Neural mechanisms of background and velocity effects in smooth pursuit eye movements

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Abstract

Smooth pursuit eye movements (SPEM) are essential to guide behaviour in complex visual environments. SPEM accuracy is known to be degraded by the presence of a structured visual background and at higher target velocities. The aim of this preregistered study was to investigate the neural mechanisms of these robust behavioural effects. $N = 33$ participants performed a SPEM task with two background conditions (present and absent) at two target velocities (0.4 and 0.6 Hz). Eye movement and BOLD data were collected simultaneously. Both the presence of a structured background and faster target velocity decreased pursuit gain and increased catch-up saccade rate. Faster targets additionally increased position error. Higher BOLD response with background was found in extensive clusters in visual, parietal, and frontal areas (including the medial frontal eye fields; FEF) partially overlapping with the known SPEM network. Faster targets were associated with higher BOLD response in visual cortex and left lateral FEF. Task-based functional connectivity analyses (psychophysiological interactions; PPI) largely replicated previous results in the basic SPEM network but did not yield additional information regarding the neural underpinnings of the background and velocity effects. The results show that the presentation of visual background stimuli during SPEM induces activity in a widespread visuo-parieto-frontal network including areas contributing to cognitive aspects of oculomotor control such as medial FEF, whereas the response to higher target velocity involves visual and motor areas such as lateral FEF. Therefore, we were able to propose for the first time different functions of the medial and lateral FEF during SPEM.

KEYWORDS
background, distractor, fMRI, frontal eye fields, functional connectivity, smooth pursuit

1 | INTRODUCTION

Smooth pursuit eye movements (SPEM) enable the tracking of a small slowly moving object with our eyes. As such they are an essential element of our oculomotor system (Leigh & Zee, 2015). Functional magnetic resonance imaging (fMRI) studies have shown that smooth pursuit performance is accompanied by activation in visual areas such as V5, lateral geniculate nucleus (LGN), posterior parietal cortex (PPC), supplementary eye fields (SEF), and medial as well as lateral frontal eye fields (FEF; Lencer & Trillenberg, 2008). Two common findings in

the literature are that pursuit performance deteriorates (1) in the presence of visual background stimuli and (2) with higher target velocity (Barnes & Crombie, 1985; Buizza & Schmid, 1986; Collewijn & Tamminga, 1984; Hutton et al., 2000; Kaufman & Abel, 1986; Kreyenmeier et al., 2017; Lisberger et al., 1981; Masson et al., 1995; Meyhöfer et al., 2019). Both effects are very robust and show high reliability over time but also substantial interindividual differences (Schröder et al., 2021). The background effect is thought to be due to mechanisms countering the optokinetic drive induced by the background (Barnes, 2008). The velocity effect is related to eye velocity and/or acceleration saturation (Buizza & Schmid, 1986). Critically, little research has been done concerning the neural underpinnings of these effects.

Evidence concerning the neural mechanisms of the background effect comes from fMRI and transcranial magnetic stimulation (TMS) literature. An fMRI study by Ohlendorf et al. (2010) identified the middle temporal area (MT+) and the visual area V7 as important visuomotor transformation sites as they were active during visual, oculomotor, and visuo-oculomotor task conditions and thus receive all necessary information to successfully transform visual information into a motor command. In addition, PPC was found to specifically respond to differential motion between the structured background and the target highlighting the pivotal role of the PPC in integrating the movement of a frame of reference relative to the target. Another line of evidence concerning the neural mechanisms underlying smooth pursuit over a structured background comes from a TMS study (Haarmeier & Kammer, 2010) pointing to the crucial role of the temporoparietal junction (TPJ) in the suppression of the optokinetic nystagmus during SPEM over a structured background. This finding is also supported by Lawden et al. (1995) who demonstrated that lesions in the inferior parietal cortex (BA 40) are associated with greater background-induced impairments in SPEM performance and additionally stressed the importance of intact cortical white matter connections.

For the velocity effect, contributions of visual cortex, angular gyrus, cerebellum, and basal ganglia could be established, as indicated by increased activation at higher velocities (Nagel et al., 2008; Nagel et al., 2012; Schröder et al., 2020). These increases in BOLD response are likely due to greater retinal slip when tracking faster stimuli (Lencer & Trillenberg, 2008).

Hence, while there is already some evidence for the neural mechanisms underlying background and velocity effects, they have not yet been systematically studied jointly. It is, therefore, important to close this significant gap in the literature as smooth pursuit in natural environments occurs almost exclusively under more complex conditions than with uniform backgrounds used in most studies (Agtzidis et al., 2020; Goettker et al., 2020). This is particularly important since known pursuit-related deficits in patient populations (e.g., schizophrenia; Levy et al., 2010) have recently been shown to be present when viewing more complex, natural stimuli (Silberg et al., 2019).

Therefore, the aim of the present study was to investigate the neural mechanisms underlying the velocity and background effects in SPEM with traditional and functional connectivity approaches in a sample of healthy participants. Specifically, we preregistered the following hypotheses: at the behavioural level, we expected lower pursuit velocity gain, higher root mean square error (RMSE), and higher catch-up saccade rate at higher compared to lower target velocity (Meyhöfer et al., 2019; Schröder et al., 2021) as well as lower gain and higher RMSE with a structured compared to a uniform background (Meyhöfer et al., 2019; Schröder et al., 2021). In addition, we expected an interaction effect of the velocity and background conditions with a larger background effect at higher compared to lower velocity for all three dependent variables (Meyhöfer et al., 2019; Schröder et al., 2021). At the neural level, we expected higher activations in the pursuit network (FEF, SEF, PPC, visual areas V1 and V5, and LGN) during pursuit versus fixation as well as higher activations in visual areas (Schröder et al., 2020) with higher compared to lower target velocity. In the background condition (vs. no background), we hypothesised higher activations in a fronto-parietal network. In addition, preregistered exploratory analyses were carried out to investigate functional connectivity differences between task conditions using psychophysiological interaction analyses (PPI; Friston et al., 1997; O'Reilly et al., 2012) and to examine associations between behavioural and BOLD effects.

2 | MATERIALS AND METHODS

This study was preregistered at https://osf.io/j8w26 and approved by the ethics committee of the Department of Psychology at the University of Bonn (#21–06-30).

2.1 | Participants

We aimed for 32 participants to take part in the study. This sample size is large enough to detect the behavioural effects observed previously, for example, $\eta_p^2 = .62$ (Meyhöfer et al., 2019; Schröder et al., 2021) for the background effects on gain. With this effect size, a minimum sample size of 11 participants is required with 95% power and a 5% α-threshold (calculated in G*Power, 3.1.9.7; Faul et al., 2007). Our target sample size of 32 is also substantially larger than sample sizes in studies analysing BOLD effects similar to those we investigated here (e.g., Nagel et al., 2008; Ohlendorf et al., 2010).

Inclusion criteria were current enrolment at a university as a student, age between 18 and 35 years, male or female gender (not diverse), right-handedness, physically, neurologically and psychiatrically healthy, normal or corrected-to-normal eye-sight (contact lenses), and good command of German language.

In this study, only healthy subjects were to be examined. Therefore, exclusion criteria were current psychiatric disorder, current or history of neurological disorders, current or history of psychotic disorders, learning disabilities, loss of consciousness for more than five minutes, and serious physical illness. To ensure safe performance of the MRI measurements, additional exclusion criteria were claustrophobia, metalliferous implants, large tattoos on the upper half of the

body, history of welding work, injury or disease of the inner ear with loss of hearing, visual impairments other than corrective contact lenses, pregnancy, currently breastfeeding a baby, and history of any heart or head surgery. To minimize effects of drugs or substances that might affect the central nervous system, we excluded subjects with a history of alcohol or drug abuse within the last twelve months and consumption of any prescription or over-the-counter medication three days previous to the examination (apart from contraceptives, thyroid medications, or vitamin supplements).

Participants were compensated with money or course credits according to their time spent in the study (€30 for full participation).

2.2 | Study procedure

Participants were recruited via advertisements on the campus of the University of Bonn, emails, and social media. The procedure was as follows.

