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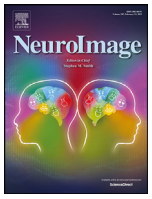

Reward-driven modulation of spatial attention in the human frontal eye-field

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ABSTRACT

Attentional selection and the decision of where to make an eye-movement are driven by various factors such as the representation of salience, task goal, and stimulus relevance, as well as expectations or predictions based on past experience. Brain systems implicated in these processes recruit cortico-subcortical areas including the Frontal Eye-Field (FEF), parietal cortex, or superior colliculus. How these areas interact to govern attention remains elusive. Priority maps of space have been observed in several brain regions, but the neural substrates where different sources of information are combined and integrated to guide attentional selection has not been elucidated. We investigated here the neural mechanisms subserving how reward cues influence the voluntary deployment of attention, in conditions where stimulus-driven capture and task-related goals compete for attention selection. Using fMRI in a visual search task in $n = 23$ participants, we found a selective modulation of FEF by the reward value of distractors during attentional shifts, particularly after high-predictive cueing to invalid locations. Reward information also modulated FEF connectivity to superior colliculus, striatum, and visual cortex. We conclude that FEF may occupy a central position within brain circuits integrating different sources of top-down biases for the generation of spatial saliency maps and guidance of selective attention.

1. Introduction

Extensive parts of the fronto-parietal cortex have evolved for the control of approach or avoidance behavior by prioritizing relevant sensory signals, while ignoring irrelevant information through the operation of top-down attentional mechanisms. Distinct functional networks in dorsal and ventral fronto-parietal cortices have been linked to different aspects of selective attention (Corbetta and Shulman, 2002). A dorsal fronto-parietal network, composed of the intraparietal sulcus (IPS) and the frontal eye fields (FEF) of each hemisphere activate when attention is voluntarily oriented in space, whereas a ventral network composed of the right inferior and middle ventral frontal cortex (VFC) plus the right temporo-parietal junction (TPJ) is implicated in the detection of behaviorally salient or unexpected stimuli (Bourgeois et al., 2012, 2013a, 2013b; Corbetta et al., 2000; Kincade et al., 2005).

A growing body of evidence has recently revealed that stimuli with emotional or motivational values can also be powerful modulators of behavior and influence attentional selection through specific top-down biases in prioritization (Anderson, 2016; Bourgeois et al., 2018, 2016a, 2018b; Pourtois et al., 2013). Value-driven selection may operate reflexively in an involuntary, stimulus-driven manner (Anderson et al., 2011; Bourgeois et al., 2017; Della Libera and Chelazzi, 2009), as observed in healthy subjects and in brain-damaged patients with neglect in whom spatial attention is impaired (Bourgeois et al., 2018).

Anatomically, several neurophysiological studies suggest that reward expectation can increase neuronal activity in brain regions controlling selective attention as well as eye-movements, including FEF, parietal cortex (Maunsell, 2004; Peck et al., 2009), or the superior colliculus (SC) (Ding and Hikosaka, 2006; Ikeda and Hikosaka, 2007). Interestingly, recent studies indicate that although threat cues can also potentiate selective attentional processing as observed for reward stimuli (Vuilleumier, 2005, 2015), the suppression of value-related distractors under threat or reward may involve a selective recruitment of prefrontal areas including FEF (Kim and Anderson, 2020b). Other studies in humans (Serences, 2008) and non-human primates (Shuler and Bear, 2006) found that reward expectation may also increase stimulus representation in sensory areas, including the primary visual cortex. Interestingly, one study in monkey demonstrated that the neuronal latency of reward value effects in V1 was similar to the latency of attentional influences (Stanisor et al., 2013). Thus, motivational value may bias the competition between sensory stimuli, just as it has been shown for selective attention, but operate (at least partly) through pathways functionally

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and anatomically distinct from the attentional systems associated with fronto-parietal cortical networks.

Other studies suggest that reward modulations may originate from dopamine signaling within the dorsal striatum (Anderson et al., 2017; Hikosaka et al., 2014, 2006). For example, Anderson et al. (2014), using a reward-association paradigm reported a selective activation of the extra-striate cortex but also of the caudate nucleus, when a previously high-rewarded visual distractor was presented in a visual search task. Moreover, using positron emission tomography (PET), Anderson et al. (2017) demonstrated that value-driven attentional biases may be predicted from reward-related DA release during learning.

All these studies highlight the intimate links between neural mechanisms controlling selective attention and those responsible for the appraisal of motivational information during goal-directed behavior. However, many standard experimental designs do not permit a firm dissociation between these two mechanisms (Maunsell, 2004). Hence, the brain areas or circuits subserving the combination/integration of value-driven, goal-directed, and stimulus-driven influences on the competition for attentional selection remain largely unresolved.

In the present study, we investigated how reward value interferes with voluntary/endogenous deployment of attention, on one hand, and with stimulus-driven/exogenous attention, on the other hand, in conditions where attention selection must resolve between competing stimuli. We designed a visual search paradigm in which goal-driven and stimulus-driven orienting of attention were systematically manipulated within the same design, allowing us to test whether and how a task-irrelevant, but previously rewarded stimulus may compete with these other mechanisms of orienting. Brain areas engaged in these processes were identified using fMRI in a group of $n = 23$ healthy volunteers.

2. Material and methods

Data will be available upon request to the Authors, without any restrictions.

2.1. Participants

Twenty-three right handed healthy volunteers (12 women, mean age 26 years, range 21–33) with normal or corrected-to-normal vision and no history of psychiatric or neurologic disorders participated in this study. Written informed consent was obtained from each participant, according to procedures approved by the local ethical committee (Geneva, Switzerland).

2.2. Paradigm, stimuli and procedure

The present experiment is based on a visual search paradigm introduced by Anderson and colleagues (Anderson et al., 2011). The task was composed of two phases, an initial learning / association phase performed outside the scanner followed by a test phase performed inside the MRI scanner.

Learning / association phase: each trial started with a central white fixation cross (0.8° × 0.8° of visual angle), presented against a black background during 1000 ms. The fixation cross was then surrounded by eight circles of different colors (blue, orange, pink, purple, red, or green) pseudo-randomly assigned to each circle across trials. These circles (diameter 3° of visual angle) were distributed evenly on an imaginary ring across the fixation cross. Their outline was situated at a distance of 4° from the central fixation cross. The target was defined as a red or a green circle (with only one of each these two colors presented on each trial), which contained a white line whose orientation varied across trials and had to be reported by the participant. One of these two targets (red or green, counterbalanced across participants) was followed by a high reward (10 CHF) on 80% of correct trials, and a low reward (1 CHF) on the remaining 20%. These percentages were reversed for the low-reward target (in the other color). The highly rewarded color (red or green) was counterbalanced across participants. Participants were not informed of the reward contingencies and probabilities. The line inside the target circle could be either vertical or horizontal (2° × 0.3° of visual angle). Participants were instructed to maintain their gaze at the central fixation and to report the orientation of this line with a corresponding key press, as fast and as accurately as possible. Incorrect responses were not rewarded (regardless of color). The target disappeared after a response or after 2000 ms if no response was made. After 1000 ms, a visual feedback informed participants about the monetary reward earned on that trial, as well as about the total reward accumulated across all trials so far. This learning / association phase comprised 240 trials (Fig. 1).

Test phase: after a short break, the learning / association phase was followed by a testing phase, performed inside the scanner. Visual stimuli were presented using E-prime (Schneider et al., 2002) running on a PC Dell Optiplex 9010 and projected on an MRI-compatible LCD Screen (CP-SX1350, Hitachi, Japan) seen through a mirror placed on the MRI head-coil. Both phases were introduced to our participants as two unrelated experiments on vision. This second condition was identical to the initial association phase, with the following exceptions. The fixation display was presented during 1000 ms. Then, a peripheral visual cue appeared, consisting of a brief white flash presented for 150 ms, overlapping with one of eight peripheral circles in gray that were distributed around fixation at the same locations as the circles shown during the initial association phase. The cue correctly indicated the target location (valid trials) on 71% of the trials during the high-predictive/endogenous condition (i.e., goal-directed), and on 50% of the trials during the low-predictive/exogenous condition (i.e., stimulus-driven). Catch trials (without target) were added on 12,5% of the trials for the high-predictive condition, and 25% for the low-predictive condition, in order to avoid anticipation and impulsive key-presses. Participants were not required to respond during those trials and were not penalized for responding. The remaining trials presented invalid cues (flashing at a location different from the target). Please note that our distribution of cue validity was chosen to maximize design efficiency but did not allow us to compare “pure” exogenous vs endogenous conditions given that the non-predictive cues were still informative about target position (1/2 probability) compared to real chance level (1/8 possible positions), even though they were clearly less likely to engage endogenous orienting. Hence, we considered these experimental conditions as high-predictive vs low-predictive cues (Fig. 1). The order of high-predictive and low-predictive sessions was counterbalanced across subjects.

