and, critically, a significant Distractor Location by Concurrent Manipulation effect ($F_{(1,\ 18)} = 36.17$, $p < .001$, $\eta^2_p = .668$). Again, this pattern of results indicates a strong influence of the concurrent manipulation on the SL of distractor location, and clashes with the idea that the experience-dependent shaping of priority for a given location might rest on a role-bound, operation-specific process, at least in some conditions. Fig. 2G represents the distractor-related SL effects calculated as the difference between the average cost in RTs for distractors presented at the *LDPL minus* the average cost in RTs for distractors presented at the *HDPL* for the synergistic (79 ms ± 16; see Fig. 2E) and antagonistic (−26 ms ± 16; see Fig. 2F) conditions, separately.

The same ANOVA on accuracy data only revealed a marginally significant Distractor Location by Concurrent Manipulation interaction ($F_{(1,\ 18)} = 3.55$, $p = .076$, $BF_{Inclusion} = 32{,}297.54$). All other effects were far from significance (all ps > .32).

2.2.5. *Simple effects of distractor spatial probability in synergistic and antagonistic conditions*

Given that SL of Distractor Location was significantly modulated by the type of concurrent manipulation of the target probability, we further characterized the learning process in the two conditions separately. First, to assess the impact of the synergistic SL manipulations, we directly compared the two locations where the distractor was shown frequently (*sHDPL*) vs. rarely (*sLDPL*), and the concurrent target probability manipulation was designed to push in the same direction in terms of expected (de)prioritization of the given location (see Table 1).

The SL of distractor location in the synergistic conditions modulated the distractor cost on RTs significantly ($t_{(18)} = 4.99$, $p < .001$, $d = 1.14$),[4] with lower costs for distractors shown at *sHDPL* (68 ms ± 8) compared to *sLDPL* (147 ms ± 12) (Fig. 2D). The same analysis on accuracy data resulted in a non-significant effect ($t_{(18)} = 1.47$, $p = .16$, $BF_{10} = .60$).

We then focused on antagonistic conditions, by directly comparing the two locations where the distractor was shown frequently (*aHDPL*) vs. rarely (*aLDPL*), and the concurrent target probability manipulation was designed to push in the opposite direction in terms of expected (de)prioritization of the given location (see Table 1).

We did not find any significant difference in RTs between trials in which the distractor appeared at the *aHDPL* vs. *aLDPL* ($t_{(18)} = 1.60$, $p = .13$, $BF_{10} = .70$),[5] albeit numerically the cost was slightly larger for distractors shown at the *aHDPL* (129 ms ± 10) than at the *aLDPL* (103 ms ± 11; Fig. 2E). The antagonistic SL effect was instead close to significance on accuracy data ($t_{(18)} = 1.87$, $p = .08$, $d = .43$, $BF_{10} = 1.01$), with higher cost for distractors shown at the *aHDPL* (2% ± 1) vs *aLDPL* (1% ± 1), at odds with what expected.

2.2.6. *Excluding spurious qualitative differences between synergistic and antagonistic conditions*

Previous analyses confirmed that SL learning effect of Distractor Location varied significantly depending on the specific concurrent manipulation applied at the given location. In particular, in the antagonistic condition, the direction of the SL effect for the distractor location was opposite to what expected on the basis of the distractor probability assignment, likely due to a prevalence of the (indirect) effect of the target probability manipulation at those locations (see below for further discussion). In both conditions, a major role of inter-trial effects was excluded (see relevant footnotes). Here we tested other potential spurious differences between the two conditions with control analyses related to participants' awareness of the applied manipulations and to the duration of the two effects in an extinction phase (see below).

Eight participants (out of nineteen) reported the impression of an uneven distribution in distractor presentation and correctly indicated at least one of the *HDPLs* and one of the *LDPLs*. A mixed ANOVA on the SL effect for the distractor location with Type of Manipulation (synergistic vs. antagonistic) as within-subject factor and Awareness (aware vs. unaware) as between factor did not show any general effect of Awareness ($F_{(1,\ 17)} = .52$, $p = .48$, $BF_{10} = .44$). Only a non-significant trend for the interaction between Awareness and Type of Manipulation emerged ($F_{(1,\ 17)} = 3.59$, $p = .08$, $\eta^2_p = .17$, $BF_{Inclusion} = 1.16$), with the difference between synergistic and antagonistic SL effects being slightly more pronounced in aware subjects. The same analysis on accuracy did not yield any significant effect of Awareness, either as main effect or interaction (all ps > .52).

As previously described for SL of target location, we analyzed the balanced extinction phase of the experiment to

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[4] As assessed on overall RT data collected in Experiment 1, the inter-trial repetition priming effect for distractor location was not significant ($t_{(18)} = .26$, $p < .80$, $BF_{10} = .25$). Still, we wanted to verify that the described SL effect was still detectable after excluding all instances in which the distractor location repeated across subsequent trials (see Ferrante et al., 2018) and this was indeed the case ($t_{(18)} = 5.33$, $p < .001$, $d = 1.22$).

[5] Note that, in the case of the antagonistic SL effect of distractor location, we found a non-significant trend after excluding all instances in which the distractor location repeated across subsequent trials ($t_{(18)} = 1.79$, $p = .09$, $d = .41$), with larger costs for distractors shown at *aHDPL* (132 ms ± 41) than at *aLDPL* (104 ms ± 47); if anything, then, the SL effect was strengthened after removing inter-trial repetition (see also footnote 3).

investigate potential differences in the lasting effects of the two experimental manipulations also in the case of SL of distractor location. A repeated-measures ANOVA on the distractor SL effect with Type of Manipulation (synergistic vs. antagonistic) and Epoch (SL vs. extinction) as within-subject factors returned a significant main effect of Type of Manipulation (synergistic SL: 48 ms ± 16; antagonistic SL: −13 ms ± 15; $F_{(1,\ 18)} = 13.96$, $p = .002$, $\eta^2_p = .44$) and a non-significant trend for a main effect of Epoch ($F_{(1,\ 18)} = 3.18$, $p = .09$, $\eta^2_p = .15$, $BF_{10} = .41$). In addition, we found a significant interaction between the two factors ($F_{(1,\ 18)} = 26.52$, $p < .001$, $\eta^2_p = .60$), reflecting stronger extinction for the synergistic (62 ms ± 15) than for the antagonistic SL effect (−27 ms ± 12), albeit the reduction of the effect was significant for both conditions (synergistic: $t_{(18)} = 4.06$, $p = .001$, $d = .93$; antagonistic: $t_{(18)} = 2.59$, $p = .02$, $d = .59$). Moreover, neither of the two SL effects was significant in the extinction epoch (all ps > .23). The same analysis on accuracy data only revealed a non-significant trend for the Type of Manipulation by Epoch interaction ($F_{(1,\ 18)} = 3.38$, $p = .08$, $\eta^2_p = .16$, $BF_{Inclusion} = 58.02$). All other effects were not significant (ps > .15). Once again, during the extinction epoch, none of the SL effects was significant (all ps > .19).

2.3. *Discussion*

Experiment 1 was designed to directly test the possibility that, in an appropriate context, an independent encoding of prioritization/de-prioritization might be reached for the very same spatial location in relation to the specific attentional operation involved in the learning process. More specifically, we wished to test whether a specific location in space might be prioritized (or de-prioritized) at the service of target selection, e.g., following high (or low) target probability, while being concurrently de-prioritized (or prioritized) at the service of distractor suppression, e.g. following high (or low) distractor probability. Were such a concomitant, operation-specific and independent SL learning process possible, one would for example expect identical SL effects for high vs. low target probability locations, as measured in antagonistic and synergistic conditions (i.e., regardless of the probability imbalance applied to distractor occurrence at the very same locations).