First, participants who responded to study advertisements were invited to fill in a short online questionnaire in order to obtain basic inclusion and exclusion criteria. Suitable participants were invited to an in-person screening at the University of Bonn. In the screening, participants provided written and informed consent. Inclusion and exclusion criteria were assessed with a semi-structured interview including detailed screening for psychiatric disorders (Ackenheil et al., 1999). Then, participants filled in a short questionnaire to obtain demographic information. Finally, they practiced the tasks they later performed in the scanner (see Section 2.3). Specifically, participants were asked to follow a moving grey pursuit target with their eyes and fixate a stationary target displayed on a computer monitor at a distance of approximately 60 cm. A total of eight blocks were presented (one 10 s-block of each pursuit condition, see Section 2.3., and four 5 s-fixation blocks). During these practice trials, eye movements were not recorded, as the main purpose was to familiarize participants with the task. The in-person screening visit took about 45 min.

Participants who met all inclusion criteria and no exclusion criteria were invited to the University Core Facility Human 3 T MRI at the University Hospital Bonn for the experimental assessment.

At the beginning of each fMRI assessment, inclusion criteria were re-confirmed verbally, and female participants were asked to provide a urine sample to test for pregnancy (OneStep®, 10 miu/ml). Then, two tasks (first a decision task not relevant to the present article and then the smooth pursuit task) were performed in the scanner and a structural scan was obtained. The experimental session took about 1 h 30 min in total.

2.3 | Task

The smooth pursuit task was designed in Experiment Builder (SR Research Ltd., Ontario, Canada, version 2.3.38) and presented on a 32-inch LCD monitor (NordicNeuroLab, 1920 × 1080 px, refresh rate: 120 Hz). The monitor was positioned at the head end of the scanner. Subjects lay on their backs—head first—in the scanner and viewed the monitor image via a first-surface reflection mirror. Distance from eye to monitor via the mirror was approximately 190 cm.

The smooth pursuit target was a grey (RGB: 192, 192, 192) circle (0.33° diameter) moving horizontally with a sinusoidal velocity pattern at two different target velocities (0.4 and 0.6 Hz) between ±6.99°. The target reached peak velocities of 17.56°/s and 26.35°/s and the duration of a full sinus cycle was 2.5 s and 1.67 s, respectively. For half of the pursuit blocks, the target was presented on a structured background (symmetrical 6-by-6-grid of white circles [0.33° diameter] on black background). For the other half of the blocks, it was presented on a blank, black background. A total of 28 pursuit blocks were presented in randomized order (sampling without replacement; 7 blocks of each task condition: 0.4 Hz no background, 0.4 Hz background, 0.6 Hz no background, 0.6 Hz background). Each pursuit block (20 s) was followed by a fixation block (10 s) where a stationary target (RGB: 192, 192, 192; 0.33° diameter) was presented at the centre of the screen. Participants were instructed to follow the target as accurately as possible with their eyes while keeping their head still in the pursuit blocks and to fixate the target in the fixation blocks. A schematic depiction of the task procedure is in Figure 1.

2.4 | Eye-movement assessment and preprocessing

Eye movements were assessed with an MR-compatible video-based combined pupil and corneal reflection long-range eye-tracker (EyeLink 1000, SR Research Ltd., Ottawa, ON, Canada). Pupil and corneal reflection of the right eye were detected with a centroid pupil-tracking algorithm at a sampling rate of 1000 Hz. Prior to the task, a five-point horizontal-vertical calibration was performed (calibration coordinates: [960,540], [960,92], [960,988], [115,540], [1805,540]).

Smooth pursuit gain was calculated as the average of the ratio of eye velocity to target velocity for the middle 50% of each half-cycle (i.e., an excursion of the target from right to left or vice versa) after blinks and saccades were excluded. Only pursuit segments longer than 50 ms were included and gain scores were time-weighted according to the duration of the segments. RMSE was obtained as a global measure of eye position error. To do so, blinks were first excluded. Then, the mean of the squared angular distance between eye and target location across time points was determined. The final RMSE measure was the square root of this mean. Saccades were detected using velocity (≥ 22°/s), amplitude (>1°), and acceleration (≥ 3800°/s²) criteria. Saccades were defined as catch-up saccades if they improved eye position error, started behind the target, and landed behind the target or if they reduced position error by at least 50% and started behind the target and landed ahead of the target. Saccadic frequency (N/s) was obtained for catch-up saccades.

2.5 | BOLD image acquisition

Imaging was conducted using a 3 T MRI scanner (Magnetom Tim Trio, Siemens, Erlangen, Germany) in the Core Facility Human 3 T MRI of
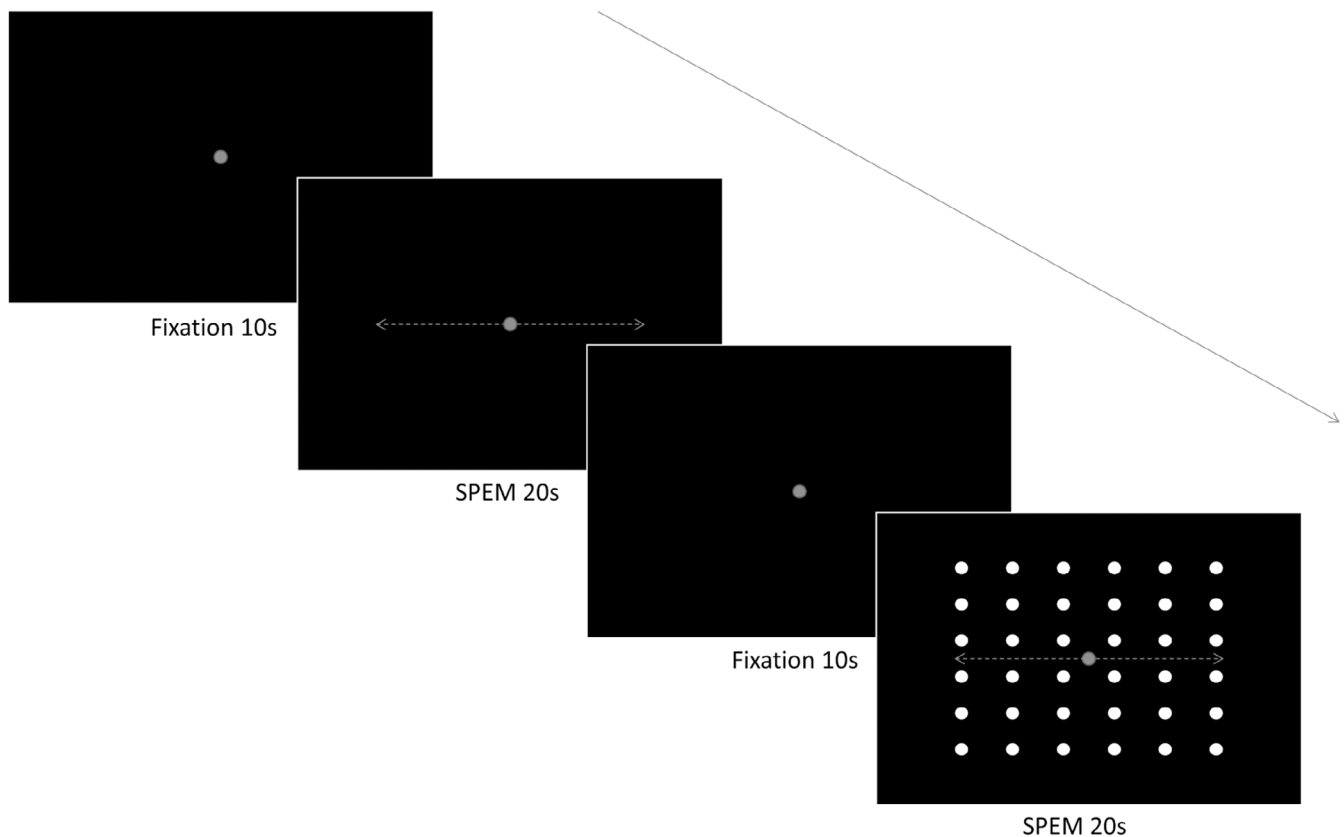
FIGURE 1 Schematic depiction of the task. Smooth pursuit eye movement (SPEM) blocks (20 s) alternated with fixation blocks (10 s). The target moved at one of two different velocities in a sinusoidal velocity pattern (0.4 vs. 0.6 Hz) and was presented on a blank screen or with background stimuli. Order of the conditions in the SPEM blocks was randomized