Following the cue and a random interval of 800–1200 ms, the target display was presented in which a white (vertical or horizontal) line appeared in a diamond shape, presented among seven other peripheral circles. The diamond and these circles could be either blue, orange, pink, or purple but never had a color previously associated with a reward. Participants had now to report the line orientation presented in the diamond shape. Before each session, they were informed of the predictive validity of the cue. It was stressed that the peripheral cues in most cases could help respond more rapidly in the high-predictive/endogenous condition, whereas it was explained that these cues were useless to predict the target position and counterproductive in the low-predictive/exogenous condition. In order to investigate the attentional capture by previously high or low rewarded information, one of the non-target circles (referred to as distractors) was either red or green (25% of trials each). However, colors were actually task-irrelevant on all trials during this testing phase. The target disappeared either after a response or after 2000 ms if no response was made. After another 500 ms, a visual feedback was shown to inform participants about the monetary reward earned on that trial (‘+ 1′ for each correct responses), as well as about the total reward accumulated across all preceding trials. Finally, a fixation display was shown for a randomly jittered interval of 2000–7000 ms. This test phase consisted of 96 trials for the low-predictive/exogenous condition (duration, around 15 min), and 160 trials for the high-predictive condition/endogenous (as the latter required more trials to perform reliable analysis of invalid trials) for a duration of approximatively 25 min.

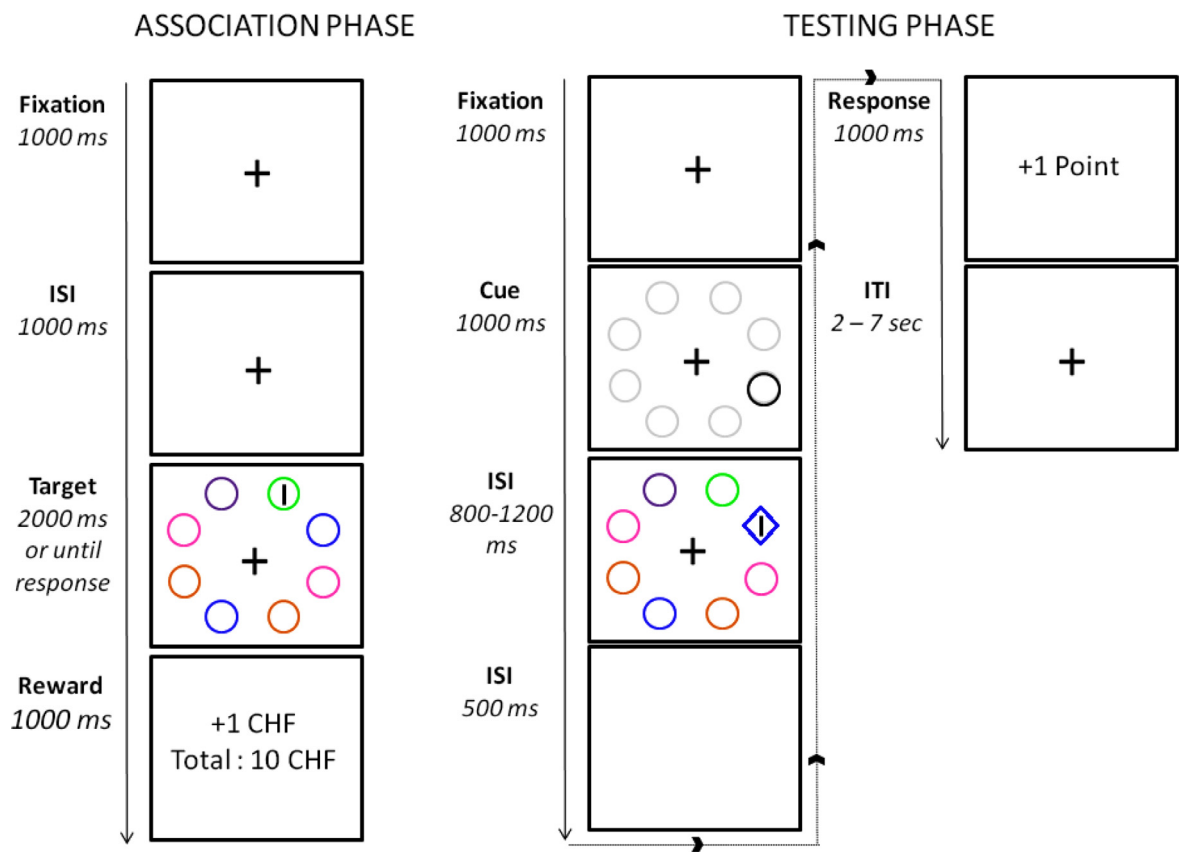

Fig. 1. Sequence of events in a given trial. During the association phase (outside the scanner), participants were asked to discriminate as fast and as accurately as possible a line, either horizontal or vertical presented in a red or in a green circle. In 80% of trials, 1 of the 2 targets (counterbalanced across participants) was followed by a high reward (10 CHF) or a low reward (1 CHF) on the remaining 20%. During the testing phase (inside the scanner), the target was preceded by a cue, either highly-predictive or low-predictive (in two separate sessions). The color of each circle changed randomly across trials. In order to investigate the attentional capture of previously high- or low-rewarded stimuli, one of the distractors was rendered in red on 25% of trials, or green on another 25% trials. Correct responses were assigned 1 point.

Thus, our experimental design had three factors: Attentional orienting (High-predictive, Low-predictive), Cue validity (Valid, Invalid) and Distractor type (Neutral, NEU; previously Low-Rewarded, LR; previously High-Rewarded, HR). Of note, the side of presentation of targets, cues and/or distractors was not taken into account since these supplementary factors would have required many more trials in order to make our main comparison of interest between both high-predictive/endogenous and low-predictive/exogenous conditions. This would have make our experiment too difficult and repetitive for participants (already long in current design, i.e., around 1h30 inside the scanner in total).

Eye movements were visually monitored during all the experiment. If a saccade took place, a feedback was given to the participants at the end of the scan runs with further instructions to fixate the central cross on the remaining trials. Both online and offline inspection of average gaze direction during the task confirmed generally good compliance with the fixation instructions.

2.3. Functional MRI data acquisition

Data were acquired with a 3T MRI scanner (Trio Tim, Siemens Medical Solutions, Erlangen, Germany). Functional images were obtained with a single-shot gradient-echo T2*-weighted EPI sequence (36 slices, matrix size 64 × 64, voxel size = 3.2 × 3.2 × 3.2 mm^3, slice gap = 0.96 mm, flip angle $\alpha = 80^\circ$, bandwidth 1562 Hz/pixel, TR = 2100 ms, TE = 30 ms), using a 32-channel phased array coil. A T1-weighted structural image was also acquired between the 2 functional runs of each scanning session (3D MPRAGE, 256 × 256 × 192 voxels, voxel size = 1.0 mm isotropic, flip angle $\alpha = 9^\circ$, TR = 1900 ms, TI = 900 ms, TE = 2.27 ms, phase oversampling 15%, slice oversampling 16.7%).

2.4. Functional MRI data analysis and statistical analysis

Functional MRI were analyzed using SPM8 (http://www.fil.ion.ucl.ac.uk). The first five functional images of each run were discarded to remove inhomogeneity of the magnetic field consecutives to the setting of the participant inside the scanner. Functional MRI images were processed within each run of acquisition independently. Functional scans were realigned, corrected for slice timing, and normalized to the coregistered MNI EPI template. Finally, functional images were smoothed with an 8 mm full-width at half-maximum (FWHM) Gaussian kernel. Data from three participants were discarded because of excessive head motion in the scanner.

Then, fMRI data were analyzed using the general linear model (GLM) implemented in SPM8 using a two-steps procedure. At the first level, the hemodynamic response for correct trials, time-locked to the cue onset and modeled with a duration until the answer given to the target, was convolved using a standard HRF for each participant. Each *ATTENTIONAL ORIENTING* session (High-Predictive, Low-Predictive) contained 6 regressors for correct trials according to the *CUE VALIDITY* (Valid, Invalid, Catch trials), and the *DISTRACTOR TYPE* (Neutral, NEU; previously Low-Rewarded, LR; previously High-Rewarded, HR). Movement parameters estimated during realignment (*x, y, z* translations and pitch, roll, and yaw rotations) as well as a constant vector were also included in the matrix as a variable of no interest. The resulting individual

maps of *t*-statistics were fed into second-level flexible factorial design with "conditions" as a within-subject factor, and "subject" as random factor, using a random effects analysis (Penny and Holmes, 2004).