At odds with this potential scenario, the SL effects measured on RTs (and, to some extent, on accuracy data) for the synergistic conditions, wherein the contingent probability schedules applied for the target and distractor occurrence pushed toward the same direction in terms of the expected prioritization/de-prioritization, resulted to be much larger with respect to the SL effects measured for the antagonistic conditions, wherein the contingent probability schedules applied for the target and distractor occurrence pushed toward an opposite direction in terms of the expected prioritization/de-prioritization. This pattern of results held true for the SL of both target and distractor location, but the difference between conditions was even more dramatic in the latter case. In fact, while the SL of target location was marginally reduced for the antagonistic condition as compared to the same effect in the synergistic condition, the SL of distractor location was even reversed for the antagonistic condition, likely due to a prevalence of the (indirect) effect of the target probability imbalance at those locations.

Albeit we are well aware that the comparison is not fully legitimate across different experimental contexts (it is however important to highlight that both studies were implemented with the same stimuli and set size), it is nonetheless suggestive to note that, numerically, the SL effect of target location measured here for synergistic conditions (69 ms) was more pronounced than that assessed repeatedly in our previous study (~40 ms; see Ferrante et al., 2018). This strongly suggests that the prioritization/de-prioritization process following SL of target probability is boosted by the contribution of the synergistic SL manipulation for distractor occurrence at the same locations. Along the same line of reasoning, the target-related SL effect measured here for the antagonistic conditions (33 ms) was numerically less pronounced (although in this case, the numerical difference was not conspicuous), likely due to the contrasting impact of the distractor manipulation at the same locations.

Overall, the observed pattern of results suggests that even conflicting target- and distractor-related SL manipulations applied concurrently to given locations result in the shaping of a *unique* priority computation, likely reflecting the plastic adjustment of the very same priority map of space. Specifically, even when the two manipulations are pitted one against the other, the resulting level of priority for a given location corresponds to some kind of weighted average of the two contrasting SL processes. In other words, the selection bias produced by the target-related SL was partially reduced by the adverse distractor contingency, while the suppression bias generated by the distractor-related SL was completely erased (or even reversed) by the concurrent target manipulation. A trend in the data indicated that the distractor cost was more sensitive to the target-related SL, or more precisely to its indirect effect, than to the distractor-related SL, strongly suggesting that the target spatial probability exerts the strongest impact on attention.

Results of Experiment 1, however, are not fully conclusive. One might also hypothesize that, in the antagonistic condition, we just observed the result of the pure target-related SL manipulation, with no contribution at all by the contrasting (and less behaviorally relevant) distractor-related SL manipulation. This alternative hypothesis might find partial support in our previous demonstration that distractor-related SL effects have a strong impact on distractor suppression, but lesser indirect impact on target selection (Ferrante et al., 2018). Indeed, in our previous paper, we demonstrated a strong (and fully comparable) direct impact of SL of target and distractor location on target selection and distractor suppression, respectively; at the same time, we observed that the indirect SL effect of target location on distractor suppression was much stronger than the indirect SL effect of distractor location on target selection (Ferrante et al., 2018). Thus it remains to be established whether the application of two contrasting manipulations in antagonistic conditions clearly results in both jointly contributing to the resulting prioritization/de-prioritization process (although perhaps with different weight) or whether, in the case of conflict, only one of the SL manipulations exerts its effects on attentional functions, by completely abolishing any contribution of the other one. We directly tested these alternative hypotheses in the subsequent experiments.

3. Experiment 2

Experiment 1 successfully showed a substantial difference between SL effects developed following synergistic vs. antagonistic spatial probability manipulations of the target and of the distractor occurrence, ruling out the possibility that an independent, role-bound and operation-specific computation of priority may occur (see Section 2). However, the specific contribution of the two contrasting manipulations in each antagonistic condition remains unclear: either the resulting SL effect derives from a (weighted) average of the independent SL effects for the target and distractor location or, in case of conflicting prioritization/de-prioritization directions, only one of the manipulations gains prevalence and becomes capable of driving plastic changes in a shared priority map of space. To disentangle between the two scenarios, a baseline condition is needed, wherein a single probability manipulation is applied, and this has to be compared with an antagonistic condition, wherein an additional probability manipulation pushes in the opposite direction in terms of prioritization. In this manner, as implemented here in Experiment 2, one could directly compare the SL of target location in *pure* conditions (where locations are only associated with a target probability imbalance) with the same SL effect in *antagonistic* conditions (where locations are associated with conflicting target and distractor probability manipulations):—were the resulting SL effects identical in the two cases, one should conclude that the secondary (antagonistic) manipulations is gated in case of conflict;- were instead the resulting SL effects different, then some kind of averaging between the two underlying priority assignment processes might have been in place in antagonistic conditions.

3.1. *Materials and methods*

The methods were identical to those described for Experiment 1 (see Section 2.1), with the following exceptions.

3.1.1. *Participants*

Twenty healthy volunteers (ten females; mean age ± SD, 22.05 ± 2.37) took part in Experiment 2.

3.1.2. *Design and procedure*

The target stimulus was presented with high probability at two locations (42% of the total trials; *high target probability location, HTPL*) and with low probability at the other two (8%; *low target probability location, LTPL*). The distractor was instead presented with high probability at one location (42%; *high distractor probability location, HDPL*), with low probability at another one (8%; *low distractor probability location, LDPL*), and with intermediate probability at the remaining two (25%; *intermediate distractor probability location, IDPL*). By matching these probabilistic manipulations, we were able to pair each location within the search array with one of the following probability combinations: (i) HTPL/IDPL, (ii) LTPL/IDPL, (iii) HTPL/HDPL, (iv) LTPL/LDPL (Table 1). The pure SL effect generated by the target spatial probability manipulation was measured by comparing (i) and (ii); we will refer to these locations as pure HTPL or *pHTPL*, and pure LTPL or *pLTPL*. Differently, (iii) and (iv) constituted the antagonistic SL pair. Here, the target and distractor spatial probabilities were combined so that the induced SL effects were theoretically pushing in opposite directions (i.e., the former increasing the attentional priority of the given location, while the latter decreasing it, and vice versa); we will refer to these locations as antagonistic HTPL or *aHTPL*, and antagonistic LTPL or *aLTPL*.

3.2. *Results*

3.2.1. *Statistical learning of target location in pure vs. antagonistic conditions*

As for Experiment 1, we initially analyzed all conditions together to obtain an overall assessment of SL of target location (see Section 2.2). We performed a repeated-measures ANOVA on mean RTs with Target Location (*HTPL* vs. *LTPL*), Concurrent Manipulation (pure vs. antagonistic) and Distractor Presence (absent vs. present) as within-subject factors. The results showed significant main effects of both Target Location ($F_{(1,19)} = 35.52$, $p < .001$, $\eta^2_p = .65$) and Distractor Presence ($F_{(1, 19)} = 75.31$, $p < .001$, $\eta^2_p = .80$), as well as a significant Target Location by Distractor Presence interaction ($F_{(1, 19)} = 7.40$, $p = .014$, $\eta^2_p = .28$). Crucially, we also observed a trend to a significant Target Location by Concurrent Manipulation interaction ($F_{(1,19)} = 3.78$, $p = .067$, $\eta^2_p = .17$, $BF_{Inclusion} = .7$). Fig. 3C represents the SL effect calculated by computing the difference in RTs for the selection of targets presented at low vs. high probability locations, separately for the pure (66 ms ± 12; see Fig. 3A) and antagonistic (44 ms ± 9; see Fig. 3B) conditions. In this case, this interaction was not further modulated by the presence/absence of a distractor ($F_{(1,19)} = 2.61$, $p = .123$, $\eta^2_p = .12$, $BF_{Inclusion} = .44$; see Section 2.2.1).

The same analysis on accuracy data revealed a significant main effect of Target Location ($F_{(1,19)} = 8.51$, $p = .009$, $\eta^2_p = .31$) and a marginally significant main effect of Distractor Presence ($F_{(1,19)} = 4.76$, $p = .04$, $\eta^2_p = .20$). No other effect or interaction was significant (all ps > .27).

