Enhanced information processing at revisited fixation locations

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Abstract

Eye tracking studies of refixation behavior suggest that refixations serve to recover information lost or missed during continued exploration of a visual scene. So far, however, these studies have ignored what happens during the previous fixations at refixated locations, i.e., the precursor fixations. Revisits to precursor fixations may be required because original acquisition was insufficient. This would suggest weakened activity at precursor fixations. Alternatively, however, it may imply that acquisition was not completed despite maximal effort. This may be related to the strategic importance of the site, excessive amount of relevant detail, and/or the formation of a strategic plan to return later. In these cases we will rather observe above-average activity at precursor fixations. We analyzed fixation-related EEG in precursor fixations, ordinary fixations, and refixations using EEG-eye movement co-registration in a natural viewing task. The analysis crucially involved matching potentially confounding eye movement characteristics between fixation categories. Compared to ordinary fixations, in precursor fixations the amplitude of fixation-related potentials over posterior areas was found to be increased and EEG alpha power over frontal areas was decreased. These findings, respectively, indicate enhanced rather than deficient visual processing at precursor fixations and enhanced oculomotor control activity. These results constitute first evidence that fixation locations that are later revisited contain visual information that is strategically important for the current task.

Keywords: natural viewing, electroencephalography, visual search, task relevance, healthy adults

Introduction

In natural viewing, the eyes often return to locations that were visited several seconds ago. Such refixations constitute up to 35% of eye movements (Mannan et al., 1997; Beck et al., 2006; Zelinsky et al., 2011). Their prevalence suggests that refixations might play an important role in visual perception. This has made them a focus of eye-tracking research (Gilchrist and Harvey, 2000; Tatler et al., 2005; Körner and Gilchrist, 2008; Zelinsky et al., 2011; Shen et al., 2014). Refixations have been ascribed a range of roles, such as recovering information that was missed or has become lost during scanning (Gilchrist and Harvey, 2000), updating representation of a previously visited location (Tatler et al., 2005); rehearsal of a fading memory representation (Zelinsky et al., 2011; Meghanathan et al., 2019); or compensating for a premature shift of attention away from the fixation (Gilchrist et al., 2001; Peterson et al., 2001). In all these cases, refixations are aimed at restoration of deficiencies arising in information processing and storage.

The deficiencies giving rise to refixation behavior, thus, originate, at the earliest, in those fixations to which the eyes later return. Let us call them *precursor* fixations. If weak information acquisition during initial scanning prompts refixations, their precursor fixations are likely to evidence weaker neural activity than average fixations. Alternatively, certain fixation locations may qualify for a later return if the information acquisition was not, or could not be completed despite the best effort. These locations may contain strategic information, an excess of important detail, and may therefore give rise to a plan to return later. In this case, we should observe more neural activity than average at precursor fixations. Finally, if refixations are prompted by memory deficits originating after the precursor fixation, for instance, by random forgetting, activity at precursor fixations should not differ from that at ordinary locations.

To decide between these contrasting predictions we studied EEG co-registered with eye movement. We reanalyzed a dataset containing EEG and eye movement recordings collected during unrestricted visual search for a contour in a field of Gabor elements (Van Humbeeck et al., 2018). Our previous analysis of refixations in this dataset were aimed at the mechanisms of refixation control (Nikolaev et al., 2018). We found refixation control effects in the presaccadic interval, and concluded that saccade planning for refixations and ordinary fixations differ in the allocation of attention when it shifts to the next saccade target. Those results involved comparing refixations with ordinary fixations. Here, we focus on the complementary, i.e., a comparison between ordinary fixations and precursor fixations.

Distinguishing between precursor fixations, ordinary fixations, and refixations, we analyzed the amplitude of the fixation-related potential (FRP), and EEG power and inter-trial coherence of EEG time-locked to the fixation onset in the postsaccadic interval. We extracted EEG epochs matched between fixation conditions on potentially confounding eye movement characteristics. Such confounds include effects of overlapping brain responses that arise in saccade sequences (Dimigen et al., 2011; Nikolaev et al., 2016). We also matched between conditions the fixation rank within a trial, in order to exclude its effect on EEG.