the University of Bonn at the University Hospital of Bonn. During the pursuit task, BOLD fMRI data were acquired with a T2*-weighted echo-planar imaging sequence (TR = 2500 ms; TE = 30 ms, matrix size = 96 × 96, number of slices = 37, slice thickness = 3 mm, interslice gap = 0.3 mm, FoV = 192 mm, flip angle = 90°, voxel size = 2 × 2 × 3.3 mm). The standard 32-channel head coil from Siemens was used for radio frequency reception. Additionally, for each participant, a three-dimensional T1-weighted high-resolution structural scan was acquired using Magnetization Prepared Rapid Acquisition with Gradient Echoes (MPRAGE) with the following parameters: TR = 1660 ms, TE = 2.54 ms, matrix size = 320 × 320, number of slices = 208, slice thickness = 0.8 mm, no interslice gap, FoV = 256 mm, flip angle = 9°, and voxel size = 0.8 × 0.8 × 0.8 mm.

2.6 | BOLD preprocessing and preregistered analyses

BOLD data were preprocessed and analysed in SPM12 running in Matlab 2018A. All fMRI results are reported whole-brain family-wise error rate (FWE) corrected ($p < .05$, peak level) voxelwise with an additional minimum cluster size threshold of 10 voxels. However, following a reviewer comment, we also report uncorrected results in the supplementary materials. Anatomical labels were obtained with the SPM Anatomy Toolbox (Eickhoff et al., 2005).

Preprocessing included realignment to the first image of the time series using a least squares approach and a six parameter (rigid body) spatial transformation, coregistration of the anatomical and functional images using the individual T1-scans, and normalization into standard space (MNI template). As a final step, the normalized images were smoothed with an 8 mm full width at half maximum (FWHM) Gaussian kernel.

At the first level, data were analysed with a general linear model (GLM) approach. The time course of each task condition (i.e., 0.4 Hz no background, 0.6 Hz no background, 0.4 Hz background, 0.6 Hz background) was modelled as a separate regressor with 20 s boxcar functions. A 128-s high-pass filter was applied to remove slow signal drifts. The six individual realignment parameters were added as additional regressors of no interest. The fixation blocks were not modelled and served as implicit baseline. First-level contrasts were calculated for the following three main effects using t-tests: pursuit (all conditions) versus fixation, the background effect (0.4 Hz background, 0.6 Hz background > 0.4 Hz no background, 0.6 Hz no background), and the velocity effect (0.6 Hz no background, 0.6 Hz background > 0.4 Hz no background 0.4 Hz background). In addition, the interaction contrast of the background and velocity factors was modelled ((0.6 Hz background > 0.6 Hz no background) > (0.4 Hz background > 0.4 Hz no background)). These first-level contrasts were then taken to the second level to calculate one-sample t-tests (random effects) for each type of first-level contrast.

2.7 | Preregistered exploratory analyses of BOLD data

2.7.1 | Functional connectivity

In addition, task-dependent functional connectivity analyses were performed with generalized psychophysiological interaction analyses (gPPI; Friston et al., 1997; McLaren et al., 2012). Ten seed regions (left and right LGN, V1, V5, PPC, FEF) were selected because of their known roles in SPEM. Seed coordinates were taken from previous literature (Schröder et al., 2020: LGN [−24, −26, −4; 22, −26, 0], V1 [−11, −80, −1; 20, −75, −3], V5 [−44, −76, 2; 43, −73, 5], FEF [−30, −6, 55; 30, −9, 50], PPC [−25, −60, 56; 24, −56, 47]). For V1, V5, PPC, and FEF, individual seed regions were identified by first positioning a 12 mm-sphere around these coordinates and then identifying the largest individual SPEM-related peak in those larger spheres (omnibus-F-map, corrected at $p < .001$) to account for inter-individual anatomical variability. In a second step, a 4 mm-sphere was placed around these individual coordinates; these smaller spheres were then used for BOLD activity extraction (see below). If no individual peak could be determined in the larger sphere, the smaller sphere was positioned around the literature coordinates. This procedure resulted in a 4 mm-sphere for every participant and seed region which was either at the coordinates of the individual BOLD peak or at the abovementioned coordinates if no significant peak was detected nearby. However, this procedure was not suitable for identifying the LGN seed regions as the 12-mm sphere is too large for LGN which is a small structure (Li et al., 2012) risking that the identified peak is not in the targeted brain area. Therefore, for LGN analyses, the same coordinates identified from the literature were used for all participants (i.e., [−24, −26, −4; 22, −26, 0]).

The first eigenvariate of the timeseries of all voxels within these 4 mm-spheres was extracted. After deconvolution, it was multiplied with the task regressors and the resulting products (i.e., the psychophysiological interaction terms) were then reconvolved with the HRF. Next, for each seed region, a GLM was modelled with all task vectors (the four SPEM conditions) and the corresponding gPPI terms as well as the seed region time course. The six motion parameters (from realignment) were entered as regressors of no interest. Then, first-level contrasts were set up: a SPEM (all four gPPI terms) versus fixation contrast, a background versus no background contrast, and a high versus low target velocity contrast. For group-level analyses, these three contrasts were taken to the second level to calculate one-sample t-tests.

2.7.2 | Multiple regressions

To explore brain-behaviour relationships, separate regression analyses were calculated at the second level using two different approaches. First, to identify correlations between BOLD response and behavioural outcomes, the first-level task contrasts for each task condition

(e.g., 0.4 Hz no background, 0.6 Hz no background, 0.4 Hz background, 0.6 Hz background) were entered into separate multiple-regression models along with the three behavioural outcome measures (gain, RMSE and catch-up saccade frequency) of the corresponding condition (12 models). Second, to identify correlations between task effects (difference measures), the first-level contrasts of these task effects (e.g., background effect, velocity effect) were entered into separate multiple-regression models along with the behavioural task effect (6 models).

2.7.3 | Correlations

In order to further explore correlations between behavioural outcomes and BOLD response, regions of interest (ROIs) were defined as significant clusters in each of the contrasts of the task effects (background vs. no background and high vs. low target velocity contrasts) and each task condition versus fixation (0.4 Hz no background versus fixation, 0.4 Hz background vs. fixation, 0.6 Hz no background vs. fixation and 0.6 Hz background vs. fixation). Mean beta weights from these ROIs were then extracted for each participant with the MarsBaR toolbox (Brett et al., 2002) yielding summary time courses for each cluster and participant. These values were then correlated with the behavioural outcome measures of the corresponding task effect (difference measure) or condition (direct performance outcome) using R and the *Hmisc* package (V.4.4.0; Harrell, 2020). Statistical outliers (see Section 2.8) were excluded. Results were corrected for multiple correlations using Bonferroni correction.

2.8 | Preregistered statistical analyses of the eye-tracking data

Behavioural data were analysed in R using the *ez* package (V.4.4.0; Lawrence, 2016) with two-factorial repeated measures ANOVA with the factors background (present and absent) and target velocity (0.4 Hz or 0.6 Hz) for each of the dependent variables smooth pursuit gain, RMSE, and catch-up saccade frequency. The alpha-level to determine significance was set to .05. Outliers were identified with boxplot criteria, that is, participants with values 1.5 times the interquartile range above the upper quartile and below the lower quartile were excluded. Analyses without the removal of outliers are reported in the supplementary material (Table S1).

3 | RESULTS

The eye-tracking data that support the findings of this study are openly available at the Open Science Framework (OSF) at https://osf.io/uez5f/. The MRI data that support the findings of this study are available on request from the corresponding author. The MRI data are not publicly available due to privacy and ethical restrictions.