3.2.2. *Simple effects of target spatial probability in pure and antagonistic conditions*

Given that the overall analysis results confirmed the effectiveness of target-related SL protocols in biasing attention across space at the service of target selection, together with a non-negligible impact of the concurrent distractor-related manipulation in the case of RT data, we further analyzed the learning process in the two conditions separately. We first focused on the pure conditions, wherein the target probability imbalance was applied in the absence of any relevant manipulation in distractor occurrence (the probability of distractor occurrence at pure locations was 25%, equal to the expected frequency in a balanced probability context; see Table 1). This manipulation was therefore expected to show similar results as described in our previous study (Ferrante et al., 2018; see Section 2.3).

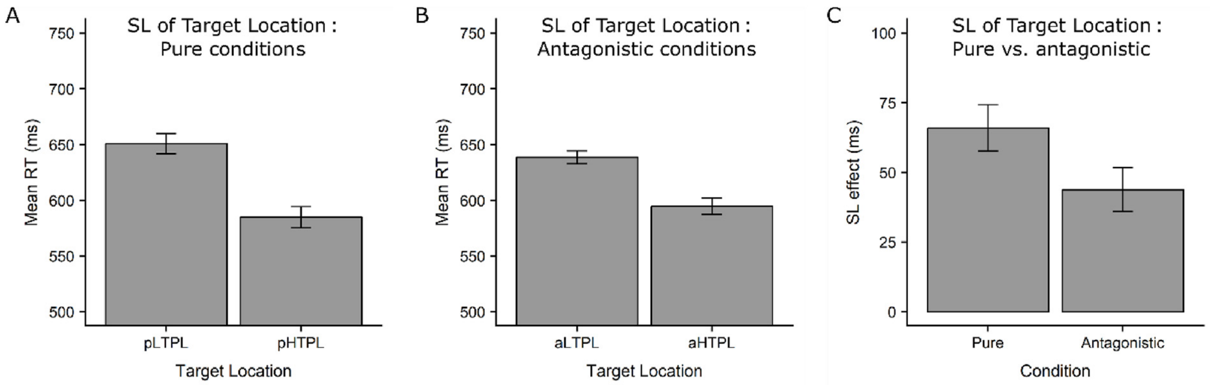

Fig. 3 – Statistical learning (SL) effects during the SL epoch in Experiment 2. (A–B) Average RTs are reported as a function of target location for pure (A) and antagonistic conditions (B). (C) Comparison between target-related SL effects measured in pure vs. antagonistic conditions. All conventions as in Fig. 2. Labels: p = pure; a = antagonistic; LTPL = low target probability location; HTPL = high target probability location.

We conducted a repeated-measures ANOVA on mean RTs with Target Location (*pHTPL* vs. *pLTPL*) and Distractor Presence (absent vs. present) as within-subject factors. The analysis revealed a significant main effect of Target Location ($F_{(1,\ 19)} = 28.41$, $p < .001$, $\eta^2_p = .60$),[6] with faster responses to targets presented at the *pHTPL* (mean ± SEM: 585 ms ± 28) compared to targets presented at the *pLTPL* (651 ms ± 35) (Fig. 3A). In addition, we found a significant main effect of Distractor Presence ($F_{(1,19)} = 79.36$, $p < .001$, $\eta^2_p = .81$), reflecting faster RTs in the absence (570 ms ± 27) vs. presence (666 ms ± 33) of the distractor. Lastly, a significant interaction between Target Location and Distractor Presence emerged ($F_{(1,19)} = 11.27$, $p = .003$, $\eta^2_p = .37$). Post-hoc comparisons indicated that the selection bias was present in both the distractor-absent (*pHTPL* = 549 ms ± 28, *pLTPL* = 590 ms ± 29; $t_{(19)} = 4.33$, $p < .001$, $d = .97$) and the distractor-present (*pHTPL* = 620 ms ± 28, *pLTPL* = 712 ms ± 36; $t_{(19)} = 5.02$, $p < .001$, $d = 1.12$) conditions. However, the SL effect (difference in RTs for targets at *pHTPL* vs. *pLTPL*) was significantly larger in distractor-present (91 ms ± 18) compared to distractor-absent (41 ms ± 9) trials ($t_{(19)} = 3.36$, $p = .003$, $d = .75$).

We then applied the same approach focusing on antagonistic conditions (see Table 1). We performed a repeated-measures ANOVA on mean RTs with Target Location (*aHTPL* vs. *aLTPL*) and Distractor Presence (absent vs. present) as within-subject factors. A significant main effect of Target Location emerged ($F_{(1,\ 19)} = 23.70$, $p < .001$, $\eta^2_p = .56$),[7] reflecting faster responses when the target was presented at the *aHTPL* (595 ms ± 30) vs. *aLTPL* (639 ms ± 33) (Fig. 3B). We also found the usual cost related to Distractor Presence ($F_{(1,\ 19)} = 56.72$, $p < .001$, $\eta^2_p = .75$), with faster RTs in distractor-absent (566 ms ± 26) than in distractor-present (667 ms ± 33) trials. The Target Location by Distractor Presence interaction was instead non-significant ($F_{(1,\ 19)} = 1.19$, $p = .29$, $BF_{10} = .50$).

3.2.3. *Excluding spurious qualitative differences between synergistic and antagonistic conditions*

Overall, the observed pattern of results conveys the idea that applying a contrasting distractor probability imbalance on given locations did exert a (mild) effect on the SL of target location, thus demonstrating that concomitant target and distractor probability manipulations act together to induce long-term adjustments of a *unique* attentional priority computation, albeit the two processes seem to have a substantially different weight (see below for further discussion).

Analogously to what performed for Experiment 1, we applied further control analyses in order to exclude spurious qualitative differences that might explain the observed differential SL effects for pure and antagonistic conditions in Experiment 2.

Based on our final assessment (see Section 2.1.3), eleven (out of twenty) of the participants reported the impression of an uneven spatial distribution of the target and correctly indicated at least one HTPLs and one LTPLs. To verify whether the difference between the pure and antagonistic SL effects depended on the participants' awareness of the spatial probability manipulation, we ran a mixed ANOVA on the SL effects with Type of Manipulation (pure vs. antagonistic) as within-subject factor and Awareness (aware vs. unaware) as between factor. The results showed a significant main effect of Awareness ($F_{(1,\ 18)} = 10.10$, $p = .005$, $\eta^2_p = .36$), reflecting overall larger SL effects (across conditions) in aware (83 ms ± 14) vs. unaware (26 ms ± 8) participants; importantly, however, we found no significant interaction between Awareness and the Type of Manipulation ($F_{(1,\ 18)} = .17$, $p = .68$, $BF_{10} = .43$), thus excluding the possibility that the difference between SL effects measured in the pure vs. antagonistic conditions was somehow to be ascribed to the participants' awareness of the applied probability imbalances. The same analytical approach did not yield any significant result on accuracy data (all ps > .09).

As described for Experiment 1, we also analyzed the balanced extinction phase of the experiment in order to

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[6] In the current experiment, inter-trial repetition priming reliably benefited target selection ($t_{(19)} = 7.94$, $p < .001$, $d = 1.78$), yielding shorter RTs when target location was the same as in the preceding trial. However, the described SL effect, as measured in the pure conditions, was confirmed after excluding all instances in which target location repeated across subsequent trials ($F_{(1,\ 19)} = 24.51$, $p < .001$, $\eta^2_p = .56$).