Activations were considered as significant when exceeding an extent threshold allowing $p < 0.05$ FDR corrected for multiple comparisons across the whole brain, with an underlying voxel height threshold corresponding to $p < 0.001$ uncorrected.

2.5. Psychophysiological interaction analysis

Psychophysiological interaction (PPI) analyses were used in order to investigate the functional connectivity between seed regions (left and right FEF) and the rest of the brain when previously HIGH and previously LOW rewarded distractors were contrasted to Neutral distractors in the high-predictive condition. We also examined the functional connectivity in this condition but when the interference of reward was maximum (for invalid trials). The coordinates of the seed region corresponded to the local maxima of each individual within a 10 mm radius sphere of the peak voxel of the group analysis. A PPI model was created for each individual using three regressors: the reward modulation (HR+LR > Neutral in the high-predictive condition), the participant's average time-course of the seed region, and the interaction between these two first regressors. Next, the PPI model obtained for each individual at the first level (fixed-effects) analysis were entered in a second-level (random-effects) analysis. Significant activations were considered as for the main analysis.

2.6. Functional connectivity analysis

Functional connectivity was assessed with the CONN toolbox (www.nitrc.org/projects/conn) to examine coupling between the main brain regions of interest (ROI) identified in the group's statistics (second-level fMRI analysis) for the comparison of previously HIGH and LOW rewarded distractors relative to Neutral distractors in the high-predictive condition (HR+LR > Neutral): right fusiform gyrus (FG), right/left Frontal Eye Field (R/L FEF), left Striatum, right Superior Parietal Lobule (R SPL), Superior Colliculus (SC). Each ROI was defined as a 10 mm-diameter sphere with center at the MNI coordinates (center) of the above listed regions. A threshold of FDR *p*-value < 0.05 was applied to evaluate the ROI-to-ROI functional connectivity results. In addition, graph theory measurements on the sub-network formed by these ROI were also computed. In particular, we characterized the 'degree' of the network's nodes, in order to define the level of 'centrality' (and efficient functional role) of each ROI and assess its influence on the information flow with the rest of the network (Rubinov and Sporns, 2010).

3. Results

3.1. Behavioral data

Only correct responses with RTs less than 3 SDs of each subject's mean were included in the analysis. These exclusions accounted for 1.87% of trials in the association phase, and 1.73% of trials in the testing phase.

3.1.1. Association phase: effect of reward learning on RTs across trials

In this phase, participants had to respond to targets presented in either red or green circles, with only one of these two colors associated with higher reward (counterbalanced across participants). Mean RTs were submitted to a repeated-measure analysis of variance (ANOVA) with the within-participant factors of reward (high, low). This analysis demonstrated numerically faster RTs when a high reward was presented (669 ms) compared to when a low reward was presented (677 ms). However, this effect failed to reach significance, $F(1,22)=1.27$, $MSE=641$, $p = 0.272$.

3.1.2. Testing phase: effect of reward history on attentional orienting

In this second phase, participants had to respond to targets presented in a diamond shape, among circles of different colors, one of which could be red or green (i.e., previously high or low rewarded) on half of the trials. The remaining 50% of the trials consisted of neutral distractors, which were rendered in other colors than red or green. Targets were preceded by a visual cue at either a valid or invalid location on 50% of the trials in the low-predictive condition, or on 71% and 29% of trials respectively in the high-predictive condition (to trigger reflexive or voluntary orienting of attention). We performed a repeated-measure analysis of variance (ANOVA) on mean RTs obtained during this phase, with the factors of orienting condition (high-predictive, low-predictive), cue validity (valid, invalid), and distractor type (neutral, previously low-rewarded, previously high-rewarded). As expected (see (Bourgeois et al., 2017)), the results indicated a main effect of validity, $F(1,19)=51.98$, $MSE=4532$, partial eta-squared=0.73, $p < 0.001$, and a significant interaction between orienting condition and validity, $F(1,19)=14.63$, $MSE=2227$, partial eta-squared=0.44, $p = 0.001$. Participants were faster to respond to valid compared to invalid trials, especially when attention was endogenously oriented. Importantly, the analysis also revealed a main effect of reward, $F(2,38)=4.74$, $MSE=1223$, partial eta-squared=0.20, $p = 0.01$. Participants were slower to discriminate targets when a previously high-rewarded distractor was presented (657 ms) compared to when a previously low-rewarded distractor (643 ms, $p = 0.048$) or a neutral distractor (642 ms; $p = 0.006$) were presented (Fig. 2).

We run a posteriori power analysis for our main behavioral results which corresponds to the main effect of Reward. With an effect size *f* of 0.20 (derived from the partial eta-square of the main effect of Reward) and 3 measurements (Neutral, High reward, Low reward), we obtained a sample size of 12 and an alpha or beta errors which are close to 0 from 23 subjects. Of note, our sample is also within the range of previous imaging studies on reward-related biases in attention (Anderson et al., 2014; Kim and Anderson, 2020a, 2019).

In sum, these behavioral results replicate previous observations and highlight that stimuli previously associated with a high monetary reward receive higher attentional priority in the subsequent visual search task and modulate orienting responses to both low-predictive (more exogenous) and high-predictive (more endogenous) cues, even though these stimuli and their reward value were no longer task-relevant in the testing phase.

3.2. Neuroimaging results

3.2.1. Whole brain analysis: main effect of spatial attentional shift

Contrasts images were first computed to assess main effect of spatial attentional shift (Invalid > Valid conditions). Consistent with previous work (Corbetta and Shulman, 2002), increased activations were observed in right attention-related parietal areas, mainly in the superior parietal lobule, precuneus, and temporo-parietal junction (Table 1, Fig. 3A). These activations were predominantly observed for the high-predictive condition (Fig. 3B). Indeed, after endogenous orienting, comparing responses to Invalid vs Valid trials revealed extensive effects in the right SPL overlapping with IPS and precuneus, as well as in the angular gyrus, temporo-parietal junction, bilateral (but left dominant) FEF, right middle frontal gyrus, and bilateral occipital cortex (Table 1, Fig. 3). After orienting to the low-predictive cues (implying less endogenous/voluntary but more exogenous/stimulus-driven effects), the Invalid vs. Valid contrast revealed similar but weaker activations in the right TPJ only (Table 1).

Our subsequent fMRI analyses were therefore focused on the high-predictive condition, given that the low-predictive attentional manipulation induced less robust activations in attentional networks for reliable comparisons between other trial subtypes. This difference between conditions is likely to reflect less efficient orienting (and hence weaker reorienting) with low-predictive cues, or might also partly result from insuffi-

Table 1
Main effect of spatial attentional shift.

	Stuctures	Side	*MNI coordinates*			cluster size	*T* value	*p* value
			x	*y*	*z*			
Invalid > Valid	**Precuneus**	R	6	-64	49	407	7.11	< 0.001*
	Sup Parietal lobe (SPL)	R	21	-70	58	407	6.5	< 0.001*
	TPJ	R	57	-49	16	160	6.38	< 0.001*
	Inferior frontal gyrus	R	48	20	22	82	6.82	< 0.001*
High-predictive cue	**Inferior frontal gyrus**	L	-42	23	28	121	6.29	< 0.001*
Invalid > Valid	**FEF**	L	-39	2	58	264	7.28	< 0.001*
	Middle frontal gyrus	R	42	11	52	58	6	<0.001*
	Superior frontal gyrus	R	30	2	64	39	5.7	0.001*
	Precuneus and SPL	R	9	-61	49	952	8.68	< 0.001*
	Angular gyrus	R	48	-49	28	214	5.59	0.001*
	TPJ	R	60	-49	16	214	5.72	0.001*
	Middle occipital	R	36	-76	34	952	8.67	< 0.001*
	Middle occipital gyrus	L	-36	-82	31	34	6.04	< 0.001*
Low-predictive cue Invalid > Valid	**TPJ**	R	39	-49	19	84	3.72	.021*

* $p < 0.05$ FWE corrected for the whole brain volume (underlying height threshold: $p < 0.001$, uncorrected).

Table 2
Main effect of reward-related influences and interaction of reward-related influences with attentional cueing.

	Structures	Side	*MNI coordinates*			cluster size	*T* value	*p* svc	Coordinates from the literature**
			x	*y*	*z*				
High-predictive cue HR+LR > Neu	FEF	R	39	14	40	31	4.5	0.024*	30 -1 40
	FEF	L	-33	5	58	2	3.28	0.085*	-42 7 58
High-predictive cue HR > Neu	FEF	R	36	14	43	3	3.36	0.027*	30 -1 40
	FEF	L	-36	2	55	7	3.59	0.014*	-42 7 58
High-predictive cue HR+LR > Neutral; Invalid > Valid	FEF	R	36	14	46	2	3.53	0. 044*	30 -1 40
	FEF	L	-36	8	55	14	3.83	0.017*	-42 7 58
High-predictive cue HR > Neutral; Invalid > Valid	FEF	L	-36	5	52	39	4.49	0.002*	-42 7 58

* $p < 0.05$ FWE corrected for the whole brain volume (underlying height threshold: $p < 0.001$, uncorrected).
** from Chica et al. (2012).

cient temporal resolution of fMRI precluding a full capture of very brief and transient phenomena as observed during more exogenous/stimulus-driven attentional shifts.