3.1 | Participants

A total of 33 (16 female, 17 male) participants took part in the study. On average, participants were 23.30 years old ($SD = 3.14$). For one participant (male), BOLD data were not saved due to technical failure. This participant is only included in the analyses of eye movement data. Data screening for movement showed that, overall, participants moved very little. However, BOLD data from one participant had to be excluded due to excessive movement ($z > 4$ and $y > 4$ mm). After exclusion of this participant, mean displacement for the six realignment parameters across participants was x: $M = -0.35$ mm, $SD = 0.34$ mm, y: $M = -0.22$ mm, $SD = 0.25$ mm, z: $M = 0.51$ mm, $SD = 0.42$ mm, pitch: $M = 0.35°$, $SD = 0.37°$, roll: $M = 0.09°$, $SD = 0.36°$, yaw: $M = 0.04°$, $SD = 0.26°$.

3.2 | Eye movements

Due to poor eye-tracking quality, data from three participants could be analysed for only a subset of the blocks (35, 22 and 30 blocks respectively, out of the total of 56 blocks) and data from one participant had to be excluded altogether. Descriptive statistics are in Table 1 and Figure 2 (visualised using raincloud plots; Allen et al., 2018, 2019).

There were three statistical outliers for pursuit gain, four for RMSE and three for catch-up saccade rate. These participants were excluded from all analyses of the respective outcome measure. Importantly, results did not change when these outliers were included (see Table S1).

Analyses of pursuit gain revealed main effects of the background ($F_{[1, 28]} = 70.55$, $p < .001$, $\eta_p^2 = .716$) and velocity factors ($F_{[1, 28]} = 542.04$, $p < .001$, $\eta_p^2 = .951$), indicating lower gain in the background condition and at higher target velocity, respectively. There was no interaction of the two factors ($p > .05$). Both effects were numerically evident in every single participant but also showed substantial variability between participants (Figure 2, panel a).

For RMSE, there was a significant main effect of velocity ($F_{[1, 27]} = 210.11$, $p < .001$, $\eta_p^2 = .886$), but no main effect of background and no interaction of the two factors (all $p > .05$; Figure 2, panel b).

Analyses of catch-up saccade rate revealed main effects of the background ($F_{[1, 28]} = 12.57$, $p < .001$, $\eta_p^2 = .311$) and velocity factors ($F_{[1, 28]} = 134.72$, $p < .001$, $\eta_p^2 = .828$). Catch-up saccade rate was higher in the background condition and at higher target velocity. There was no interaction of the two factors ($p > .05$, Figure 2, panel c).

3.3 | BOLD

3.3.1 | SPEM versus fixation

The SPEM task elicited higher BOLD response than fixation in a widespread network (Figure 3, Table 2). Higher activation during SPEM versus fixation was found in visual and motion processing areas (left and right calcarine, right lingual gyrus, left cuneus, and middle occipital gyrus) extending into cerebellum. SPEM also led to increased activity in left LGN, bilateral precentral gyrus (including left medial and lateral FEF and right lateral FEF), right superior parietal cortex, left midcingulate cortex (MCC) as well as posterior-medial frontal cortex (including SEF).

For the reverse contrast (Fixation > SPEM, Figure S1), significant BOLD response differences were observed in bilateral middle occipital gyrus (extending into right angular gyrus), left and right fusiform gyrus (extending into cerebellum), bilateral insulae (extending into right Heschl's Gyrus) as well as left Rolandic Operculum.

3.3.2 | Background versus no background

The background condition elicited greater BOLD response than the no background condition in nine clusters (Figure 3, Table 3). The largest cluster encompassed visual cortex (lingual, calcarine and middle occipital gyri) and extended into left superior parietal cortex and precuneus. There were separate clusters containing right superior parietal cortex and middle occipital gyrus and left middle temporal gyrus. In addition, increased BOLD response was found in left LGN, bilateral superior frontal gyrus (containing medial FEF and extending into precentral gyrus), left lateral FEF and right posterior-medial frontal cortex (including SEF). The opposite contrast (no background > background, Figure S1) yielded greater BOLD response in one cluster in right cuneus. Results without correction for multiple comparisons yielded even more widespread activity (Figure S2 and Table S2).

3.3.3 | High versus low target velocity

Faster targets yielded greater BOLD response than slower targets in two clusters (Figure 3, Table 4). The first large cluster was located in the visual cortex (bilateral calcarine gyri and left cuneus) and encompassed V1 and surrounding areas. The second (smaller) cluster

TABLE 1 Descriptive statistics of smooth pursuit performance outcomes

Velocity	Background	Gain		RMSE		Catch-up saccade rate	
		M	SD	M	SD	M	SD
0.4 Hz	absent	77.44	7.51	2.50	0.38	1.01	0.35
	present	67.40	14.86	2.45	0.38	1.22	0.36
0.6 Hz	absent	56.95	10.39	3.46	0.58	1.60	0.38
	present	46.82	13.26	3.43	0.53	1.74	0.41

Note: Means (M) and standard deviations (SD) of the behavioural outcome measures gain (in %), root mean square error (RMSE; in °), and catch-up saccade rate (N/s) in the four task conditions.
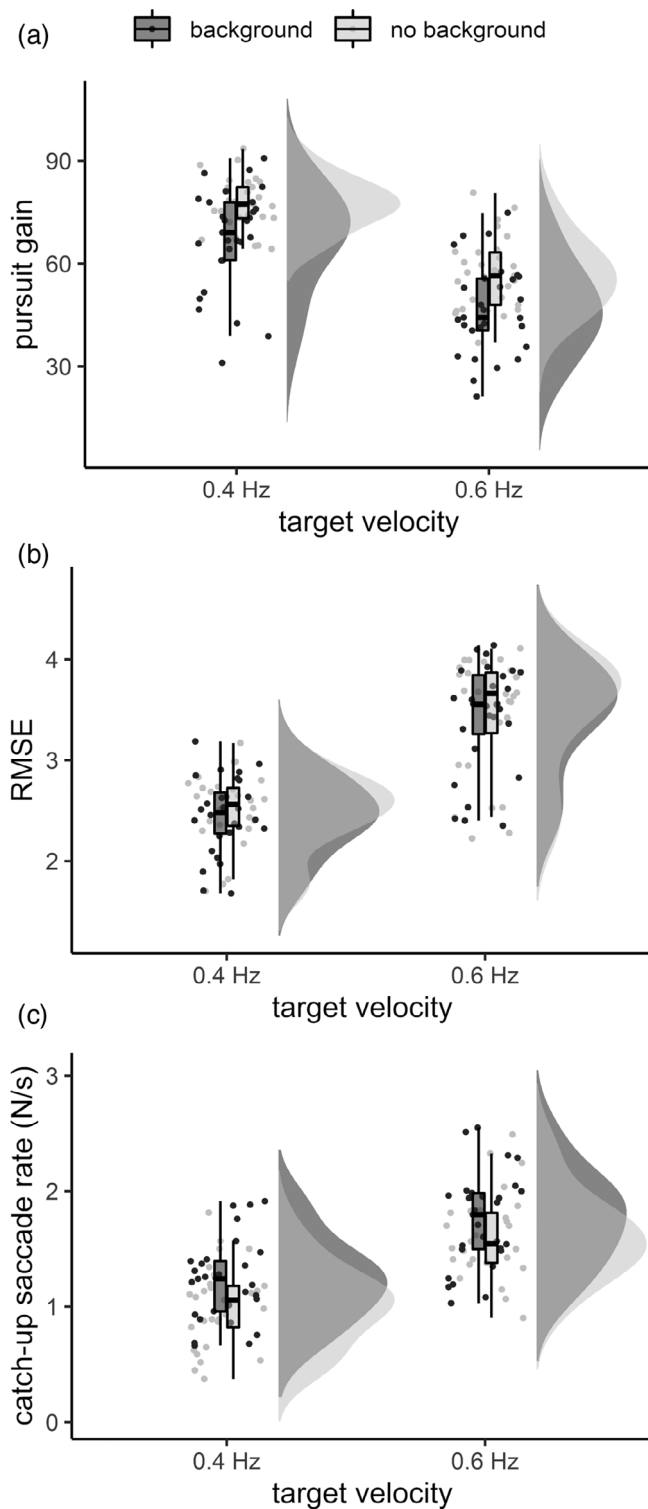
FIGURE 2 Effects of background and target velocity on smooth pursuit gain (in %; panel a), root mean square error (RMSE; in °; panel b), and catch-up saccade rate (N/s; panel c)

comprised left precentral gyrus (including lateral FEF). For the reverse contrast (Figure S1), higher BOLD response with slower versus faster targets was observed in left temporal pole. Positive results without correction for multiple comparisons were also found outside primary visual cortex (e.g., in FEF, SEF and V5; Figure S3 and Table S3).