We found that compared to ordinary fixations, precursor fixations were characterized by increased FRP amplitude over posterior areas, in combination with a decrease in frontal alpha power for the entire postsaccadic interval. These findings indicate enhanced information acquisition at precursor fixations and suggest that these locations contain strategically important information for the eyes to return to later.

Methods

We used a dataset of EEG eye-movement co-registration, from which we previously analyzed stimulus conditions (Van Humbeeck et al., 2018) and compared the EEG of refixations and ordinary fixations (Nikolaev et al., 2018). The precursor fixations from this dataset have not been analyzed previously.

Participants

23 healthy adults (two male) took part in the experiment. Data from two participants were removed: one because of problems during eye movement recording and another because of excessive EEG artifacts. The mean age of the remaining 21 participants was 21.6 (range = 18-33) years. All participants gave written informed consent. The study was approved by the Ethics Committee of the Faculty of Psychology and Educational Sciences of KU Leuven.

Stimuli and procedure

Gabor patches of approx. 0.3-0.4° of visual angle were randomly positioned with a mean distance of 0.7° between them in large displays of 30 x 30° of visual angle at a viewing distance of 55 cm. In half of the trials, seven patches formed a contour because their orientation was aligned +/- 25° with the neighboring patches (contour-present trials). The contour was embedded at a random location of the display. In the other half of the trials, the orientation of all patches was random (contour-absent trials). Details of the display design and results of the eye movement analysis of contour integration were reported elsewhere (Van Humbeeck et al., 2013).

Participants initiated a trial by pressing the space bar on the computer keyboard. At the beginning of a trial a fixation cross was presented for a random duration between 500 and 1000 ms. Next, a display was presented for 8 s. Contour-present or contour-absent displays were presented in random order. Participants searched for a contour and indicated its presence or absence within the following 5 s response interval by pressing “p” or “q” keys of the computer keyboard. A feedback screen indicated whether or not the response was correct. 120 contour-present and 120 contour-absent trials were presented. The trials were organized in 6 blocks of 40 trials with two-minute breaks between blocks. A short practice session preceded the experiment.

Eye movement recording

The display size necessitates the use of eye movements to search for a contour. Eye movements were recorded with a desktop version of the EyeLink 1000 eye tracking system (SR Research Ltd., Ontario, Canada). The sampling frequency was 250 Hz. A chinrest stabilized participant’s head. A 9-point calibration was performed before each block and whenever it was needed during the block, e.g., if participants occasionally moved their head away from the chinrest. The mean number of calibrations per experiment across participants was 17.7 (range 8-32, SD=7.9). A maximum of 2° error margin between calibration and validation was allowed. The space bar press at the beginning of the trial triggered a drift correction, which allowed tracking errors to be kept within 2°.

EEG recording

EEG was recorded at a sampling rate of 250 Hz using a 256-channel Geodesic Sensor Net (EGI, a Philips company, Eugene, OR, USA). The net included electrodes for recording the vertical and horizontal electrooculogram. The recording reference was Cz. EEG was filtered online with an analog high-pass filter of 0.1 Hz and a 100-Hz low-pass filter. Stimulus presentation, EEG, and eye tracking were synchronized by sending a TTL pulse through a parallel port from the stimulus presentation computer to the eye tracking and EEG systems at the beginning of each trial.

Selection of refixations, precursor fixations and ordinary fixations

We considered contour-absent trials only, because in these trials, visual search invariably lasted for the full 8 s, whereas discovery of a contour at an unidentified moment would end the search for the remaining interval. To maximize the number of epochs, we considered trials with both correct and incorrect responses; the scan path length (the number of fixations per trial: 23.2 vs. 23.4, respectively) and the number of refixations (see their definition below) per trial (4.0 vs. 3.7, respectively) were not different (both $p > 0.13$) between correct and incorrect responses, indicating similarity of eye movement behavior. We excluded from EEG analyses the first fixation in a trial, because it is affected by the stimulus onset-related potential (Dimigen et al., 2011). We also excluded fixations immediately preceding a refixation, because these contain preparatory EEG activity specific for refixations (Nikolaev et al., 2018).