[7] Note that the SL effect measured in the antagonistic conditions was confirmed after excluding all instances in which target location repeated across subsequent trials ($F_{(1,\ 19)} = 15.42$, $p < .001$, $\eta^2_p = .28$; see footnote 5).

investigate potential differences in the lasting effects of the pure vs. antagonistic target probabilistic manipulations. A repeated-measures ANOVA on target-related SL effects measured on RTs was performed with Type of Manipulation (pure vs. antagonistic) and Epoch (SL vs. extinction) as within-subject factors. A significant main effect of Epoch ($F_{(1,\ 19)} = 14.06$, $p = .001$, $\eta^2_p = .43$) indicated an overall larger SL effect, as assessed across conditions, during the SL epoch (57 ms ± 13) than during the extinction epoch (22 ms ± 12), with both epochs showing a SL effect significantly different from zero (ps < .02). Remarkably, however, the interaction between the two factors was not significant ($F_{(1,\ 19)} = 1.57$, $p = .23$, $BF_{Inclusion} = .49$), suggesting that pure and antagonistic SL effects underwent a similar degree of extinction. The same analysis on accuracy data did not show any significant effect (all ps > .55), except for a non-significant trend for a main effect of Epoch ($F_{(1,\ 19)} = 3.27$, $p = .09$, $\eta^2_p = .15$, $BF_{10} = 1.11$).

3.2.4. *Between-experiment comparison of pure vs. synergistic SL effects*

As discussed in the previous section, we reasoned that the synergistic manipulation of target and distractor probability applied in Experiment 1 might have been successful in inducing magnified changes in the attentional priority of given locations, due to putatively additive effects of the target and distractor probability manipulations. Were this the case, one would expect the synergistic target-related SL effect measured in Experiment 1 (69 ms) to outdo the SL effect of the pure target probability manipulation applied here in Experiment 2 (66 ms). In contrast with our prediction, however, the difference in the magnitude of the two SL effects—as measured reliably in both experiments on RT data—was not supported statistically ($t_{(37)} = .14$, $p = .89$, BF = .31).

3.3. *Discussion*

Experiment 2 was performed in order to directly compare SL effects of target location as induced in pure conditions, i.e. for locations in which only a target probability imbalance was applied, with the SL effects of target location induced in antagonistic conditions, i.e. for locations where the target probability imbalance was pitted against a contrasting distractor probability imbalance. The pure conditions, which served as a baseline assessment of the SL effect, showed the expected change in the attentional priority of the given locations: performance was enhanced for selecting targets at the location where they appeared more (vs. less) frequently.

Importantly, in the antagonistic conditions, we found a reduction in the magnitude of the target-related SL effect, which was to be ascribed to the contrasting force exerted by the distractor probability manipulation. Notably, however, the target-related SL effect was not canceled out by the antagonistic distractor probability imbalance, as one would have expected if the contribution of the two underlying SL processes was fully balanced. Rather, the reduction of the target-related SL effect appeared to be mild, well in line with what emerged in Experiment 1 (see Section 2.2).

The pattern of results obtained in Experiment 2 thus seems to suggest that, when the two forms of SL are pitted one against the other, both of them concur in inducing lasting changes of a *unique* attentional priority computation for the given locations in space (a point that was not fully resolved based on the evidence collected in Experiment 1; see above), but with substantially different weight, as the target probability manipulations appear to prevail substantially.

Albeit the described scenario is quite clear, a point of weakness in the interpretation of the results might come from how Experiment 2 was designed. As illustrated before, we aimed at comparing the SL effects of an antagonistic manipulation to those of a pure manipulation of target probability, which was needed as a reference. The resulting experimental design, however, might have a potentially hidden confound. In simple words, a potential difference in the strength of the target and distractor probability manipulations may come from the fact that, in the case of the former, there were only two possible levels of probability (high vs. low), pushing towards a marked dichotomy in the priority assignment of different locations. Conversely, in the case of the distractor probability manipulation, there were three levels of probability (high, intermediate and low), which might have resulted in a milder differentiation of priority level assignments during the learning process. Were this the case, one might expect to find a specular pattern of results in an experiment aimed at using the pure SL of distractor location as a reference, and therefore designed with a target occurrence schedule contemplating three levels of probability and a distractor occurrence schedule contemplating only two levels of probability across locations. On the contrary, if the results collected in Experiment 2 reflect a genuine differential weight in the impact of SL processes related to target and distractor probability, a prevalence of the former will again be observed in such an experiment, which we performed as Experiment 3 (see Section 4).

Following Experiment 2, we also compared the results obtained in the pure conditions with what emerged in the synergistic condition of Experiment 1: although numerically the SL effect measured in the latter was slightly larger than that measured in the former, this result was not supported statistically. Albeit caution is mandatory when comparing results across different experiments in terms of magnitude, this finding might again be in line with a relatively feeble contribution of indirect distractor-related SL effects, as previously discussed (see also Ferrante et al., 2018). In other words, this could be interpreted as yet another evidence that the contribution of induced plastic changes in attentional priority by target and distractor probability manipulations is not balanced, with the relative weight of the latter being consistently weaker and therefore not even exerting a strong boosting effect, when paired synergistically to the former. Another possibility, however, is that of a sort of roof effect related to the synergistic conditions, which might reflect a sub-additive underlying algorithm, such that the contribution of the distractor-related evidence for the priority tagging of a given location might change with the absolute priority conveyed by the target-related evidence, which incidentally is further in line with a strong interdependence of the two processes leading to priority assignment; in other words, distractor-related information might become relevant only when there is uncertainty (or an intermediate level of priority) in the evidence already furnished by the target probability manipulation. In principle, were this the case, the reverse should also be verified (i.e., a larger weight of the distractor-related evidence when the target-related evidence is uncertain). The third experiment, in which distractor probability was manipulated alone (pure conditions) or pitted against a contrasting target probability manipulation (antagonistic conditions), was also meant to gain further understanding on this matter.

4. Experiment 3

As anticipated above, in Experiment 3, we compared the SL effect of distractor location induced in pure conditions, i.e. when the only relevant probability imbalance was charged to distractor occurrence across given locations, with the SL effect of distractor location induced in antagonistic conditions, i.e. when the distractor probability imbalance was contrasted by a target probability manipulation pushing towards an opposite direction in terms of expected priority assignments. We expected a reduction in the magnitude of the distractor-related SL effect in antagonistic conditions, with the strength of that reduction being critical to really understand the relative contribution of the target- and distractor-related learning processes. Were a substantial reduction, or even the complete elimination, of any SL effect of distractor location found in antagonistic conditions in this experiment, one would be allowed to confirm the relative weakness of the distractor-related learning process, and especially of its indirect effects.

4.1. *Materials and methods*

The methods were identical to those of previous experiments (see Sections 2.1 and 3.1), with the only exceptions described below.

4.1.1. *Participants*

Twenty volunteers (twelve females; mean age ± SD, 22.15 ± 3.45) took part in Experiment 3.

4.1.2. *Design and procedure*

The distractor was presented with high probability at two locations (42% of the total trials; *high distractor probability location, HDPL*) and with low probability at the other two (8%; *low distractor probability location, LDPL*). The target stimulus was presented with high probability at one location (42%; *high target probability location, HTPL*), with low probability at another one (8%; *low target probability location, LTPL*) and with intermediate probability at the remaining two locations (25%; *intermediate target probability location, ITPL*). By matching these probability schedules, we obtained two pure conditions (*pHDPL* and *pLDPL*) and two antagonistic conditions (*aHDPL* and *aLDPL*; see Table 1).

4.1.3. *Data analysis*

To directly assess modulations of the cost associated with distractor presence, all analyses were conducted on the so-called *distractor cost*, i.e. the difference between average RTs (or accuracy) in distractor-present vs. distractor-absent trials.