3.3.4 | Background velocity interaction

There were no activation differences for the background effect at higher versus lower target velocity and the reverse contrast. Results without correction for multiple comparisons yielded two small clusters for the positive and three small clusters for the negative contrast (Figure S4 and Table S4).

3.4 | Functional connectivity

PPI analyses did not yield any significant differences in functional connectivity between the background and no background conditions, between the high and low target velocity conditions or in the reverse contrasts for any of the seed regions. A detailed description of the connectivity maps underlying the SPEM versus fixation contrasts is in the supplementary material (Figures S5 and S6 and Tables S5–S14). These are broadly similar to those reported in our previous study using the same seed voxels (Schröder et al., 2020).

3.5 | Brain-behaviour relationships

3.5.1 | Multiple regressions

The multiple regression analyses did not yield any significant associations between BOLD and the behavioural outcome variables.

3.5.2 | Correlations

There were no significant correlations between BOLD response and the behavioural variables for the task effects. For the direct performance outcomes, we found three significant correlations before correction for multiple analyses. Note, that these correlations did not survive Bonferroni correction. There was a negative correlation between the BOLD response in left V5 and pursuit gain in the 0.6 Hz no background condition ($R = -.47$, $p_{uncorr} = .01$) indicating that higher BOLD response in this area was associated with poorer pursuit performance. Catch-up saccade rate was positively correlated with activity in right FEF (lateral extending into medial) in the 0.6 Hz no background condition ($R = .50$, $p_{uncorr} = .009$). In the 0.4 Hz background condition, pursuit gain positively correlated with activity in left medial FEF ($R = .38$, $p_{uncorr} = .048$). There were no further significant correlations for any of the clusters and direct performance measures. Detailed correlation results are in Tables S15–S20.

4 | DISCUSSION

In this preregistered study, eye movement and BOLD data from 33 healthy participants were collected as they performed SPEM in the presence and absence of a structured background at two different target velocities.
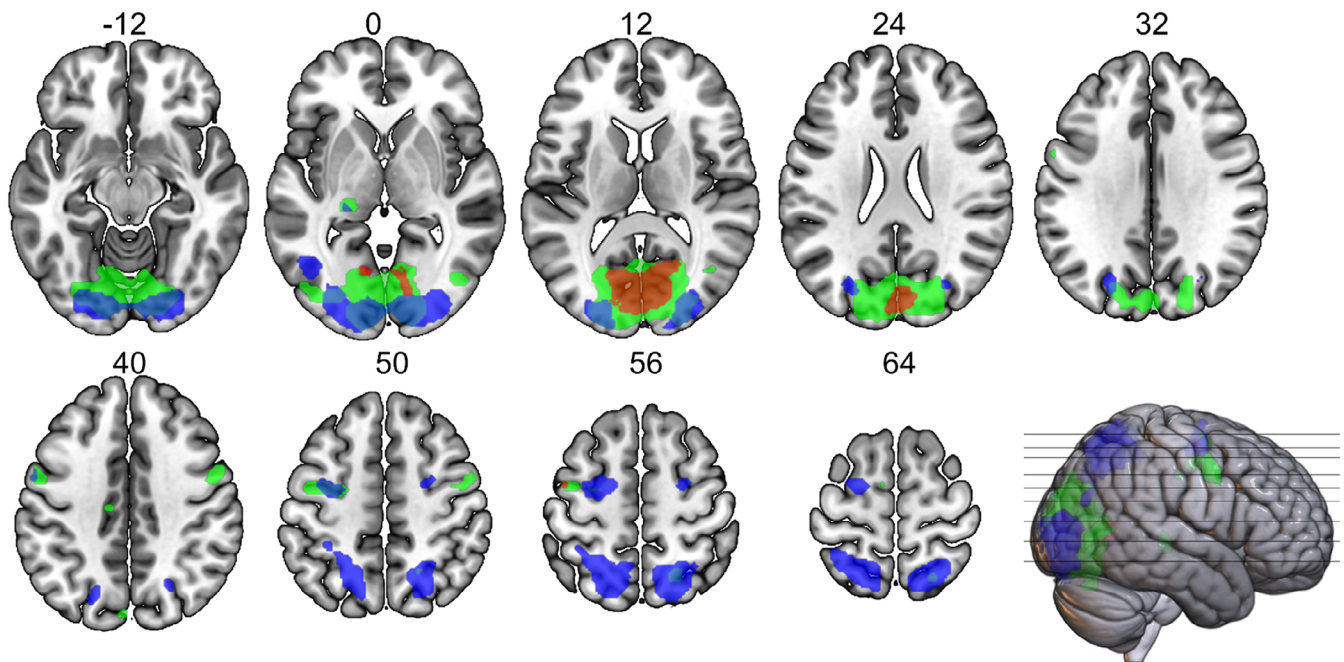
FIGURE 3 Blood oxygen level-dependent (BOLD) response during smooth pursuit. Results of one-sample t-tests (random effects) of the SPEM versus fixation (green), background versus no background (blue) and high versus low target velocity (red) conditions, respectively. Results are reported whole-brain family-wise error rate (FWE) corrected voxelwise ($p < .05$, peak level) with an additional minimum cluster size threshold of 10 voxels. The left hemisphere is depicted on the left. Upper labels refer to the z coordinate of the slices (Montreal Neurological Institute [MNI] space). Significant clusters are binarized.

At the behavioural level, the presence of a structured background decreased pursuit gain and increased the number of catch-up saccades but had no effect on RMSE. Faster targets led to decreased pursuit gain, increased RMSE, and increased rates of catch-up saccades. No interaction of the velocity and background factors could be observed for any of the dependent variables.

In terms of BOLD activity, the smooth pursuit task activated areas in the known oculomotor network including LGN, visual cortex, PPC, medial and lateral FEF, SEF, and cingulate gyrus. Differences in BOLD response between the background conditions were found in extensive clusters in visual, parietal, and frontal areas. In contrast, the velocity effects yielded BOLD response only in visual areas and a small left-hemispheric lateral FEF cluster. Functional connectivity analyses revealed widespread connectivity maps for the SPEM contrasts but did not provide any additional information concerning the neural underpinnings of the background and velocity effects. Correlations of behaviour and BOLD response could only be identified for pursuit gain and saccade frequency at 0.6 Hz in the no background condition, where higher BOLD response was associated with poorer performance, and for the 0.4 Hz background condition, where higher gain was associated with higher BOLD response in left medial FEF. However, none of these survived correction.

4.1 | Behavioural effects

In line with our hypotheses and previous studies, pursuit gain was reduced and saccade rate increased in the presence of a structured

background and with faster targets (Meyhöfer et al., 2019; Schröder et al., 2021). Strikingly, effects on gain were highly robust as they were identified in every single participant. Likely, pursuit performance was affected because the structured background induced optokinetic drive (Barnes, 2008) which had to be cancelled. This cancellation might be based on the processing of extraretinal signals and accomplished by reducing sensitivity to global motion in the direction opposite of the pursuit eye movement (Lindner et al., 2001; Lindner & Ilg, 2006).