In each trial we identified refixations within a sequence of fixations (Fig. 1A). A refixation was defined as a fixation within a radius of 2° of visual angle from a previous fixation. A 2° criterion has repeatedly been used in refixation studies (Gilchrist and Harvey, 2000; Solman et al., 2011; Anderson et al., 2013). It assures that fixation and a refixation overlap on the fovea. We did not consider as refixations any subsequent fixations prior to leaving the 2° range. If a refixation occurred within 2° from two or more close (<2°) precursor fixations, we scored it as a refixation only once. When two or more sequential refixations occurred, we took only the first one. After applying these criteria, on average 15.8% (SD = 3.1, range 10.6-22) of eye movements per participant were counted as refixations.

To select precursor fixations, we identified all fixations that later receive refixations. Their number was slightly less than the number of refixations (Table 1) because several refixations could originate from the same precursor fixation. Precursor fixations and refixations were separated by, on average, 9 (SD = 1.2, range 7-10.9) intervening fixations.

To select ordinary fixations, we excluded precursor fixations and refixations (including the ones discarded during the selection) from all the fixations in a trial. The number of ordinary fixations was more than 4 times larger than that of refixations. This large number made the matching of eye movement characteristics and fixation ranks between *Precursor Fixation*, *Ordinary Fixation,* and *Refixation* categories feasible through the procedure described below.

Table 1. The number of fixations per participant available at various stages of the analysis (mean, SD). The column for Ordinary fixations splits in two after matching because this category was matched with Precursor Fixation (left) and Refixation categories (right) separately.

	Precursor fixations	Ordinary fixations		Refixations
Initial number	532 (98.2)	3005 (324.1)		708 (131.5)
After setting limits	157 (32.5)	827 (100.4)		197 (45.4)
After matching	157 (32.5)	157 (32.5)	197 (45.4)	197 (45.4)
After EEG artifact rejection	148 (33.5)	149 (32.9)	187 (41.5)	185 (41.0)

Selection of EEG epoch duration
We contrasted the fixation-related EEG between precursor fixations and ordinary fixations and between refixations and ordinary fixations in two independent analyses.

To evaluate processes associated with information acquisition at fixation we analyzed EEG time-locked to the fixation onset. We set the duration of EEG epochs to 250 ms in order to include the lambda wave and following fixation-related activity. The lambda wave reflects the response of visual cortex to the shift of visual image, that is, represents perceptual processes at fixation (Thickbroom et al., 1991; Kazai and Yagi, 1999; Dimigen et al., 2009). Fixation-related activity following the lambda wave may reflect further information processing, including memory encoding. This activity is treated as analogous to later stimulus-evoked activity and its traditional ERP components (Dandekar et al., 2012; Kamienkowski et al., 2012; Brouwer et al., 2013).

A 250-ms EEG epoch should not be interrupted by intervening eye movements. Therefore we limited the minimal duration of the current fixation to 250 ms. The current fixation duration was no longer than 1000 ms. The duration of the current saccade was not to exceed 100 ms. Setting these limits reduced the number of fixations available for analysis considerably (Table 1), mostly due to the removal of short fixations.

Matching saccade size and fixation rank between fixation categories
Due to the non-uniform distribution of fixation durations in natural viewing behavior, effects of eye movements on EEG are systematic and confound effects of experimental conditions (Dimigen et al., 2011; Dias et al., 2013; Nikolaev et al., 2016). One of the solutions to this problem is matching eye movement characteristics between experimental conditions (Dimigen et al., 2011; Kamienkowski et al., 2012; Dias et al., 2013; Nikolaev et al., 2016). The choice of eye movement characteristics for matching depends on whether the analysis targets brain processes in the pre- or postsaccadic interval. We are interested in information acquisition in the postsaccadic interval. In the postsaccadic interval, EEG depends mainly on the size of the current saccade (Yagi, 1979; Nikolaev et al., 2016). Consequently, we matched EEG epochs on this eye movement characteristic. In addition, the fixation rank, i.e., the position in the order of fixations within a trial, may affect the EEG (Kamienkowski et al., 2018). Therefore, along with saccade size, we matched fixation rank between conditions of interest. We did not match saccade direction because it does not systematically affect the lambda activity (Nikolaev et al., 2016). Moreover, saccade direction is interrelated with saccade size (Tatler and Vincent, 2008), which was matched.