4.2. *Results*

4.2.1. *Statistical learning of distractor location in pure vs. antagonistic conditions*

To obtain an overall assessment of SL of distractor location, we first considered the distractor costs in all experimental conditions together. We therefore performed a repeated-measures ANOVA with Distractor Location (*HDPL* vs. *LDPL*) and Concurrent Manipulation (pure vs. antagonistic) as within-subject factors. The analysis resulted in a significant main effect of Distractor Location ($F_{(1,19)} = 8.76$, $p = .008$, $\eta^2_p = .31$), a significant main effect of Concurrent Manipulation ($F_{(1, 19)} = 14.77$, $p = .001$, $\eta^2_p = .44$) and, most crucially, a significant interaction between the two factors ($F_{(1, 19)} = 7.85$, $p = .011$, $\eta^2_p = .29$). Fig. 4C represents the SL effects calculated as the difference between the average cost in RTs for distractors at the LDPL *minus* the average cost for distractors presented at the HDPL, for the pure (63 ms ± 13; see Fig. 4A) and antagonistic (−5 ms ± 13; see Fig. 4B) conditions.

The same ANOVA on accuracy data yielded a significant interaction Distractor Location by Concurrent Manipulation ($F_{(1, 19)} = 7.00$, $p = .02$, $\eta^2_p = .27$), reflecting an opposite pattern in the SL effect between the pure (2% ± 1) and the antagonistic condition (−2% ± 1), with the latter showing an inversion in polarity (i.e., the SL effect goes in the opposite direction to what was expected). All main effects were instead non-significant (all ps > .55).

In sum, the SL of distractor location was completely canceled out in the antagonistic condition, or even reversed, confirming a strong prevalence of the target-related SL process.

4.2.2. *Simple effects of distractor spatial probability in pure and antagonistic conditions*

Given the significant impact of the concurrent manipulation, we again set out to characterize pure vs. antagonistic conditions, separately. First, we directly analyzed the pure SL of distractor location, by comparing distractor costs for the two locations where distractors were shown frequently (*pHDPL*) vs. rarely (*pLDPL*), in the absence of any target frequency imbalance (see Table 1). The difference between distractor costs at the two locations was highly reliable ($t_{(19)} = 4.85$, $p < .001$, $d = 1.08$; Fig. 4A),[8] reflecting a smaller distractor interference at *pHDPL* (75 ms ± 9) than at *pLDPL* (138 ms ± 11).

The same analysis on accuracy data led to a non-significant result ($t_{(19)} = 1.31$, $p = .21$, $BF_{10} = .49$).

We then applied the same approach focusing on the antagonistic conditions, by directly comparing distractor costs for the two locations where the distractor was shown frequently (*aHDPL*) vs. rarely (*aLDPL*), and the concurrent target probability manipulation was designed to push in the opposite direction in terms of the expected priority assignment for the given location (see Table 1).

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[8] Overall, for RT data, we did not find evidence for any inter-trial repetition priming effect for the distractor location on distractor costs ($t_{(19)} = .05$, $p = .96$, $BF_{10} = .23$). Still, we removed all instances in which the distractor was presented at the same location in subsequent trials and verified that pure SL effect was still statistically reliable ($t_{(19)} = 4.78$, $p < .001$, $d = 1.07$).

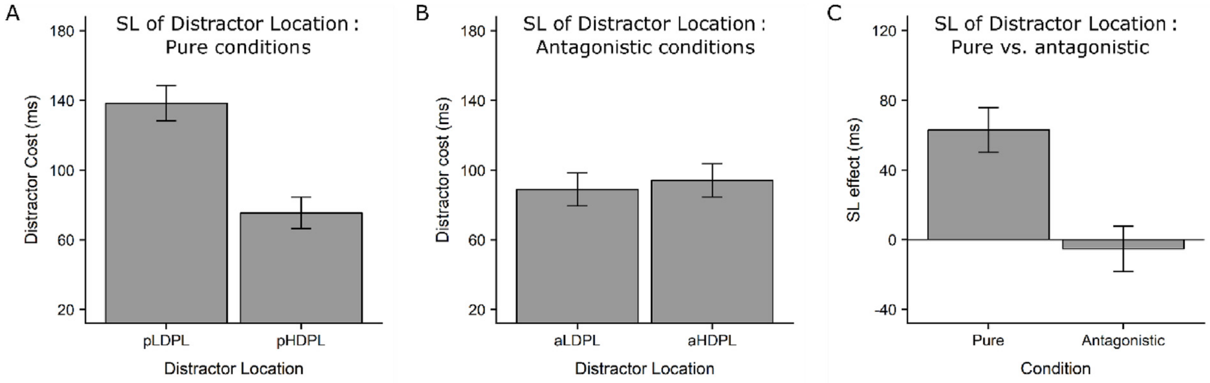

Fig. 4 – Statistical learning (SL) effects during the SL epoch in Experiment 3. (A–B) Average distractor costs are reported as a function of distractor location for pure (A) and antagonistic conditions (B). (C) Comparison between distractor-related SL effects measured in pure vs. antagonistic conditions. All conventions as in Fig. 2. Labels: p = pure; a = antagonistic; LDPL = low distractor probability location; HDPL = high distractor probability location.

We did not find any significant difference between RT distractor costs for the two locations (*aHDPL*: 94 ms ± 9; *aLDPL*: 88 ms ± 11; $t_{(19)} = .39$, $p = .70$, $BF_{10} = .25$)[9]; numerically, the cost was even slightly larger for distractor shown at the *aHDPL*, at odds with what expected solely based on the distractor probability manipulation (Fig. 4B). Instead, the difference in distractor costs was significant on accuracy data ($t_{(19)} = 2.54$, $p = .02$, $d = .57$), with reliably higher accuracy costs for distractors presented at the *aHDPL* (2% ± 1) vs *aLDPL* (0% ± 1).

4.2.3. *Excluding spurious qualitative differences between pure and antagonistic conditions*

As for previous experiments, we also applied some control analyses related to participants' awareness and to the time course of the SL effects, with the general aim of excluding spurious explanations for the observed differential SL effects for the pure vs. antagonistic conditions.

Five participants (out of twenty) reported the impression of an uneven spatial distribution of the distractor and correctly indicated at least one of the *HDPLs* and one of the *LDPLs*. Due to the small number of "aware" participants, in this case we proceeded by excluding them and repeating the analyses to assess SL of distractor location for the non-aware participants only. For the pure conditions, this approach confirmed a statistically significant SL effect on RTs ($t_{(14)} = 3.50$, $p = .004$, $d = .90$) and a non-significant effect on accuracy data ($t_{(14)} = 1.72$, $p = .11$, $BF_{10} = .86$). For the antagonistic conditions, quite surprisingly, we observed a marginally significant SL effect on RTs ($t_{(14)} = 2.09$, $p = .06$, $d = .54$, $BF_{10} = 1.38$) and a significant effect on accuracy data ($t_{(14)} = 2.74$, $p = .02$, $d = .71$). Importantly, after limiting the analyses to non-aware subjects, a strong and reliable difference was confirmed in the comparison between SL effects measured in the pure vs. antagonistic conditions, both in terms of RTs ($t_{(14)} = 3.98$, $p = .001$, $d = 1.03$) and accuracy ($t_{(14)} = 2.98$, $p = .01$, $d = .77$).

As described for previous experiments, we also analyzed the balanced extinction phase to investigate potential differences in the lasting effects of the two experimental manipulations. A repeated-measures ANOVA on the distractor SL effect with Type of Manipulation (pure vs. antagonistic) and Epoch (SL vs. extinction) as within-subject factors yielded a significant main effect of Type of Manipulation ($F_{(1, 19)} = 17.96$, $p < .001$, $\eta^2_p = .49$), reflecting an overall larger SL effect in the pure (46 ms ± 13) than in the antagonistic (−3 ms ± 11) conditions. No other effect was significant (all ps > .11).

The same analysis on accuracy data revealed a significant effect of Type of Manipulation ($F_{(1, 19)} = 7.08$, $p = .02$, $\eta^2_p = .27$), again with a larger SL effect in the pure (1% ± 0) than in the antagonistic condition (−1% ± 1). No other effect was significant (all ps > .11).