Contrary to our hypotheses, we did not observe interactions of background and target velocity for any of the dependent variables although we had purposely selected stimuli conditions that had yielded a strong interactive effect in a prior behavioural study (Schröder et al., 2021). A reason for this discrepancy could be that pursuit performance was generally worse compared to previous laboratory investigations using similar tasks (Meyhöfer et al., 2019; Schröder et al., 2021; Schröder et al., 2022) presumably because of the unusual and uncomfortable environment in the scanner and distracting external stimuli such as scanner noise in this study (see also Koch et al., 2003). Therefore, it can be assumed that participants did not reach optimal performance levels and thus more subtle effects such as the interaction reported previously could not emerge. Importantly, there was also no evidence for interactive effects at the level of neural activity. However, it should be noted that even small changes in task design could have prevented the emergence of such effects as has been shown for other cognitive tasks (Ruge et al., 2013). For example, SPEM blocks in this study were shorter in the fMRI design compared to our earlier study (Schröder et al., 2021),

Anatomical label (functional label)	Cluster size	t-value	MNI coordinates		
			x	y	z
SPEM > Fixation					
L Cerebellum	9744	13.16	−10	−78	−14
R Calcarine Gyrus (V1)		12.88	12	−80	10
R Lingual Gyrus		12.68	14	−90	−6
R Calcarine Gyrus		12.24	6	−88	6
L Calcarine Gyrus		11.89	−6	−82	12
L Calcarine Gyrus		11.17	−6	−88	4
R Lingual Gyrus		10.73	10	−78	−2
L Cuneus		10.66	−6	−86	26
L Middle Occipital Gyrus		10.32	−18	−94	6
L Calcarine Gyrus		10.22	−14	−78	16
L Thalamus (including LGN)	98	8.88	−20	−28	2
R Precentral Gyrus (lateral FEF)	178	8.09	50	−2	40
R Precentral Gyrus		6.12	42	−8	48
L Precentral Gyrus (lateral FEF)	285	7.77	−26	−8	48
L Precentral Gyrus (extending into medial FEF)		7.45	−36	−8	52
R Middle Temporal Gyrus	237	7.74	44	−64	6
N/A[a]		6.87	34	−64	8
L Precentral Gyrus (lateral FEF)	76	7.27	−56	2	38
L Precentral Gyrus		6.34	−60	6	30
R Superior Parietal Lobule	86	7.07	20	−58	54
R Superior Parietal Lobule		7.05	22	−60	62
L Posterior-Medial Frontal Cortex (SEF)	25	6.89	−8	−2	60
N/A[b]	13	6.65	−12	−18	38
Fixation > SPEM					
L Middle Occipital Gyrus	39	7.69	−42	−80	30
L Rolandic Operculum	72	7.25	−42	−18	12
R Insula Lobe	152	6.96	42	−10	4
R Insula Lobe		6.13	38	−18	14
R Middle Occipital Gyrus	19	6.90	44	−78	28
R Angular Gyrus		6.27	48	−70	38
R ACC	15	6.58	10	34	6
L Fusiform Gyrus	84	6.51	−26	−42	−20
R Fusiform Gyrus	14	6.28	26	−48	−16
L Insula Lobe	13	6.23	−40	4	−12

[a]Nearest grey matter: R Calcarine Gyrus.
[b]Nearest grey matter. L MCC.

and SPEM blocks were interleaved with fixation blocks. Therefore, the sensitivity of the background × target velocity interaction effect to changes in task configurations should be systematically investigated in the future.

While the velocity effect was also found for RMSE, there was no background effect on this variable which is not consistent with our hypotheses and our own previous result (Schröder et al., 2021). This failure to obtain the RMSE background effect was surprising especially given the large effect on pursuit gain. A first explanation may be

that RMSE is primarily a measure of eye position while gain reflects velocity. RMSE is thus a much more global measure of pursuit quality that is dependent on multiple influences (Smyrnis, 2008). Second, RMSE is calculated for the entire duration of the pursuit segments (excluding blinks) while gain is calculated only for the middle 50% of each half-cycle after exclusion of blinks and saccades. Crucially, however, limiting the calculation of RMSE to the same time window as pursuit did not change the pattern of results (data not shown). Third, it is conceivable that the highly structured background distractor

TABLE 3 BOLD response in the background versus no background and no background versus background contrasts

Anatomical label (functional label)	Cluster size	t-value	MNI coordinates		
			x	y	z
Background present > absent					
R Calcarine Gyrus (V1)	5419	15.03	16	−92	−4
L Calcarine Gyrus (V1)		13.43	−10	−98	−4
L Middle Occipital Gyrus		13.40	−18	−100	2
L Superior Parietal Lobule		13.38	−22	−56	60
R Middle Occipital Gyrus		12.96	26	−94	8
L Lingual Gyrus		11.18	−14	−92	−12
L Superior Parietal Lobule		10.63	−30	−54	66
L Middle Occipital Gyrus		10.41	−26	−90	0
L Lingual Gyrus		9.84	−26	−88	−16
L Precuneus		8.99	−12	−64	58
L Middle Occipital Gyrus		7.92	−24	−72	30
L Superior Frontal Gyrus (medial FEF)	453	9.78	−26	−6	58
L Precentral Gyrus (medial FEF)		7.84	−36	−6	50
L Superior Frontal Gyrus		6.22	−14	−6	72
R Superior Parietal Lobule	1205	9.21	24	−64	62
R Superior Parietal Lobule		7.90	22	−68	48
R Superior Frontal Gyrus (medial FEF)	86	7.87	24	−4	52
R Precentral Gyrus (medial FEF)		5.93	32	−2	48
L Middle Temporal Gyrus	187	7.86	−44	−64	2
N/A[a]	20	6.86	−22	−30	2
R Middle Occipital Gyrus	38	6.68	30	−74	24
R Posterior-Medial Frontal Cortex (SEF)	14	6.57	12	−4	70
L Precentral Gyrus	25	6.54	−56	0	38
Background absent > present					
R Cuneus	19	6.58	14	−84	26

[a]Nearest grey matter: L Thalamus (including LGN).

TABLE 4 BOLD response in the 0.6 versus 0.4 Hz and 0.4 versus 0.6 Hz contrasts

Anatomical label (functional label)	Cluster size	t-value	MNI coordinates		
			x	y	z
0.6 Hz > 0.4 Hz					
L Cuneus (V1)	2214	10.13	2	−86	20
L Calcarine Gyrus (V1)		9.51	−8	−76	10
L Calcarine Gyrus		8.73	−16	−66	8
L Precentral Gyrus (lateral FEF)	14	7.02	−46	−6	54
0.4 Hz > 0.6 Hz					
L Temporal Pole	32	7.91	−40	14	−26

stimuli are not only disruptive but also help to guide eye movements, for example, by limiting the vertical displacement of the target to a confined space (Eggert et al., 2009; Goettker et al., 2020; Ladda et al., 2007). This is especially important since RMSE (in contrast to gain) comprises horizontal and vertical deviations. At a descriptive level, vertical deviation of the eye from the target was indeed lower in the background condition in our data (data not shown). Thus, the background distractors may have simultaneously reduced vertical eye displacements and increased horizontal displacements (as evidenced by reduced gain) but these two processes may have cancelled each other out when measured in terms of RMSE. However, these speculations cannot fully explain the divergence from previous studies and should, therefore, be addressed systematically in future investigations.

4.2 | Pursuit network

The task-related activations in visual cortex, medial and lateral FEF, SEF, PPC, cingulate gyrus, and LGN for the SPEM versus fixation contrasts were in line with our hypotheses and corresponded well with the results from previous investigations (Berman et al., 1999; Dieterich et al., 2009; Haller et al., 2008; Kimmig et al., 2008; Konen et al., 2005; Konen & Kastner, 2008; Lencer et al., 2004; Nagel et al., 2006; Nagel et al., 2008; Petit & Haxby, 1999; Schröder et al., 2020; Tanabe et al., 2002). This underlines the validity of our task design, the accurate recording and analysis of the BOLD signal and the overall robustness of SPEM BOLD correlates for sinusoidal target stimuli in the medium velocity range.