Matching was done separately between precursor and ordinary fixations and between refixations and ordinary fixations. Precursor fixations and refixations were distributed unequally, skewing towards the left and right edge of a trial, respectively (Fig. 1B). Matching was straightforward; because of the considerably larger number of ordinary fixations than precursor fixations and refixations, and the former's almost uniform distribution within a trial, we were able to select epochs of ordinary fixations matching in saccade size and fixation rank for both precursor fixations and refixations.

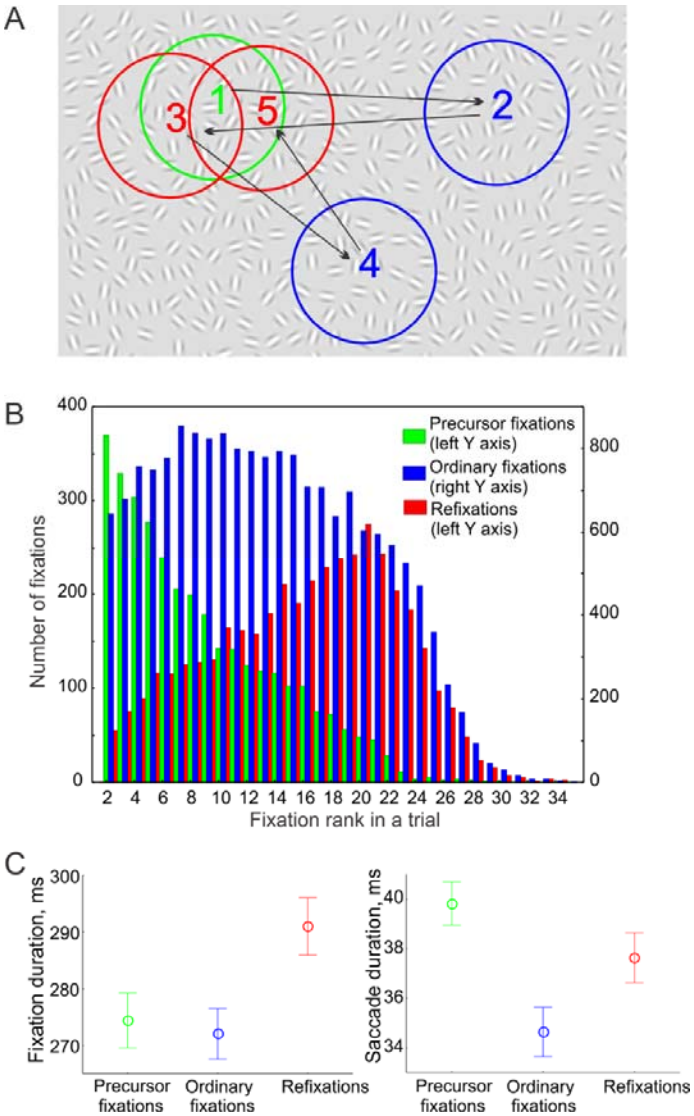

Fig. 1. A: Fixation categories. Circles represent areas within a radius of 2° of visual angle around the fixation point. Numbers indicate an order (rank) of subsequent fixations. Fixation 1 is a precursor fixation; Fixations 2 and 4 are ordinary fixations; Fixations 3 and 5 are refixations. B: Distributions according to fixation rank within trials of three categories of fixations. The data are filtered according to the saccade size and fixation duration criteria specified in the text, but yet unmatched, and pooled across participants. C: Saccade and fixation durations for three fixation categories (before filtering). Data points are the means, and error bars are the standard errors across 21 participants.