4.2.4. *Between-experiment comparison of pure vs. synergistic SL effects*

As discussed for the previous experiment, if the synergistic manipulation of target and distractor probability applied in Experiment 1 was successful in inducing magnified changes in the attentional priority of the given location, due to putatively additive effects of the target and distractor manipulations, one would expect the synergistic distractor-related SL effect measured in Experiment 1 (79 ms) to outdo the SL effect of the pure distractor probability manipulations applied here in Experiment 3 (63 ms). In contrast with our prediction, however, the difference in the magnitude of the two SL effects—as measured reliably in both experiments on RT data, was not supported statistically ($t_{(37)} = .77$, $p = .45$, $BF_{10} = .38$). Thus again, at odds with our expectations, the synergistic condition did not produce potentiated changes in the priority of given locations.

4.3. *Discussion*

Experiment 3 was designed to directly compare SL effects of distractor location as induced in pure conditions, i.e. for locations in which only a distractor probability imbalance was applied, with SL effects of distractor location in antagonistic conditions, i.e. for locations where the distractor probability

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[9] After removing all trials in which the distractor appeared in the same location across subsequent trials, we confirmed that the SL effects of distractor location was not significant in the antagonistic condition ($t_{(19)} = .49$, $p = .63$, $BF_{10} = .26$; see footnote 7).

imbalance was pitted against a contrasting target probability imbalance. The pure conditions, which served as a baseline assessment of the SL effect, showed the expected change in the attentional priority of the given locations: the distractor cost was more pronounced for locations where the distractor was shown rarely and less evident for locations where it was shown frequently.

Importantly, in the antagonistic conditions, we found a breakdown of the distractor-related SL effect, which was to be ascribed to the contrasting force exerted by the target probability manipulation. Notably, in this experiment, the distractor-related SL effect was completely canceled out, or even slightly reversed, by the (indirect) effects of the antagonistic target probability imbalance, fully in line with a predominant contribution of the target-related SL process.

The pattern of results obtained in Experiment 3 thus confirms that, when the two forms of SL are pitted one against the other, both of them concur in inducing lasting changes of a *unique* attentional priority computation for the given locations in space. In this third experiment, the relative contribution of the target and distractor probability manipulations in the induction of attentional priority changes appears to be almost balanced, albeit with a slight prevalence of the former (a slight inversion of the SL effect of distractor location was indeed assessed, at least on accuracy data, corresponding to the prevalence of the indirect target-related SL effect). We tend to interpret this nuanced finding well in favor of a general prevalence of the target-related SL process because here the distractor schedule, comprising only two probability levels, was in principle more efficient in producing a dichotomy in the attentional priority of locations, as compared to the more graded expected differences induced by the three-level target probability schedule. Based on this reasoning and together with evidence collected in Experiments 1 and 2, we interpret the slight prevalence of the target-related SL effect reported here as a genuine result.

Following Experiment 3, we also compared the results obtained here in the pure conditions with what emerged in the synergistic conditions of Experiment 1: albeit numerically the distractor-related SL effect measured in the latter was larger than that measured in the former, this result was not supported statistically. This evidence seems to substantiate the idea that a sub-additive mechanism is at place when two probability assignments are engaging synergistic SL processes charged to the very same spatial location; in simple words, the magnitude of the SL effect is not augmented substantially in synergistic conditions, because the evidence collected either based on the target or the distractor probability imbalance alone is already enough to induce the largest possible change in the priority level of a given location or, better, the largest meaningful change in priority as read by a winner-take-all mechanism, akin to the one hypothesized to be at place in the reading of priority maps (see Section 5).

It is not legitimate to use the latter described evidence, i.e. the absence of an increment of the SL effect in the synergistic condition, to gain further elements in favor of, or against, a prevalence of the target-related SL process at the expense of the distractor-related SL process. However, if one were to choose the most parsimonious interpretation based on the whole ensemble of collected results, it is highly likely that the SL effect of distractor location measured in the synergistic condition of Experiment 1 does reflect primarily the indirect effect of the target-related SL process (as it is overall predominant) and, only to a small extent, the direct effect of the distractor-related SL process (as it generally seems to have a lesser impact).

5. General Discussion

Recent findings in the literature fully established the existence of dedicated mechanisms for the filtering of irrelevant, yet salient distractors (Chelazzi et al., 2019; Gaspelin & Luck, 2018a, 2019; Noonan et al., 2018), which allow to actively and selectively inhibit highly interfering visual inputs (Cosman et al., 2018; Gaspelin & Luck, 2018b; Ipata et al., 2006). Critical brain regions, including in particular areas within the VAN (Corbetta & Shulman, 2002), have a specific role in orchestrating distractor suppression, independently from contributing to the enactment of target selection mechanisms (Chelazzi et al., 2019; Lega et al., 2020; Marini et al., 2016).

In this framework and in light of the demonstration that long-term, experience-dependent shaping of attentional processes occurs also for distractor filtering mechanisms (e.g., Ferrante et al., 2018), it is plausible to hypothesize that priority is independently adjusted at the service of specific attentional operations. In other words, by implementing plasticity within dedicated hubs of the distractor suppression circuitry, one could obtain a role-bound adjustment of the priority of given items and locations at the service of future distractor rejections, without affecting target selection processes. Such potential scenario might possibly reflect the existence of distinct priority maps for selection and suppression or, at least, the possibility that information resulting from different learning processes are kept functionally segregated also at the level of the final (shared) priority map.

At odds with this hypothesis, some data in the literature, including from our previous work (Ferrante et al., 2018), suggest that SL processes in the attentional domain, in relation to both the target and distractor spatial probability distribution, might induce lasting alterations in a *unique* priority computation, likely occurring via plastic changes within shared spatial priority maps (Awh et al., 2012; Bisley & Goldberg, 2010; Fecteau & Munoz, 2006; Gottlieb, 2007; Itti & Koch, 2001; Ptak, 2012; Ptak & Fellrath, 2013; Serences & Yantis, 2006; Thompson & Bichot, 2005). In particular, SL is known to induce indirect effects, i.e. changes in distractor filtering efficiency due to an uneven distribution of targets across locations and changes in target selection efficiency due to an uneven distribution of distractors across locations (e.g., Lin et al., 2021; Ferrante et al., 2018; Kong et al., 2020; Wang & Theeuwes, 2018a). These indirect effects are thought to reflect changes in the absolute, overall priority of given locations following either of the two SL processes, with measurable effects on every future attentional operation (Chelazzi et al., 2019; Ferrante et al., 2018).

The described scenario clashes with the idea that a (partially) separate circuitry responsible for distractor filtering might be shaped independently by forms of long-term, adaptive learning, which might serve the purpose of selectively optimizing specific attentional operations, if beneficial in a given context. However, previous evidence was not conclusive. Critically, in fact, indirect effects of SL processes have previously been measured in the presence of an isolated probability manipulation associated with a given location, either linked to the target or to the distractor (Lin et al., 2021; Ferrante et al., 2018; Kong et al., 2020; Wang & Theeuwes, 2018a), i.e. when the attentional priority of a specific location was under the influence of a single learning process. The present study was developed with the aim of directly testing whether, when spatial probability manipulations for both the target and the distractor are pitted one against the other in relation to the very same location, dedicated mechanisms might be engaged to support a role-bound encoding of the priority of single locations in relation to the specific attentional operation involved in the learning process (target selection vs. distractor suppression).