Higher BOLD response during fixation (vs. SPEM) might reflect deactivations during SPEM or increased BOLD during fixation. The results found in bilateral insulae have also been observed in past oculomotor studies, albeit with less consistency compared to the results for the reverse contrast (Dieterich et al., 2003; Dieterich et al., 2009; Konen et al., 2005). Clusters in angular gyrus might reflect default mode network activity (Seghier, 2013) during fixation or deactivation during SPEM, respectively.

4.3 | Background effect

The BOLD response in the background versus no background contrasts spread across almost the entire SPEM network and also included regions that were not significant in the simple SPEM contrast. Specifically, we observed increased BOLD in visual cortex, superior and inferior parietal cortex, FEF and LGN. Decreased BOLD in the background condition was found in one cluster in right cuneus.

4.3.1 | LGN and visual cortex

The widespread cluster located in LGN and visual cortex during pursuit with (vs. without) a structured background is not surprising, given the higher visual complexity of the structured background pattern compared to the simple black background (Kastner et al., 2006; Ohlendorf et al., 2010). In addition, there was evidence of increased BOLD response in the laterally located left visual area V5, an area which is essential for motion processing, but not in its right counterpart (Zeki, 2015). Similarly, no target-velocity-related BOLD modulation was found for V5 in the current and a previous investigation (Schröder et al., 2020). It has been shown that V5 is more strongly activated by pursuit of a single dot compared to motion tracking of a large pattern of stimuli (Schraa-Tam et al., 2009). This pattern of results along with evidence that TMS induced perturbations on area V5 affect pursuit performance independent of background (Haarmeier & Kammer, 2010) suggests that area V5—albeit essential for successful pursuit performance—does not contribute significantly to the inhibition of interfering, stationary background stimuli. Instead, it might preferably process the local movement of the pursuit target.

The only region deactivated during background processing was cuneus which could be associated with the execution of eye movements without sustained attention (Corbetta et al., 1998).

4.3.2 | Parietal cortex

In line with our hypotheses, we observed increased BOLD response in areas of the parietal cortex, especially superior and PPC. While peaks were in a similar location to the SPEM versus fixation contrast peaks, the background-related clusters had a much wider extent. Consistent with previous investigations, results were stronger in the right hemisphere (Corbetta et al., 1993; Nobre et al., 1997; Thiebaut de Schotten et al., 2011).

The PPC has been associated with a number of different functions during pursuit. First of all, it is worth stating its pivotal role in guiding attention (Corbetta et al., 1995; Culham et al., 1998; Thiebaut de Schotten et al., 2011). Crucially, pursuit of a visual stimulus with an auditory stimulus moving in antiphase (vs. phase) led to increased posterior parietal BOLD response while not impacting performance (Baumann & Greenlee, 2009). Similarly, Ohlendorf et al. (2007) identified PPC as the only region differentially activated in conditions with divided versus focused attention during pursuit. This pattern of results was further elaborated by Ohlendorf et al. (2010) who found PPC to react to differential motion of target and background. In addition, BOLD response in PPC increased with higher numbers of background stimuli. This suggests that PPC might integrate movement of the target relative to a frame of reference. This line of argument is also supported by Trenner et al. (2008) who found increased BOLD response in PPC in response to a critical SPEM stimulus that was preceded by a faster versus slower background stimulus suggesting that PPC contributes to perceptual stability during SPEM by comparing internal reference signals with retinal signals. In summary, PPC appears to serve smooth pursuit by guiding attention and processing movements relative to an internal and/or external frame of reference (Ohlendorf et al., 2010; Tikhonov et al., 2004; Trenner et al., 2008).

While effects in PPC were very strong, we could not find evidence for differential BOLD response in TPJ and/or inferior parietal cortex during background versus no background processing as we had hypothesised based on previous literature (Haarmeier & Kammer, 2010; Lawden et al., 1995). TPJ might become relevant only when the pursuit system has to operate against even more salient background patterns (Lawden et al., 1995) or with brief (vs. continuous) background perturbations (Haarmeier & Kammer, 2010).

4.3.3 | Frontal eye fields

In agreement with our findings, smooth pursuit and saccade task performance typically involves both medial and lateral subregions of FEF (both located in Brodmann area 6 and also referred to as superior and inferior FEF; Cieslik et al., 2016; Dieterich et al., 2009; Ettinger

et al., 2008; Lencer et al., 2004; McDowell et al., 2008; Vernet et al., 2014). Interestingly, the peak coordinates of FEF activations in the background conditions were located more medially than in the conditions without background and in the overall SPEM contrast, although there was also substantial overlap of the clusters. While the literature is scarce concerning the roles of FEF subregions in pursuit (Coiner et al., 2019), more evidence regarding their function in saccades has been accumulated (McDowell et al., 2008). Specifically, McDowell et al. (2008) proposed that medial FEF is more involved in volitional saccades whereas lateral FEF is more closely associated with reflex-like, automatic saccadic eye movements. More recent meta-analytical evidence showed that FEF activation peaks during prosaccades lie more laterally than FEF activation peaks in antisaccades (Cieslik et al., 2016). Strikingly, the activation peaks in that study correspond remarkably well with the lateral and medial peaks in our data. The authors proposed that lateral FEF is involved in the motor output, whereas medial FEF plays a more important role in higher cognitive processes (Cieslik et al., 2016). A similar pattern of results was also observed by Ettinger et al. (2008) who temporally differentiated the saccadic inhibition and response generation phases of antisaccades to provide evidence suggesting that medial FEF is more strongly related to saccadic inhibition whereas lateral FEF is more closely linked to generation of the motor command. Lee et al. (2006) demonstrated that the number of alternatives in a cued saccade task correlates positively with activation in medial but not in lateral FEF suggesting that the former can be regarded as an interface between stimulus inputs and responses whereas the latter is associated with processes such as response execution. Similarly, there is evidence for stronger involvement of medial FEF in the execution of new sequences of saccades compared to familiar sequences, possibly due to higher demands on sensorimotor transformation processes (Grosbras et al., 2001; Simó et al., 2005).

In addition to these findings from saccade research, the literature on decision-making presents evidence that more lateral regions in PFC and PPC are involved with action planning based on rules and external cues while more medial regions in these areas are involved in voluntary, self-determined action plans (Bode et al., 2014).

But how do these results from research on saccades and action planning relate to smooth pursuit? To our knowledge, the question of functional specialization of FEF subregions during pursuit has not yet been systematically investigated. Here, we argue that a similar pattern of functional specialization of FEF subregions can be found in pursuit as in saccades: lateral FEF take on a more motor-related role involved in the execution of the movement—which is supported by findings of stronger connectivity of lateral FEF and motor areas (Cieslik et al., 2016)—while medial FEF come into play mainly when more complex demands are placed on the system and higher cognitive processes are of greater importance (Jin et al., 2021), for example, by inhibiting the processing of distracting background stimuli. How medial and lateral FEF subregions correspond to the dynamic gain control of retinal and extraretinal signals during ongoing pursuit has to be investigated in the future (Drew & van Donkelaar, 2007; Gagnon et al., 2006; Nuding et al., 2009). Nevertheless, it is important to emphasise that both regions are necessary for successful pursuit. For example, Lencer et al. (2004) showed that both lateral and medial FEF are active in a standard pursuit task. However, increased BOLD response related to predictive pursuit during target blanking was robustly observed in bilateral medial FEF and left lateral but not in right lateral FEF, confirming that medial FEF are particularly important under circumstances of higher cognitive demands (Jin et al., 2021).

4.3.4 | Other areas

Lindner et al. (2006) identified the Crus I in the lateral cerebellum as the functional correlate of an internal reference signal that is engaged in predicting sensory experiences during smooth pursuit over structured backgrounds. While some of the clusters related to increased BOLD response in the background (vs. no background) conditions extended into the cerebellum in our study, we are unable to directly compare our results as the cerebellum was not entirely inside the mask of our second level analysis. We, therefore, strongly recommend that future analyses include cerebellar regions to further investigate their role in smooth pursuit with structured background stimuli.