Previously we used a matching procedure based on computing the Mahalanobis distance (Nikolaev et al., 2016, 2018). But this procedure does not benefit from the possibility of selecting items from the larger set as optimal matches for the items from the smaller set. To make use of this advantage we proceeded in two steps: matching fixation ranks and matching saccade sizes. To match precursor and ordinary fixations, we first sorted epochs of the Ordinary Fixation category by descending fixation rank. Then, we removed, one by one, epochs from the top of the sorted list (i.e., ones with the highest fixation rank) from the Ordinary Fixation category, evaluating the difference in rank between precursor and ordinary fixations after each removal with a t-test. We repeated the removal until the p-value of the fixation rank difference reached 0.9, i.e., until the difference in rank was removed with high confidence.

In the second step, we sorted fixations of the *remaining* ordinary fixations by ascending saccade size. This, because saccade size was larger in the precursor that ordinary fixations (Fig. 1C). Then we performed the same stepwise removal until the p-value of the saccade size difference reached 0.9. After these two steps the number of fixations was still considerably larger in the Ordinary than in the Precursor Fixation category. Therefore we randomly selected a number of ordinary fixations, equal to that of the precursor fixations. This matching procedure was applied separately to individual participant data. After this procedure the number of fixations available for the analysis was the same as before (Table 1), in contrast to the considerable reduction that would have occurred after using the procedure with the Mahalanobis distance (Nikolaev et al., 2018). Note that p-values may decrease as a result of the subsequent removal and the random selection, but since initially the p-values were very high (0.9) they did not come close to the significance threshold of 0.05 for any participant (p-values across participants for fixation rank: mean $p = 0.68$, SD = 0.23, range 0.21-0.99; for saccade size: mean $p = 0.72$, SD = 0.21, range 0.28-0.99).

In addition to removing differences in fixation rank and saccade at individual level, this matching procedure eliminated differences at group level. We tested this by averaging fixation ranks and saccade sizes within each participant and comparing these mean values in a group of 21 participants with a paired t-test: for fixation rank, $p = 0.09$; for saccade size, $p = 0.15$.

We repeated the same procedure for matching fixation ranks and saccade sizes between refixations and ordinary fixations. Here, at individual level, for fixation rank, the *p*-values had mean $p = 0.61$, SD = 0.24, range 0.21-0.92; for saccade size, the *p*-values had mean $p = 0.58$, SD = 0.26, range 0.20-0.95 and at the group level, for fixation rank, $p = 0.98$; for saccade size, $p = 0.72$. For both precursor fixations and refixations, a match at the individual and group levels was thus achieved for all 21 participants.

EEG analysis

We analyzed the amplitude of potentials time-locked to fixation onset (fixation-related potential, FRP), as well as EEG power and inter-trial coherence in the postsaccadic interval. Inter-trial coherence (ITC, (Delorme and Makeig, 2004), aka the phase-locking factor (Tallon-Baudry et al., 1996), shows EEG synchronization across trials in reference to a phase-locking event, in our case, the fixation onset. ITC values vary between 0 and 1; 0 indicates no phase-locking and 1 indicates perfect phase-locking of EEG across epochs to the fixation onset.

BrainVision Analyzer (Brain Products GmbH, Gilching, Germany) was used for EEG preprocessing. EEG was filtered with zero phase shift Butterworth filters of the 2nd order with a low cut-off of 0.5 Hz and with a high cut-off of 30 Hz (45 Hz for the time-frequency analyses) and a 50 Hz notch filter. 100 of 256 electrodes close to the cheeks and neck were removed because they often had poor contact due to the long hair of our mostly female participants, and showed strong muscle artifacts. The remaining electrodes were visually inspected and excluded if they appeared to be noisy. The vertical electrooculogram (VEOG) was obtained as the EEG difference between electrodes placed above and below the eyes. The horizontal electrooculogram (HEOG) was obtained as the EEG difference between electrodes placed near the right and left outer canthi of the eyes.