We planned three related experiments using modified versions of the additional singleton task (Theeuwes, 1992) in which participants were asked to select a relevant target, while ignoring a salient distractor, when present. In each experiment, we applied concurrent target- and distractor-related SL protocols to the very same locations. In particular, in Experiment 1, we employed *antagonistic* conditions, wherein the two SL protocols pushed towards opposite directions in terms of priority assignment (if the target-related manipulation pushed towards a prioritization of the given location, the distractor-related one pushed towards its de-prioritization, and vice versa), and *synergistic* conditions, wherein the two SL protocols pushed towards the same direction in terms of priority assignment. Were concomitant, operation-specific and independent SL learning processes possible, one would have expected identical SL effect for the high vs. low target (or distractor) probability locations, as measured in antagonistic and synergistic conditions, regardless of the probability imbalance applied to the distractor (or target) at the very same locations. At odds with this possibility, the SL effects measured for the antagonistic conditions resulted to be significantly reduced with respect to those measured for the synergistic conditions; this pattern of results held true for the SL of both the target and distractor location, but the difference between conditions was even more dramatic in the latter case. The marked reduction of SL effects in antagonistic conditions was confirmed in Experiment 2 (target-related effects) and in Experiment 3 (distractor-related effects): here the antagonistic conditions were compared with conditions where a pure manipulation was applied, allowing us to exclude that the secondary (adverse) manipulation was gated in case of conflict, in favor of the idea that the measured SL effects corresponded to a weighted average between the two underlying, concurrent learning processes in the antagonistic condition. In other words, we successfully demonstrated that the application of two contrasting manipulations in antagonistic conditions clearly resulted in both contributing to a resulting *unique* prioritization/de-prioritization process, i.e. with both target-related and distractor-related SL processes concurring in the induction of lasting changes of the attentional priority of the given locations within spatial priority maps. Albeit both target-related and distractor-related SL contributed to determine the final priority assignment for a given location, we also assessed a relatively stronger impact of the former in all experiments: as a matter of fact, while the target-related SL effect was markedly reduced by the antagonistic distractor manipulation, the distractor-related effect was fully erased, or even reversed, by the adverse target probability manipulation. This is well in line with the stronger indirect effects for the SL of the target vs. distractor location reported in our previous study (Ferrante et al., 2018) and it might suggest that, at least in some contexts, the shaping of priority within spatial priority maps is more susceptible to history-driven plasticity linked to task-relevant than to salient, distracting stimuli.

In Experiment 1, we also tested a synergistic condition, wherein the target- and distractor-related SL protocols were designed to push towards the same direction in terms of prioritization/de-prioritization. Contrary to our expectation, the SL effect measured in synergistic conditions was not found to be reliably more pronounced than that measured in pure conditions in other experiments (Experiment 2 and 3; see also the comparison with results of our previous work, Ferrante et al., 2018). The collected evidence tends to support the idea that, instead of a linear summation process, a sub-additive mechanism is at place when two probability assignments engage synergistic processes charged to the very same spatial location: in such conditions, the magnitude of SL effects is not augmented substantially, likely because the evidence collected either based on the target or the distractor probability imbalance alone is already enough to induce the largest meaningful change in the priority of the given location as read by a winner-take-all mechanism (Desimone & Duncan, 1995), akin to the one hypothesized to be at work within priority maps of space (e.g., Awh et al., 2012; Bisley & Goldberg, 2010; Fecteau & Munoz, 2006; Gottlieb, 2007; Itti & Koch, 2001; Ptak, 2012; Ptak e Fellrath, 2013; Serences & Yantis, 2006; Thompson & Bichot, 2005). Albeit it was not the specific focus of the present work, a direct comparison of results collected within synergistic conditions vs. pure conditions within a single experiment might be of help in the future to further strengthen this hypothesis.

As a potential limitation to the current study, we should note that no significant modulation depending on the concurrent manipulation (antagonistic vs. synergistic) emerged across target locations in the distractor-absent condition for Experiment 1 (albeit the qualitative pattern was in the expected direction, as reported for full transparency; see Fig. 2D). In principle, this might be interpreted as reflecting the lack of proactive suppression for the given locations, in turn favoring the idea of an independent encoding of priority at the service of selection and suppression processes. However, the mentioned result was not clear from a statistical point of view and it was in contrast with the prevailing pattern of evidence collected within other experiments (see Results). For instance, SL of distractor location was completely divergent in antagonistic vs. pure conditions in Experiment 3, contrary to the idea that priority encoding for selection and suppression at the very same location might be anyhow independent. Thus, we think that it is unsafe to over-interpret the meaning of the mentioned result in the current context and we stick to the overall most plausible interpretation of our findings (see below). Still, future studies might help understand whether the unexpected data found in the distractor-absent condition for Experiment 1 might somehow be linked to a context-dependent impact of distractor-related weights.

Overall, the collected data are strongly in favor of the idea that assessing statistical regularities in the occurrence of meaningful visual stimuli, either being the target or a salient distractor, induces a SL process at the service of future attentional deployment which consists in the due alteration of a *unique* priority level for a given location, based on all evidence collected in the course of both past selections and rejections. Thus, changes in priority seem to be implemented as plastic alterations at the level of spatial priority maps as a common substrate for attentional guidance, at the service of both target selection and distractor suppression (Chelazzi et al., 2019; Ferrante et al., 2018), even in the extreme contextual framework where an independent, operation-specific encoding of priority for selection and filtering might be advantageous, e.g. when evidence collected for the two attentional operations are one against the other (as in the antagonistic conditions tested here). This idea is in line with previous studies, which reached similar conclusions, albeit in less stringent conditions (e.g., Ferrante et al., 2018; Lin et al., 2021; Kong et al., 2020; Wang & Theeuwes, 2018a).

However, the generality of this notion has been questioned by other studies proposing a differentiation in the level at which plastic changes do occur following SL of the distractor probability distribution, depending on the degree of similarity in the target- and distractor-defining features (Sauter et al., 2018, 2019, 2021). In particular, it has been shown that the SL-induced location-specific modulation of the attentional capture effect is more pronounced when the salient distractor is defined by a feature that pertains to the same dimension as the one defining the target (same-dimension distractor) with respect to when it pertains to a different dimension (singleton-distractor); in addition, and most critically, while the SL effect induced by a same-dimension distractor was systematically shown to produce a strong indirect effect on target selection, these authors found that the SL effect induced by a different-dimension distractor did not yield any significant transfer effect (Sauter et al., 2018, 2019, 2021). In line with the theoretical framework of the *dimension-weighting account* (Müller et al., 1995), which states that dimension-specific feature contrast signals are attentionally weighted before being joined into the priority *master* map (Müller et al., 2003), the authors interpret the described pattern of results as a sign that SL might impact at different levels depending on the specific nature of the distracting item: in the case of a same-dimension distractor, location-dependent SL induces changes in the attentional priority of given locations, while in the case of a different-dimension distractor, a down regulation of the overall signal arising from the distractor-defining feature dimension is thought to occur (Sauter et al., 2018, 2019, 2021). In our study, the distractor stimulus was defined by a different feature (i.e., color) with respect to that defining the target stimulus (i.e., shape), such that, following the dimensional-weighting account, we should have expected no transfer effects of the distractor probability manipulation onto target selection, at odds with our current and previous findings (Ferrante et al., 2018). It could be argued that our distractor was not a pure different-dimension distractor, since it slightly differed from all other items in the display also in relation to its shape, but we think that this nuance might quite unlikely be a suitable explanation of the observed results. As a matter of fact, we strongly believe that the salience of the distractor in our paradigm, and the ensuing attentional capture effect, was fully based on its color: the latter dimension varied randomly from trial to trial (as the color of the target stimulus), and made the distractor perceptually salient with respect to the rest of the display, much more than the (very mild) salience signal derived from its shape (which was constant for the entire duration of the experiment). In other words, we are quite sure that what made the distractor a distractor was its color and not its shape, akin to a different-dimension distractor with respect to the shape-defined target, in turn suggesting that, at least in some conditions, distractor-related SL might change the overall priority of a given location also in cases where filtering could in principle be applied parsimoniously at the level of a specific feature dimension.