3.2.2. Whole brain analysis: main effect of reward

We next examined the main effect of reward on brain responses by contrasting previously HIGH and previously LOW rewarded distractors with Neutral distractors during the high-predictive condition. Interestingly, this contrast showed activations in the right FEF (Table 2, Fig. 4). Activations in left FEF failed to reach significance (Table 2). Nonetheless, more symmetrical activations of the FEF were observed when contrasting only HIGH and Neutral distractors (Table 2). No significant modulation was observed in SPL or TPJ even when lowering thresholds to more liberal values. A similar comparison of LOW and Neutral distractors showed only weaker activation in right FEF, which did not survive the correction threshold (p svc=0.387), while there was no modulation of left FEF whatsoever (see Fig. 4). However, a direct contrast of HIGH and LOW reward produced no significant effect, even when lowering thresholds to more liberal values.

3.2.3. Whole brain analysis: interaction reward x validity

To examine the modulation of attentional orienting by the previous reward value of distractors, we computed the interaction between reward and validity (HR+LR > Neutral; Invalid > Valid for the high-predictive/endogenous condition). Greater response to previously rewarded distractors than neutral distractor on invalid compared to valid conditions was selectively observed in the left FEF (Table 2, Fig. 4). Significant activations were also observed but to a lesser extent in the right FEF (Table 2, Fig. 4). The same pattern of activations was observed when only HIGH rewarded distractors were compared to Neutral distractors, mostly for the left FEF (Table 2). This again implies that reward effects were mainly driven by the HR condition. As can be seen in activation parameter estimates from FEF (Fig. 4), there was no modulation by reward on valid trials on either side. However, a formal two-way interaction of (HR-LR) in Invalid > Valid conditions failed to show a significant increase above threshold in FEF even when lowering thresholds to more liberal values and activated only the left primary motor cortex (xyz= -36 -25 40, $T = 4.83$, $p = 0.036$ FWE).

3.2.4. Relation to behavioral effects

For completeness, we also tested for differential activation patterns in fMRI directly related to the behavioral interference on RTs caused by the previously rewarded distractors. A whole-brain statistical regression map was computed at the second level using contrast images from the global reward effect (previously HIGH+LOW rewarded distractors > Neutral distractors), with the behavioral reward interference magnitude calculated as followed: RTs for previously HIGH and LOW rewarded distractors – RTs for Neutral distractors. A significant positive correlation was found in the left FEF (-36 -10 -61, T-score=3.63, $p_{svc} = 0.001$ uncorrected).

3.2.5. Functional connectivity analyses

A psychophysiological interaction (PPI) analysis was performed to determine the functional coupling of the left or right FEF with other brain regions during the processing of previously rewarded distractors (vs. neutral) distractors (see Materials and methods). This was examined across all trials, and also more specifically when the interference of reward cues was maximum (i.e., invalid trials). The right and left FEF demonstrated increased functional connectivity with the right fusiform gyrus and the superior colliculus, respectively, when previously

Table 3
Psychophysiological Interaction (PPI) analysis.

	Seed	Co-activation	Side	*MNI coordinates*			cluster size	*T* value	*p* value
				x	*y*	*z*			
High-predictive cue HR+LR > Neu	Right FEF	fusiform	R	33	-64	14	87	4.59	0.012*
	Left FEF	sup colliculus		0	-37	-8	27	5.14	0.011**
High-predictive cue invalid HR+LR > Neu	Right FEF	striatum	L	-24	-1	1	76	4.48	0.010*

* $p < 0.001$ at the cluster level uncorrected for the whole brain volume (underlying height threshold: $p < 0.001$, uncorrected).
** p svc < 0.05 FWE corrected at the cluster level for the whole brain volume (underlying height threshold: $p < 0.001$, uncorrected). Coordinates from the literature -10 -38 -16.

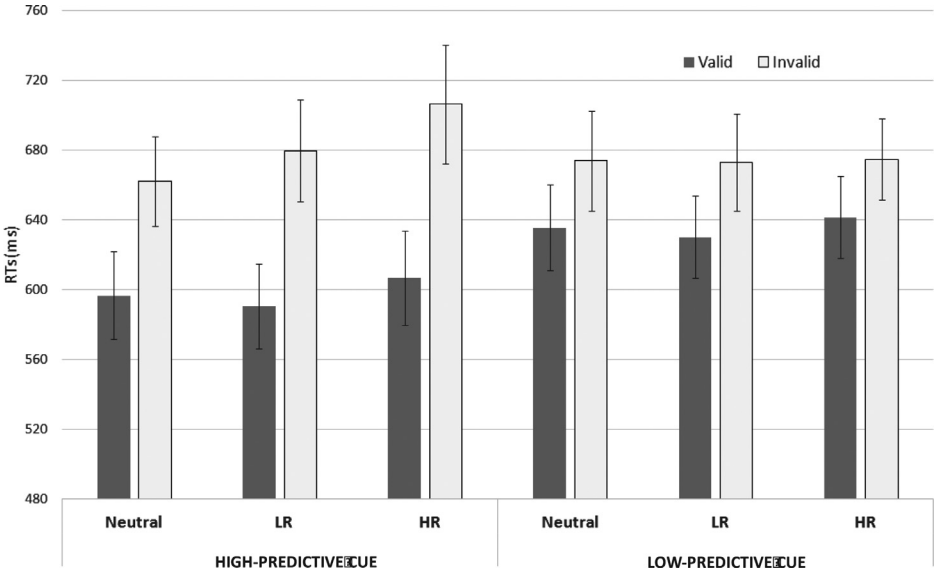

Fig. 2. Behavioral results of the Testing phase. Mean Response Times (in ms) and Standard errors obtained during the testing phase for the high-predictive/endogenous and low-predictive/exogenous conditions, valid and invalid distractors when a neutral distractor, a previously low-rewarded distractor (LR) or a previously high-rewarded distractor (HR) was presented.

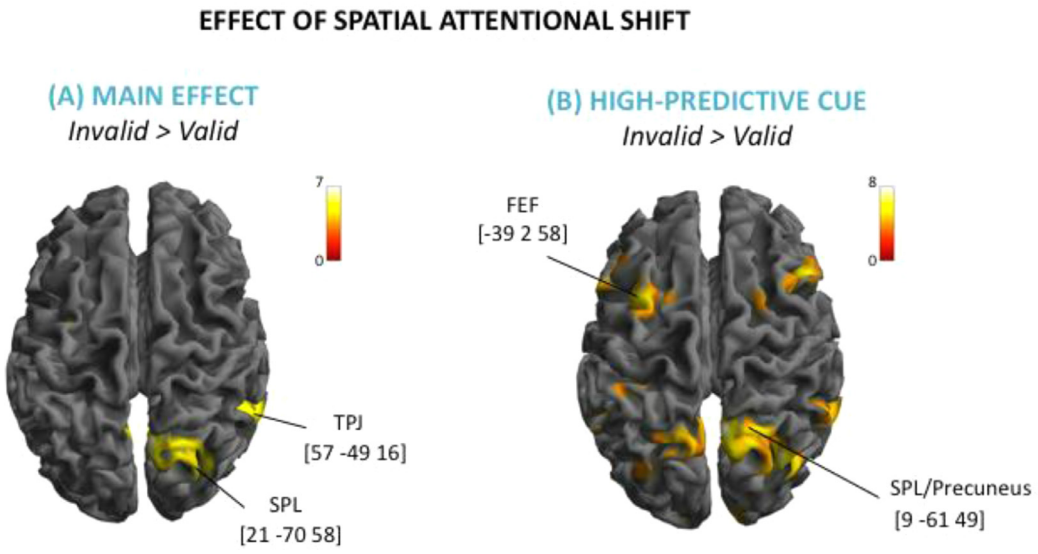

Fig. 3. Brain areas activated by spatial attentional shifts (see also Table 1). Whole brain maps showing increased activation in right-dominant attention networks, mainly in Superior Parietal Lobule (SPL)/precuneus, frontal eye field (FEF), and temporo-parietal junction (TPJ) ($p < 0.05$ FWE corrected for the whole brain volume).

rewarded (HR and LR) distractors were presented relative to Neutral distractors (Table 3, Fig. 5). Interestingly, the PPI analysis performed on the right FEF in the same condition (HR+LR > Neutral) but for invalid trials only revealed increased connectivity with the left striatum (Table 3, Fig. 5).