In contrast to our hypotheses, we did not obtain increased activation in prefrontal cortex in the background versus no background conditions as could have been expected based on previous literature (Bucher et al., 1997; Schmid et al., 2001; Wager et al., 2005). Thus, while pursuit over structured backgrounds draws on networks generally associated with oculomotor function and the control of attention, it does not appear to particularly rely on areas of higher cognitive control. However, it is possible that these higher cognitive areas are not consistently involved throughout the entire pursuit block, but only at certain points in time, for example, at pursuit initiation or when predictive or memory-related processes are more important (Ding et al., 2009; Kawawaki et al., 2006; Nagel et al., 2006; Schmid et al., 2001).

4.4 | Velocity effect

Interestingly, while the velocity effect was large at the behavioural level and could be observed in every single participant, neural effects were limited to the visual cortex and a small cluster in the left lateral FEF. The increased BOLD response in visual cortex is not only consistent with our hypothesis but also a very close replication of our own previous study with slower targets (0.2 and 0.4 Hz) in an even larger sample, in which, however, we did not observe increased FEF activity with faster targets (Schröder et al., 2020). In contrast to Nagel et al. (2008, 2012), we could not identify increased BOLD response with higher target velocities in other areas. However, there were significant differences in task design that might have led to the observed differences. Crucially, Nagel et al. (2008, 2012) presented short target ramps and a higher number of velocity conditions better fit to study the initiation of pursuit whereas our design was optimized to capture the neural mechanisms of continuous pursuit suggesting that the

contribution of different brain areas to pursuit of different velocities is time-dependent.

Higher BOLD response in visual areas might reflect differences in retinal input between the two conditions as higher target frequency was associated with lower gain and thus higher retinal image slip. The BOLD response in the lateral FEF cluster (also observed by Nagel et al., 2008; Nagel et al., 2012) could reflect higher demands on the motor output system in the higher velocity condition (Cieslik et al., 2016).

The only area with higher BOLD response during lower (vs. higher) target velocity was left temporal pole, an area that has been associated with mind wandering (Christoff et al., 2009).

4.5 | Task-based functional connectivity

Connectivity maps from the five seed regions (bilateral) showed widespread connectivity patterns, similar to those observed in a previous investigation from our group (Schröder et al., 2020). Strikingly, however, we could not delineate any differences in connectivity between the task conditions, that is, in the background versus no background or high versus low target velocity contrasts. While the latter matches our previous observation at target velocities of 0.2 and 0.4 Hz (Schröder et al., 2020), the former was surprising at first sight, given the large background effect in the traditional BOLD analyses and our a priori expectation that the increased demands in the background condition may be accompanied by enhanced connectivity. However, it should be noted that PPI analyses tend to have higher numbers of false negative results due to the high correlation of the PPI and task vectors (O'Reilly et al., 2012) which could have hindered the detection of significant differences.

4.6 | Brain-behaviour relationships

Correlations between BOLD response and the behavioural performance outcomes became nonsignificant after appropriately correcting for multiple testing. Due to their exploratory nature, the three correlations that were significant without correction are briefly discussed here. In the ROI-based analysis, there was a negative correlation between activity in left V5 and pursuit gain in the no background condition at 0.6 Hz indicating that poorer performance was associated with higher response in that area. This pattern of results is surprising and not in line with a prior study that found positive correlations between V5 activity and pursuit velocity (Nagel et al., 2006). A possible explanation of this finding is that participants with poorer performance rely more heavily on visual (vs. extraretinal) information. There was a positive correlation between BOLD response in left medial FEF and pursuit gain, which is also not in line with Nagel et al. (2006) who reported negative correlations between pursuit velocity and BOLD response in FEF. Our results highlight the importance of medial FEF for SPEM performance in the presence of structured backgrounds.

Furthermore, a positive correlation between catch-up saccade rate and BOLD response in right FEF (lateral FEF extending into medial FEF) was obtained at 0.6 Hz in the no background condition which means that higher BOLD response in that area was associated with more frequent catch-up saccades consistent with the involvement of lateral and medial FEF in the generation of both pursuit and saccades (Haller et al., 2008; Petit et al., 1997). Interestingly, however, Haller et al. (2008) did not obtain event-related BOLD response during SPEM related to corrective saccades. The discrepancy between our and their result may lie in the different target velocities applied and the different statistical design as we did not use an event-related design but focused on correlations between BOLD and overall rate of catch-up saccades. In addition, the positive association was only found in one of four conditions in our study in only one of multiple clusters, strongly calling for replication. In general, these results should be interpreted with caution, as they did not survive correction for multiple analyses. This is further supported by the fact that in another study with an even larger sample we did not find such correlations (Schröder et al., 2020). However, we strongly recommend to investigate how activity in the components of the oculomotor network relates to individual differences in SPEM performance in future studies appropriately powered for interindividual differences research.

4.7 | Limitations

The results presented in this study have to be interpreted in the light of some limitations. First, while we had sufficient statistical power to detect the expected background and velocity effects at the behavioural and neural levels, statistical power might have been too low to observe significant correlations between these two levels of measurement and to determine BOLD differences in terms of task-dependent functional connectivity (Dubois & Adolphs, 2016; O'Reilly et al., 2012). This criticism is supported by the fact that coactivations in the regression analyses were indeed evident at a more liberal threshold but did not survive FWE-correction. Second, while our study—along with others (Agtzidis et al., 2020)—can be seen as a first step towards studying smooth pursuit BOLD correlates of more complex visual scenes, the background stimuli we employed here were still artificial. Therefore, future studies should focus on more natural and dynamic scenes in order to broaden our understanding of how the smooth pursuit system works in more complex contexts with higher ecological validity (Goettker et al., 2020).

Third, we did not include a fixation control condition with structured background but without pursuit eye movements. Therefore, part of the activation differences between the background conditions can simply be attributed to different visual content. However, it should be noted that this cannot be the only source of differences in BOLD response, as other studies have shown activations unique to pursuit (Dieterich et al., 2009; Kimmig et al., 2008; Ohlendorf et al., 2010; Schraa-Tam et al., 2009). Fourth, we employed two relatively high target velocities, for example, as compared to Kimmig et al. (2008). Adding further and slower velocities might have been useful to explore the

BOLD correlates of SPEM velocity effects in even more detail. However, we carefully selected the 0.4 Hz and 0.6 Hz velocities employed here based on the magnitudes of effects and good to excellent reliabilities in our own previous investigation (Schröder et al., 2021).

Fifth, we did not account for individual differences in anatomical location of the LGN in every participant. Therefore, analyses with seed regions in this area should be interpreted with caution as we cannot ultimately dismiss the possibility that we did not hit the targeted brain area. Future studies could use a localizer task to inform decisions on seed region centre coordinates.

Lastly, we cannot ultimately rule out that part of the BOLD response during the pursuit task was accounted for by saccades. Crucially, however, saccadic frequency only correlated with BOLD response in one ROI (right lateral FEF extending into medial FEF) in one of four conditions. In addition, saccadic frequency did not predict BOLD response in our regression analyses, and in an elaborate study that independently modelled pursuit blocks and corrective saccades, no saccade-specific activation could be obtained (Haller et al., 2008).

5 | CONCLUSION

In this preregistered study, we identified distinct BOLD correlates of behaviourally robust background and velocity effects in SPEMs. Despite greater performance deterioration with increased target velocity, BOLD response for this contrast was limited to visual cortex and lateral FEF. Conversely, pursuit over a structured background was associated with a distributed visuo-fronto-parietal network of perceptual, oculomotor, and attentional brain regions. To our knowledge, this is the first study to propose distinct functions of medial and lateral FEF in smooth pursuit and we strongly recommend further investigation of functional specialisation of these regions in the future.

CONFLICT OF INTEREST
The authors declare that they have no conflict of interest.

DATA AVAILABILITY STATEMENT
The eye-tracking data that support the findings of this study are openly available at the Open Science Framework (OSF) at https://osf.io/uez5f. The MRI data that support the findings of this study are available on request from the corresponding author. The MRI data are not publicly available due to privacy and ethical restrictions.

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