The results reported in the current study are well in line with the idea that, in addition to hosting top-down and bottom-up attentional control signals, spatial priority maps are shaped by experience-dependent attentional biases (e.g., Awh et al., 2012; Chelazzi et al., 2019; Chelazzi & Santandrea, 2018; Chun & Jiang, 1998; Ferrante et al., 2018; Jiang, Swallow, & Rosenbaum, 2013,Jiang, Swallow, Rosenbaum, et al., 2013; Theeuwes, 2018, 2019), including those derived from SL in the attentional domain. Many years ago, Chun and Jiang (1998) proposed a sort of "context map" wherein the attentional weights of given locations are modulated by the repeated presentation of a spatial configuration of the target among distractors; the authors suggested that each map contains context-specific information that is used to improve target selection efficiency when the learned context is in place (*contextual cueing*; Chun & Jiang, 1998, 2003). The various studies describing SL of the target and distractor statistical probability distribution support a similar idea: the neural activity within specific portions of the spatial priority map(s) coding for locations where the target was presented more frequently (or the distractor was presented rarely) is enhanced, whereas neural activity within portions of the priority map(s) coding for locations where the target was presented rarely (or the distractor was presented frequently) is suppressed (e.g., Chelazzi et al., 2019; Ferrante et al., 2018). The spatial priority map account has recently been questioned by Jiang (2018), who proposed that the target-related probability effect does not modulate activity within priority maps responsible of *where* attention is deployed, but rather it affects *how* attention moves across the visual space. Specifically, the author suggests that SL of the target probability distribution generates a so-called *attentional habit*, namely a structure sequence of attentional shifts in the visual environment elicited by a given context (Jiang, 2018; Jiang & Sisk, 2019). This critical distinction also rests on the observed peculiarities of the SL-induced attentional biases generated by imbalances in the target occurrence across locations, such as longer persistence (Jiang, Swallow, Rosenbaum, et al., 2013) and lower working memory demand (Won & Jiang, 2015) with respect to what characterizes goal-driven attentional control signals. The attentional habit account finds support in the neurophysiological observation that activity within the fronto-parietal attentional network is under the influence of the caudate nucleus (Hikosaka et al., 2000; Yamamoto et al., 2012), whose dopaminergic activity is considered to underpin habit learning (Graybiel, 2008). Along similar lines, value-learning is considered to generate attentional habits (Anderson, 2016; Luque et al., 2017) and to same extent also reward-related attentional learning, albeit it is still not fully determined in what circumstances reward-dependent spatial biases are successfully generated and in what cases they are not (Anderson & Kim, 2018; Chelazzi et al., 2014; Wolf et al., 2017; Won & Leber, 2018). An assumption of the attentional habit hypothesis is that every successful target selection tends to increase the likelihood that the same attentional shift would occur in the future (Jiang, 2018; Jiang & Sisk, 2019). The same reasoning might be applied to filtering mechanisms, supposing that every successful rejection of interfering information will reinforce the suppression of the vector that would have driven attention towards the salient distractor. This hypothesis is fascinating and overall it leads to very similar hypotheses with respect to the priority map account proposed here, such that the instantiation of two scenarios might well be considered as not mutually exclusive. Nonetheless, we tend to interpret the result of our current study as quite clearly supporting the spatial priority account, as it will not be easy to imagine how a unique, or prevailing, attentional habit might emerge in the context of the antagonistic spatial probability manipulations tested here.

The present study might also contribute to the long-lasting debate about the possibility to fully counteract the attentional capture generated by a salient distractor (Folk & Remington, 1998; Luck et al., 2021; Theeuwes, 2010). Gaspelin and Luck (2018a, 2019) suggested that observers may *learn* how to efficiently inhibit salient distractors, that is experience with interfering information is needed first to then instantiate a pre-attentive filtering process that might successfully prevent attentional capture, i.e. a *proactive* inhibition (Gaspelin & Luck, 2018a, 2018b, 2019). Previous studies indeed demonstrated that observers learn to cope effectively with specific distractors after practice, both in the case of highly predictable distractors, for which the learning process is very fast, and for more variable distractors, which may require more attentional resources and longer exposure to engage a successful learning process (e.g., Cosman & Vecera, 2012; Cunningham & Egeth, 2016; Kelley & Yantis, 2009; Vatterott et al., 2018; Vatterott & Vecera, 2012). Here we propose that such learned, proactive filtering mechanisms might indeed be instantiated as a lasting suppression of a given location (or object) within spatial priority maps, for instance as a result of the SL of the imbalanced spatial probability distribution of a salient distractor. In this type of learning, specific locations frequently associated with the occurrence of a distracting item might be systematically suppressed with respect to other locations where the distractors appear rarely. In other contexts, where no imbalances are applied to spatial locations, there might still be forms of *learning to suppress* that might generate the instantiation of more general filtering mechanisms to be enacted for all task-relevant locations. This has been demonstrated to be the case for paradigms wherein distractors are present in a great proportion of the total trials leading the system to switch to forms of *proactive* (instead of *reactive*) filtering, in turn resulting in smaller distractor costs (Chelazzi et al., 2019; Marini et al., 2013; Müller et al., 2009). In such circumstances, the attentional system tends to proactively deprioritize all interfering, bottom-up signals, independently of the locations where they occur (Ferrante et al., 2023). Correlates for these forms of proactive control have been found within fronto-parietal regions (e.g., Chelazzi et al., 2019; Kelley & Yantis, 2010; Marini et al., 2016; see also Lega et al., 2019), including areas in the dorsal attention network already linked to the instantiation of spatial priority maps (Awh et al., 2012; Bisley & Goldberg, 2010; Fecteau & Munoz, 2006; Gottlieb, 2007; Itti & Koch, 2001; Ptak, 2012; Ptak & Fellrath, 2013; Serences & Yantis; Thompson & Bichot, 2005).

In conclusion, the current study demonstrated that concurrent target- and distractor-related SL processes do concur to the plastic adjustments of a *unique* computation of priority, likely within the very same priority map(s) of space; when the two SL processes are pitted one against the other, the resulting priority for a given location corresponds to a weighted average of the two contrasting SL processes, with imbalances of the target spatial probability exerting a relatively stronger impact overall. We interpret these results as a strong evidence in favor of the idea that shared spatial priority map(s) do encode priority of given attentional locations (or objects) at the service of both target selection and distractor filtering. Of course we do not exclude the possibility that under certain conditions learned changes in priority at the service of both selection and suppression do occur (also) at the level of feature dimension maps (Liesefeld & Müller, 2019; Sauter et al., 2018, 2019, 2021).

As previously discussed, a number of studies in recent years have substantiated the idea that dedicated distractor filtering mechanisms exist to support active suppression of irrelevant, but highly salient and interfering information (e.g., Lega et al., 2020; see Chelazzi et al., 2019 for a review). The current line of research was developed with the exact purpose to verify whether long-term, adaptive attentional learning might shape such (partially) separate circuitry, independently from any attentional learning processes occurring within the target selection circuitry, with the ultimate goal of independently optimize specific attentional operations, if beneficial in the given context. Clearly, also in case of conflicting SL manipulations related to the target and distractor frequency distribution, as implemented in the current study, such an independent shaping of priority was demonstrated to be impossible, strongly advocating for the idea that plasticity instead occurs at the level of shared hubs of priority computation. This apparently contradictory scenario might simply derive from a quite complex functional architecture of visual attention, wherein signals that regulate and inform the *unique* priority computation we are referring to here, still have different sources within the separate circuitries that independently support target selection and distractor filtering. All signals of this kind will then converge, with specific weights, on a shared priority map which might more directly support a unique and coordinated attentional choice at the service of the individuals' behavior.

Open practices section

The study in this article earned Open Data and Open Material badges for transparent practices. Datasets, analyses codes and all digital study materials are available at: https://osf.io/q65vy/?view_only=eaebab2713de4e4795851b8ae562e2c0.

CRediT author statement

Oscar Ferrante: Methodology, Software, Validation, Formal analysis, Investigation, Data curation; Writing – original draft, Visualization. **Chelazzi Leonardo:** Conceptualization, Methodology, Formal analysis, Resources, Data curation, Writing - review & editing, Supervision, Funding acquisition. **Elisa Santandrea:** Conceptualization, Methodology, Formal analysis, Writing - review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare no competing interests.

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