Functional brain connectivity was also assessed between relevant ROIs for the HR+LR > Neutral effects in the high-predictive condition, using pairwise correlation (Fig. 6, *a* and *b*) and graph theory analysis (Fig. 5, c). Significant positive correlations (*FDR p-value <0.05*) between ROI indicated the strongest connections for SPL with several other areas within attentional brain networks including bilateral FEF as well as FG (Fig. 6, *a* and *b*). Parameters from the graph analysis revealed the highest node degree for the left FEF, indicating the efficiency of this region in interacting the most consistently (relative to the other nodes)

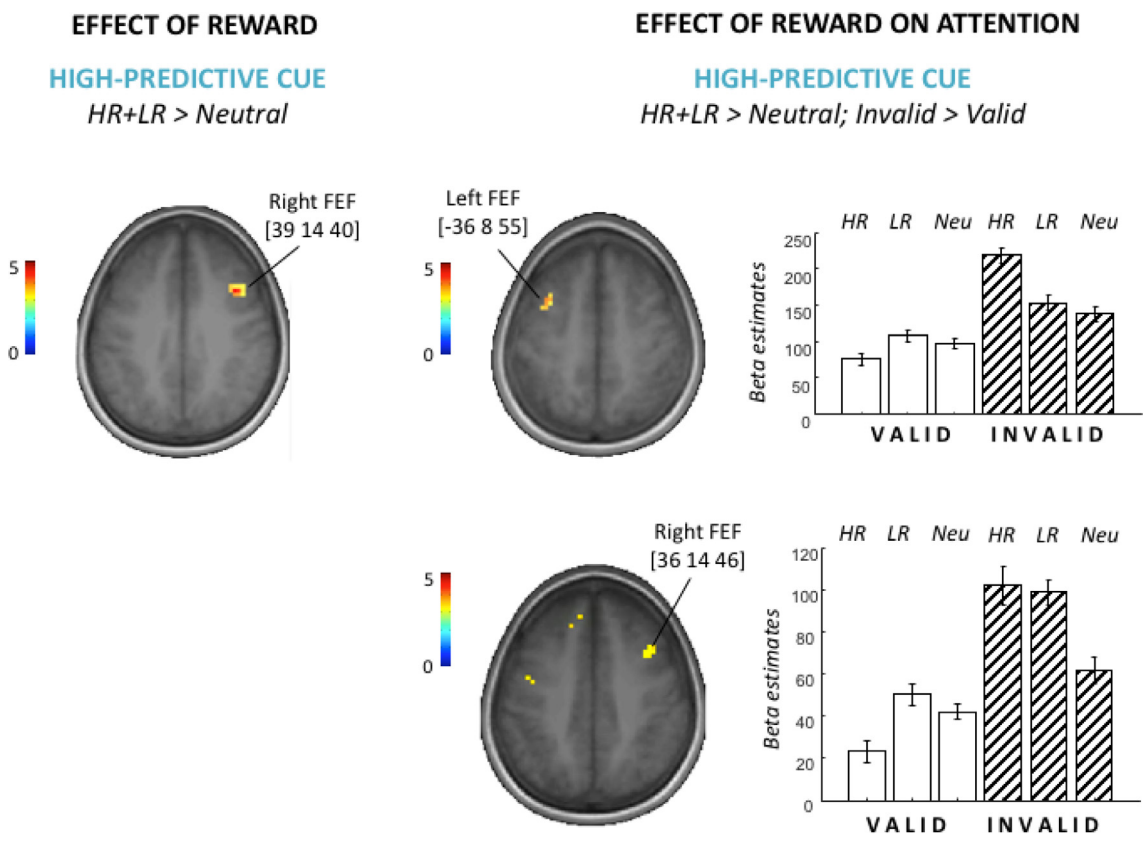

Fig. 4. Brain areas showing reward-related influences during goal-directed attentional orienting. The main effect of reward (left panel) and reward effects as a function of spatial attention (right panel) both revealed selective activations in the frontal eye fields (FEF). Plots of activity parameters illustrates beta weights as a function of cue validity (valid vs invalid). Errors bars represent standard errors of the mean.

with all other ROIs within the network (Fig. 6, *c*), and thus confirming a central role of this region during attentional orienting in the presence of rewarded distractors.

4. Discussion

Our results demonstrate that stimuli previously associated with a monetary reward received higher attentional priority in a subsequent visual search task, mitigating attentional orienting induced by high-predictive or low-predictive spatial cues. Value-driven attentional capture occurred even though these stimuli and reward were no-longer task-relevant during visual search, confirming previous reports (Anderson et al., 2011; Bourgeois et al., 2018; Bourgeois et al., 2017, 2016b; Chelazzi et al., 2014; Della Libera and Chelazzi, 2006; Sanz et al., 2018). Anatomically, our fMRI results revealed a network of core regions involved in selective attention and priority maps instantiation that activated during spatial shifts and were modulated by reward value of visual stimuli. These regions included FEF and parietal cortex, as well as SC and striatum. Among these regions, the FEF was found to play a crucial role, by showing combined effects of both goal-directed attentional shifts and reward-related influences when attention was endogenously oriented. Although reward and attention refer to different concepts, these two factors have often been confounded in experimental tasks, for instance when responses to attended stimuli are reinforced by delivering rewards, giving rise to uncertainty regarding not only the neural bases of these two functions (Maunsell, 2004) but also the pathways through which they interact in the guidance of attention to relevant information.

Here, by using a paradigm where the different factors guiding attention were manipulated separately, we could shed new light on this issue. Our fMRI results indicated that FEF was engaged by both attentional orienting mechanisms and the appraisal of motivational information. These data provide novel evidence that high-level priority maps may be generated in this region by integrating distinct types of cues such as value-based attributes, stimulus salience, and goal-related signals that presumably originate from different brain structures and converge to FEF in order to control attention shifts and eye-movements.

FEF is an extensively studied area of the prefrontal cortex known to be crucially implicated in eye-movements and selective attention (Vernet et al., 2014 for a review). This structure is a core region of the dorsal fronto-parietal network (also encompassing IPS), predominantly active when attention is voluntarily oriented in space (Corbetta and Shulman, 2002; see also Grosbras et al., 2005). Previous work showed that FEF contains priority maps of space (Thompson and Bichot, 2005), which consist of a representation of the visual scene in which an object's bottom-up distinctiveness and its behavioral relevance to the observer (based on current task goals, expectation, experience, etc.) compete to ultimately guide eye movements and covert visual attention (Bisley and Mirpour, 2019; Bourgeois et al., 2020; Fecteau and Munoz, 2006; Mirpour et al., 2018). Target-related activity in FEF may in turn generate top-down influences modulating neuronal responses to sensory information at the same location (Schafer and Moore, 2007), in addition to oculomotor signals to SC (Bisley and Mirpour, 2019). Recent electrophysiology studies demonstrated that FEF may also keep track of which locations have been already examined during search and could thus be a source of inhibitory tagging signals to parietal cortex (Mirpour et al., 2019).

Interestingly, other findings (Fernandes et al., 2014) suggest that FEF may not actively compute saliency maps based upon bottom-up features such as color, intensity, or orientation along multiple sensory dimensions, unlike the notion of saliency map proposed by Itti and Koch (2000). Instead, it may be dominated by final stages of top-down target-selection and saccade planning, in good agreement with its re-

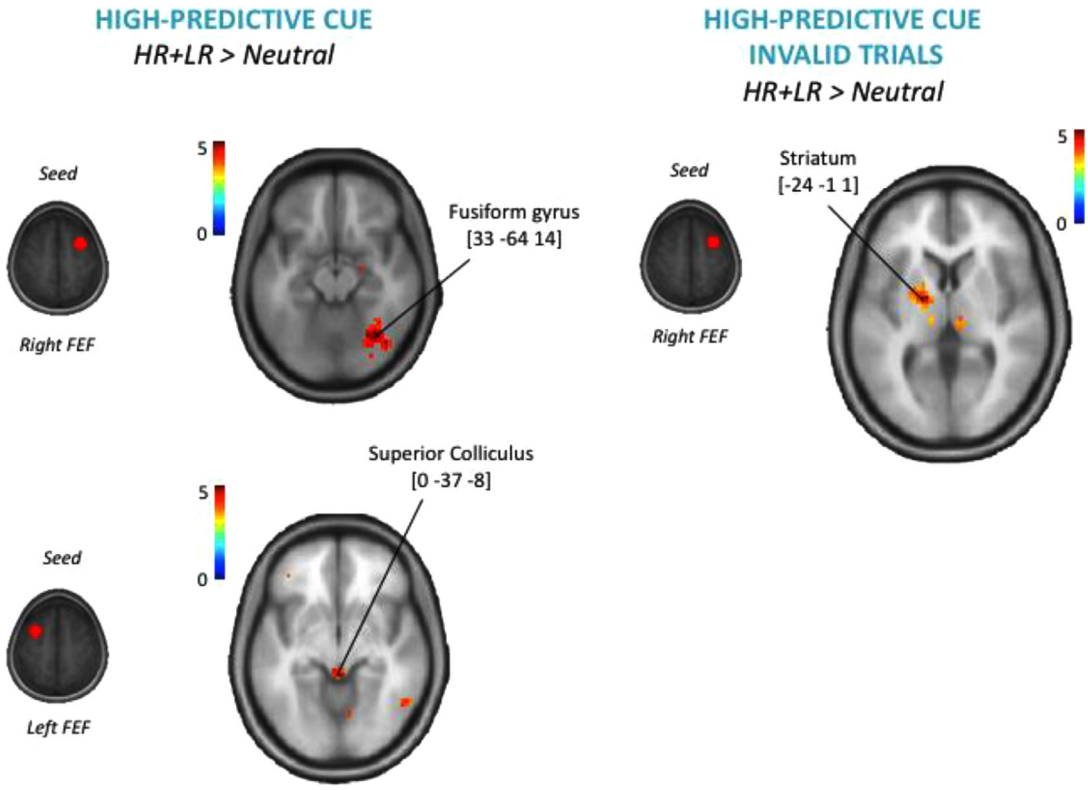

Fig. 5. Brain areas showing psychophysiological interaction (PPI) effects. Significant functional coupling was observed between the left and the right FEF with the right fusiform gyrus and the SC, respectively, when previously rewarded (HR and LR) distractors were compared to neutral distractors (Left panel). Increased functional coupling between the right FEF and the left striatum was also observed when HR and LR distractors were compared to neutral distractors in trials with the largest interference cost on attention (invalid trials) (right panel) (see also Table 3).

cruitment by goal-driven shifts after invalid cues as found in our study. Notably, however, previous evidence in monkeys demonstrate spatially selective modulation of FEF neurons when a reward is associated with visual targets (Ding and Hikosaka, 2006). These authors recorded neurons in both the FEF and basal ganglia during a rewarded memory-guided saccade task. They showed that both FEF and the basal ganglia contribute to reward-based biases in saccade generation, consistent with activations found in these two regions in our study. Interestingly, FEF preferentially encoded reward location while basal ganglia preferentially encoded reward size. Accordingly, other studies also reported activations of the basal ganglia, including caudate nucleus and nucleus accumbens, during the processing of reward outcomes and anticipation of reward in visual attention and motor decision tasks (Anderson et al., 2014; Hikosaka et al., 2014; Kim and Hikosaka, 2013; O'Doherty, 2004). In line with these findings, our work provides novel evidence to indicate a central role of FEF in representing behaviorally salient locations and mediating reward value effects on selective attention.

In contrast, monkey neurophysiology research reported that activity in the lateral intraparietal area (LIP), another major node of attention networks engaged by spatial shifts, did not correlate with subjective value (Mirpour and Bisley, 2012). However, the latter study also found that downstream normalization of LIP activity, which may occur on the way to other regions such as FEF or SC, may lead to a partial correlation with estimates of reward value (Mirpour and Bisley, 2012). This would be consistent with reward signals being ultimately integrated with other top-down attention signals at the level of brain-wide networks, in which FEF could play a central role in resolving different sources of competition for attentional selection and motor saccade generation.

In broad keeping with this notion, our functional connectivity analysis revealed that the (left) FEF had the highest degree in a network of task-responsive ROIs. The degree of a node within a network is equal to the number of links connected to that node. Thus, nodes with a high degree correspond to regions with the strongest interaction, structurally and/or functionally, with other nodes of the network (Rubinov and Sporns, 2010). One could expect that the right FEF would be more implicated rather than the left FEF, given classic hemispheric asymmetries in attention. If other studies also reported a left-lateralized pattern for value-driven attention (Kim and Anderson, 2019), the left dominance observed in our results should be taken with caution and could reflect insufficient power, anatomical variability, or some unknown laterality effects. Indeed, the side of presentation of targets, cues and/or distractors was not taken into account since these supplementary factors would have required many more trials in order to make our main comparison of interest between both high-predictive/endogenous and low-predictive/exogenous conditions. Thus, further investigation may consider laterality factors in their analyses to elucidate hemispheric asymmetries in the capture of attention by reward-associated stimuli. Moreover, in the context of future research, since FEF might be implicated both to generate saccade commands or to covertly allocate attention in space without eye movements a more rigorously measuring of eye movements should be necessary to further clarify the role of this brain region in value-driven attentional mechanisms.

We should note that reward effects might be partly confounded by more general selection history effects (Anderson et al., 2021), whereby distracting effects of HR and LR stimuli might be caused by more frequent selection during the training phase and then induce differential attentional biases by non-specific reinforcement. Although this confound is shared with many previous studies, selection history seems insufficient to explain our main findings. In our paradigm, prior rewards were associated with two colors (e.g. red or green) but other non-rewarded colors were also repeatedly presented during the learning phase and could reappear among distractors in the neutral (no-reward) condition

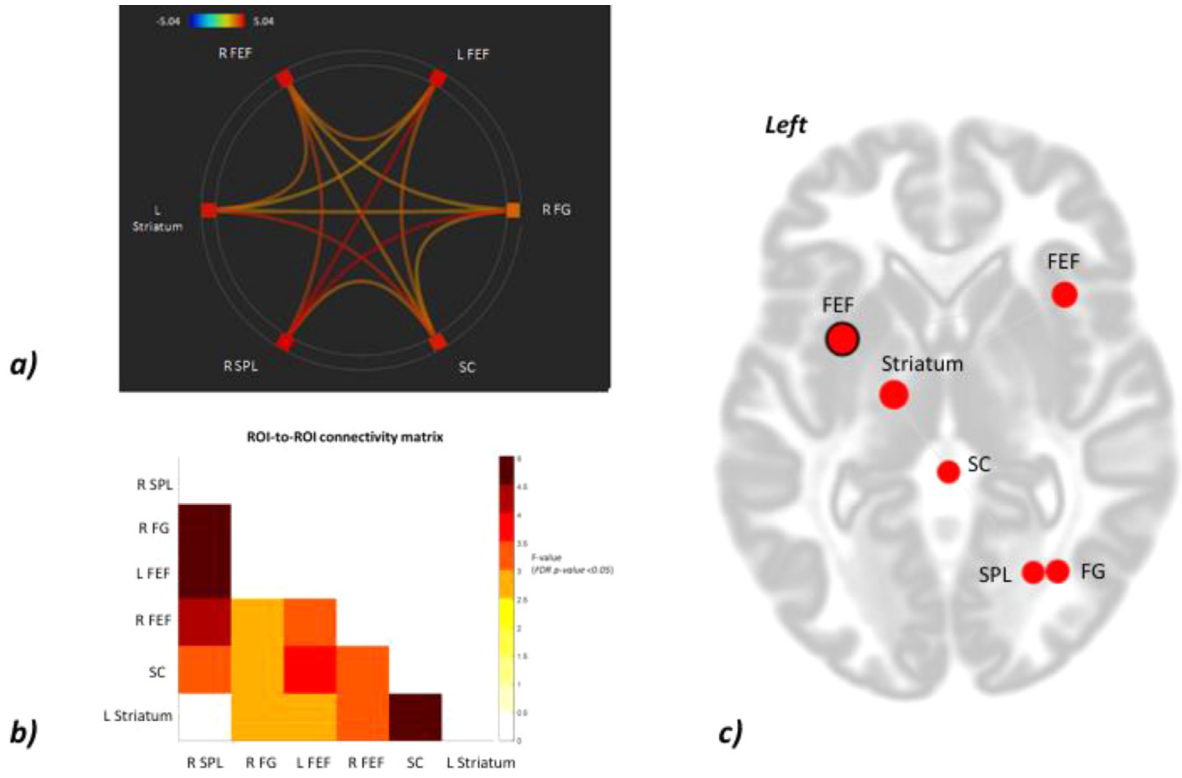

Fig. 6. Functional connectivity results between regions of interest (ROIs). (a) A connectome ring plot is shown to depict the significant connections (*FDR p-value<0.05*) between ROIs previously identified in our whole-brain analysis. The strength of connections (always positive) is color-coded according to the reported color-bar. (b) To better compare these connections, their strength is reported in the lower part of a symmetric correlation matrix between each pair of ROIs, color-coded according to a more graded color-bar. (**c**) Results of graph analysis showing the network's nodes "degree": the size of nodes is proportional to the value of the "degree". The L FEF has the highest degree in the network, meaning that it is the node forming the strongest connections with other nodes in the network.

during the test phase. Therefore, non-rewarded colors associated with the location of targets in the test phase differed from colors of HR and LR distractors in their lack of systematic pairing with prior reward, but did not differ from the history of other distractor colors. In addition, critical reward effects on attentional shifts in left FEF were consistently stronger for HR than LR (see activation parameter plotted in Fig. 4) although both distractor types had the same selection history during learning. This indicates that the left FEF was sensitive to the magnitude of reward. In contrast, however, the right FEF appeared responsive to both high and low reward, and could perhaps be more globally affected by selection history or non-specific reinforcement effects rather than by reward only. Recent work has begun to define an integrative account of selection history in relation to reward learning and habit formation (Anderson et al., 2021) in which value-driven attention may constitute a specific instance of experience-driven attention, along with other learning effects such as statistical dependencies among objects, stimulus frequency, or inter-trial priming. Be that as it may, our paradigm was not designed to disentangle these processes, and these issues warrant more specific investigation in future studies, including the role of potential hemispheric asymmetries in FEF.

More critically, our connectivity data further support a central role of FEF in orchestrating the selection of diverse top-down biases. The FEF can influence saccade generation via direct projections to the superior colliculus and/or via an indirect pathway through the basal ganglia (Ding and Hikosaka, 2006). Remarkably, here we found an activation of the SC in our PPI analysis of left FEF coupling during the processing of previously rewarded compared to neutral distractors, and SC also showed strong connectivity values with the striatum in pairwise correlation analysis (Fig. 5b). In addition to traditional oculomotor signals, visual saliency effects have also been demonstrated in the SC, mainly in the primate visual-only superficial layer (SCs), which is heavily interconnected with early visual areas (White et al., 2017a, 2017b). White et al. (2017b) recorded SC neurons during free viewing of natural dynamic scenes and observed modulations by the magnitude of a saliency representation, independent of the actual saccade goal. These results indicate that the output of the SC saliency map alone cannot provide sufficient information to determine gaze. Reward information might be provided to SC through projections received from striatum. Interestingly, Ikeda et al. (2003) reported an increase firing of monkey SC neurons when the visual stimulus indicated an upcoming reward during a memory-guided saccade task, which occurred mostly in saccade-related SC neurons in the deep layer that receive inputs from both the FEF and basal ganglia (Ikeda and Hikosaka, 2003). Thus, we hypothesize that FEF may ultimately influence selective attentional shifts and saccade generation via connections to the superior colliculus, with an indirect pathway through the basal ganglia being more strongly engaged when a reward is at stake (Ding and Hikosaka, 2006), or perhaps more generally sensitive to prior selection history regardless of reward magnitude {Anderson et al., 2021 #2701} as possibly reflected by greater connectivity with right FEF (see hemispheric asymmetries in Fig. 4). Value-driven modulation of goal-directed attention could also reach back to visual cortical levels to boost saliency in visual sensory processing regions (Serences, 2008), while the parietal cortex might construct distinctive priority maps of space that integrates other processes, including the inhibition of locations that have been previously attended or explored (Mirpour et al., 2019).

In sum, our study provides converging evidence from behavioral measures as well as stimulus-driven and connectivity fMRI to shed new light on brain mechanisms trough which different types of top-down biases interact during attentional orienting. Our new data reveal a pivotal role of the FEF in integrating task-related and reward-related signals presumably mediating the generation of spatial saliency maps and

guidance of selective attention to behaviorally relevant objects in the environment.

Data availability statement

Data will be available upon request to the Authors, without any restrictions.

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Credit authorship contribution statement

Alexia Bourgeois: Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft, Writing – review & editing, Funding acquisition. **Virginie Sterpenich:** Formal analysis. **Giannina Rita Iannotti:** Formal analysis, Writing – original draft. **Patrik Vuilleumier:** Conceptualization, Methodology, Formal analysis, Resources, Writing – original draft, Writing – review & editing, Supervision, Funding acquisition.

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References

Anderson, B.A., 2016. The attention habit: how reward learning shapes attentional selection. Ann. N. Y. Acad. Sci. 1369 (1), 24–39. doi:10.1111/nyas.12957.

Anderson, B.A., Kim, H., Kim, A.J., Liao, M.R., Mrkonja, L., Clement, A., Gregoire, L., 2021. The past, present, and future of selection history. Neurosci. Biobehav. Rev. 130, 326–350. doi:10.1016/j.neubiorev.2021.09.004.

Anderson, B.A., Kuwabara, H., Wong, D.F., Roberts, J., Rahmim, A., Brasic, J.R., Courtney, S.M., 2017. Linking dopaminergic reward signals to the development of attentional bias: a positron emission tomographic study. Neuroimage 157, 27–33. doi:10.1016/j.neuroimage.2017.05.062.

Anderson, B.A., Laurent, P.A., Yantis, S., 2011. Value-driven attentional capture. Proc. Natl. Acad. Sci. U. S. A. 108 (25), 10367–10371. doi:10.1073/pnas.1104047108, doi:1104047108 [pii].

Anderson, B.A., Laurent, P.A., Yantis, S., 2014. Value-driven attentional priority signals in human basal ganglia and visual cortex. Brain Res. 1587, 88–96. doi:10.1016/j.brainres.2014.08.062.

Bisley, J.W., Mirpour, K., 2019. The neural instantiation of a priority map. Curr Opin Psychol 29, 108–112. doi:10.1016/j.copsyc.2019.01.002.

Bourgeois, A., Badier, E., Baron, N., Carruzzo, F., Vuilleumier, P., 2018a. Influence of reward learning on visual attention and eye movements in a naturalistic environment: a virtual reality study. PLoS ONE 13 (12), e0207990. doi:10.1371/journal.pone.0207990.

Bourgeois, A., Chelazzi, L., Vuilleumier, P., 2016a. How motivation and reward learning modulate selective attention. Prog. Brain Res. 229, 325–342. doi:10.1016/bs.pbr.2016.06.004.

Bourgeois, A., Chica, A.B., Migliaccio, R., Thiebaut de Schotten, M., Bartolomeo, P., 2012. Cortical control of inhibition of return: evidence from patients with inferior parietal damage and visual neglect. Neuropsychologia 50 (5), 800–809.

Bourgeois, A., Chica, A.B., Valero-Cabre, A., Bartolomeo, P., 2013a. Cortical control of inhibition of return: causal evidence for task-dependent modulations by dorsal and ventral parietal regions. Cortex 49 (8), 2229–2238. doi:10.1016/j.cortex.2012.10.017, doi:S0010-9452(12)00326-7 [pii].

Bourgeois, A., Chica, A.B., Valero-Cabre, A., Bartolomeo, P., 2013b. Cortical control of inhibition of return: exploring the causal contributions of the left parietal cortex. Cortex 49 (10), 2927–2934. doi:10.1016/j.cortex.2013.08.004, doi:S0010-9452(13)00205-0 [pii].

Bourgeois, A., Guedj, C., Carrera, E., Vuilleumier, P., 2020. Pulvino-cortical interaction: an integrative role in the control of attention. Neurosci. Biobehav. Rev. 111, 104–113. doi:10.1016/j.neubiorev.2020.01.005.

Bourgeois, A., Neveu, R., Bayle, D.J., Vuilleumier, P., 2017. How does reward compete with goal-directed and stimulus-driven shifts of attention? Cogn. Emot. 31 (1), 109–118. doi:10.1080/02699931.2015.1085366.

Bourgeois, A., Neveu, R., Vuilleumier, P., 2016b. How does awareness modulate goal-directed and stimulus-driven shifts of attention triggered by value learning? PLoS ONE 11 (8), e0160469. doi:10.1371/journal.pone.0160469.

Bourgeois, A., Saj, A., Vuilleumier, P., 2018b. Value-driven attentional capture in neglect. Cortex 109, 260–271. doi:10.1016/j.cortex.2018.09.015.

Chelazzi, L., Estocinova, J., Calletti, R., Lo Gerfo, E., Sani, I., Della Libera, C., Santandrea, E., 2014. Altering spatial priority maps via reward-based learning. J. Neurosci. 34 (25), 8594–8604. doi:10.1523/JNEUROSCI.0277-14.2014.

Chica, A.B., Paz-Alonso, P.M., Valero-Cabre, A., Bartolomeo, P., 2012. Neural bases of the interactions between spatial attention and conscious perception. Cereb. Cortex doi:10.1093/cercor/bhs087s, doi:bhs087 [pii].

Corbetta, M., Kincade, J.M., Ollinger, J.M., McAvoy, M.P., Shulman, G.L., 2000. Voluntary orienting is dissociated from target detection in human posterior parietal cortex. Nat. Neurosci. 3 (3), 292–297.

Corbetta, M., Shulman, G.L., 2002. Control of goal-directed and stimulus-driven attention in the brain. Nat. Rev. Neurosci. 3 (3), 201–215.

Della Libera, C., Chelazzi, L., 2006. Visual selective attention and the effects of monetary rewards. Psychol. Sci. 17 (3), 222–227. doi:10.1111/j.1467-9280.2006.01689.x.

Della Libera, C., Chelazzi, L., 2009. Learning to attend and to ignore is a matter of gains and losses. Psychol. Sci. 20 (6), 778–784. doi:10.1111/j.1467-9280.2009.02360.x, doi:PSCI2360 [pii].

Ding, L., Hikosaka, O., 2006. Comparison of reward modulation in the frontal eye field and caudate of the macaque. J. Neurosci. 26 (25), 6695–6703. doi:10.1523/JNEUROSCI.0836-06.2006, doi:26/25/6695 [pii].

Fecteau, J.H., Munoz, D.P., 2006. Salience, relevance, and firing: a priority map for target selection. Trends Cogn. Sci. 10 (8), 382–390. doi:10.1016/j.tics.2006.06.011.

Fernandes, H.L., Stevenson, I.H., Phillips, A.N., Segraves, M.A., Kording, K.P., 2014. Saliency and saccade encoding in the frontal eye field during natural scene search. Cereb. Cortex 24 (12), 3232–3245. doi:10.1093/cercor/bht179.

Grosbras, M.H., Laird, A.R., Paus, T., 2005. Cortical regions involved in eye movements, shifts of attention, and gaze perception. Hum. Brain Mapp. 25 (1), 140–154. doi:10.1002/hbm.20145.

Hikosaka, O., Kim, H.F., Yasuda, M., Yamamoto, S., 2014. Basal ganglia circuits for reward value-guided behavior. Annu. Rev. Neurosci. 37, 289–306. doi:10.1146/annurev-neuro-071013-013924.

Hikosaka, O., Nakamura, K., Nakahara, H., 2006. Basal ganglia orient eyes to reward. J. Neurophysiol. 95 (2), 567–584. doi:10.1152/jn.00458.2005.

Ikeda, T., Hikosaka, O., 2003. Reward-dependent gain and bias of visual responses in primate superior colliculus. Neuron 39 (4), 693–700 doi:S0896627303004641 [pii].

Ikeda, T., Hikosaka, O., 2007. Positive and negative modulation of motor response in primate superior colliculus by reward expectation. J. Neurophysiol. 98 (6), 3163–3170. doi:10.1152/jn.00975.2007, doi:00975.2007 [pii].

Itti, L., Koch, C., 2000. A saliency-based search mechanism for overt and covert shifts of visual attention. Vis. Res. 40 (10–12), 1489–1506. doi:10.1016/s0042-6989(99)00163-7.

Kim, A.J., Anderson, B.A., 2020a. Arousal-biased competition explains reduced distraction by reward cues under threat. eNeuro (4) 7. doi:10.1523/ENEURO.0099-20.2020.

Kim, A.J., Anderson, B.A., 2020b. Threat reduces value-driven but not salience-driven attentional capture. Emotion 20 (5), 874–889. doi:10.1037/emo0000599.

Kim, H., Anderson, B.A., 2019. Dissociable neural mechanisms underlie value-driven and selection-driven attentional capture. Brain Res. 1708, 109–115. doi:10.1016/j.brainres.2018.11.026.

Kim, H.F., Hikosaka, O., 2013. Distinct basal ganglia circuits controlling behaviors guided by flexible and stable values. Neuron 79 (5), 1001–1010. doi:10.1016/j.neuron.2013.06.044.

Kincade, J.M., Abrams, R.A., Astafiev, S.V., Shulman, G.L., Corbetta, M., 2005. An event-related functional magnetic resonance imaging study of voluntary and stimulus–driven orienting of attention. J. Neurosci. 25 (18), 4593–4604.

Maunsell, J.H., 2004. Neuronal representations of cognitive state: reward or attention? Trends Cogn. Sci. 8 (6), 261–265. doi:10.1016/j.tics.2004.04.003, S1364661304001020 [pii].

Mirpour, K., Bisley, J.W., 2012. Dissociating activity in the lateral intraparietal area from value using a visual foraging task. Proc. Natl. Acad. Sci. U. S. A. 109 (25), 10083–10088. doi:10.1073/pnas.1120763109.

Mirpour, K., Bolandnazar, Z., Bisley, J.W., 2018. Suppression of frontal eye field neuronal responses with maintained fixation. Proc. Natl. Acad. Sci. U. S. A. 115 (4), 804–809. doi:10.1073/pnas.1716315115.

Mirpour, K., Bolandnazar, Z., Bisley, J.W., 2019. Neurons in FEF keep track of items that have been previously fixated in free viewing visual search. J. Neurosci. 39 (11), 2114–2124. doi:10.1523/JNEUROSCI.1767-18.2018.

O'Doherty, J.P., 2004. Reward representations and reward-related learning in the human brain: insights from neuroimaging. Curr. Opin. Neurobiol. 14 (6), 769–776. doi:10.1016/j.conb.2004.10.016.

Peck, C.J., Jangraw, D.C., Suzuki, M., Efem, R., Gottlieb, J., 2009. Reward modulates attention independently of action value in posterior parietal cortex. J. Neurosci. 29 (36), 11182–11191. doi:10.1523/JNEUROSCI.1929-09.2009.

Penny, W.D., Holmes, A.P., WD, P., 2004. Random effects analysis. In: Frackowiak RSJ, A.J., Zeki, S. (Eds.), Human Brain Function. second ed, Academic Press, pp. 843–850.

Pourtois, G., Schettino, A., Vuilleumier, P., 2013. Brain mechanisms for emotional influences on perception and attention: what is magic and what is not. Biol. Psychol. 92 (3), 492–512. doi:10.1016/j.biopsycho.2012.02.007.

Rubinov, M., Sporns, O., 2010. Complex network measures of brain con-

nectivity: uses and interpretations. Neuroimage 52 (3), 1059–1069. doi:10.1016/j.neuroimage.2009.10.003.

Sanz, L.R.D., Vuilleumier, P., Bourgeois, A., 2018. Cross-modal integration during value-driven attentional capture. Neuropsychologia 120, 105–112. doi:10.1016/j.neuropsychologia.2018.10.014.

Schafer, R.J., Moore, T., 2007. Attention governs action in the primate frontal eye field. Neuron 56 (3), 541–551. doi:10.1016/j.neuron.2007.09.029.

Schneider, W., Eschman, A., Zuccolotto, A., 2002. E-prime User's Guide. Psychology Software Tools Inc, Pittsburg.

Serences, J.T., 2008. Value-based modulations in human visual cortex. Neuron 60 (6), 1169–1181. doi:10.1016/j.neuron.2008.10.051, doi:S0896-6273(08)00951-3 [pii].

Shuler, M.G., Bear, M.F., 2006. Reward timing in the primary visual cortex. Science 311 (5767), 1606–1609. doi:10.1126/science.1123513.

Stanisor, L., van der Togt, C., Pennartz, C.M., Roelfsema, P.R., 2013. A unified selection signal for attention and reward in primary visual cortex. Proc. Natl. Acad. Sci. U. S. A. 110 (22), 9136–9141. doi:10.1073/pnas.1300117110.

Thompson, K.G., Bichot, N.P., 2005. A visual salience map in the primate frontal eye field. Prog. Brain Res. 147, 251–262. doi:10.1016/S0079-6123(04)47019-8.

Vernet, M., Quentin, R., Chanes, L., Mitsumasu, A., Valero-Cabre, A., 2014. Frontal eye field, where art thou? Anatomy, function, and non-invasive manipulation of frontal regions involved in eye movements and associated cognitive operations. Front. Integr. Neurosci. 8, 66. doi:10.3389/fnint.2014.00066.

Vuilleumier, P., 2005. How brains beware: neural mechanisms of emotional attention. Trends Cogn. Sci. 9 (12), 585–594. doi:10.1016/j.tics.2005.10.011, doi:S1364-6613(05)00302-5 [pii].

Vuilleumier, P., 2015. Affective and motivational control of vision. Curr. Opin. Neurol. 28 (1), 29–35. doi:10.1097/WCO.0000000000000159.

White, B.J., Berg, D.J., Kan, J.Y., Marino, R.A., Itti, L., Munoz, D.P., 2017a. Superior colliculus neurons encode a visual saliency map during free viewing of natural dynamic video. Nat. Commun. 8, 14263. doi:10.1038/ncomms14263.

White, B.J., Kan, J.Y., Levy, R., Itti, L., Munoz, D.P., 2017b. Superior colliculus encodes visual saliency before the primary visual cortex. Proc. Natl. Acad. Sci. U. S. A. 114 (35), 9451–9456. doi:10.1073/pnas.1701003114.