For the FRP analysis, EEG was segmented into epochs from -100 to 250 ms relative to fixation onset. For the time-frequency analyses, EEG was initially segmented into epochs from -600 to

750 ms relative to fixation onset, in order to avoid the edge effects of the wavelet transformation. After the transformation, the epoch duration was reduced to the same -100 to 250 ms relative to fixation onset.

Artifact rejection involved the removal of EEG epochs with an absolute amplitude difference between neighboring sample points higher than 50 µV, with amplitude exceeding 100 µV in an interval of 200 ms, or with amplitude lower than 0.5 µV in an interval of 100 ms. If the percentage of bad epochs in a channel exceeded 2%, the channel was removed. The number of epochs entering the EEG analysis after artifact rejection is provided in Table 1. We ensured that eye movements were still matched after removal of artifact epochs. Oculomotor artifacts were corrected using independent component analysis (ICA) (Jung et al., 2000) with a restricted Infomax algorithm. Epochs concatenated across all fixation categories were fed to ICA. ICA components (N = 43.5, SD = 5.1 per participant) were rejected when the sum of squared correlations with the HEOG or the VEOG channel exceeded 0.3. The EEG was then recreated without these components. After ICA, the removed channels (N = 2, SD = 3.7 per participant) were interpolated with spherical spline interpolation. EEG was re-referenced to average reference. For the FRP analysis, EEG epochs were averaged for each fixation category.

For the time-frequency analyses, we used two-cycle Morlet complex wavelets for 10 logarithmically-spaced central frequencies in the range from 2 to 30 Hz. The wavelet duration was 318 ms at 2 Hz and 21 ms at 30 Hz. After obtaining complex time-frequency data points for every epoch, these data were averaged and transformed into absolute power. ITC was calculated as the average across epochs of the normalized phase angles for a given number of channels, time points, and wavelet scales with a routine of BrainVision Analyzer.

FRP amplitude and EEG power were baseline corrected relative to the interval from 0 to 20 ms after the fixation onset. This interval is supposed to be free of saccade execution artifacts, where perception-related EEG activity has not started yet (Rama and Baccino, 2010).

Statistical analysis

For the FRP analysis, we applied two complementary approaches of search for differences in FRP amplitude between fixation categories. The first approach involved estimation of the FRP amplitude in *a priori* selected time windows and regions of interest (ROIs). The second approach involved the cluster-based permutation test (Maris and Oostenveld, 2007). For the time-frequency analyses, we used the cluster-based permutation test only.

We selected eight ROIs over the left and right hemisphere, namely, frontal, central, parietal and occipital brain regions, which were defined around landmark electrodes of the International 10-20 System of Electrode Placement: F3, F4, C3, C4, P3, P4, O1, O2. For each ROI, we averaged amplitudes over one central and six surrounding electrodes. This approach involved 56 (=7*8) electrodes, symmetrically and systematically distributed over the head. Such an approach is generally suggested for high-density electrode montages (Dien and Santuzzi, 2005). We selected two time windows: the first window of 70-110 ms after fixation onset. This window covered the lambda wave. The second window of 110-250 ms after the fixation onset covered the late components of the fixation-related potential.

FRP amplitude was compared between fixation categories with a repeated measures ANOVA. The Huynh-Feldt correction for p-values associated with two or more degrees of freedom was applied in case of sphericity violation. Fisher's LSD (least significant difference) test was used

for post-hoc analyses. The statistical analyses were performed with STATISTICA 10 (StatSoft Inc., Tulsa, OK, USA).

A priori tests do not require correction for multiple comparisons and therefore have higher statistical power than permutation tests. Moreover, they are more likely to detect narrowly distributed effects that occur across a small number of time points and electrodes (Groppe et al., 2011). But these tests use preselected time windows and electrodes and will therefore miss effects outside the preselected areas. Thus, in addition to *a priori* tests, we used the cluster-based permutation test (Maris and Oostenveld, 2007), implemented in MNE-Python (Gramfort et al., 2013). This test controls for the multiple comparison problem by employing cluster-wise statistics. Clusters are defined by data points that show the same effect and are contiguous in the dimensions of the dataset. We entered into the cluster-based permutation test data points from 20 to 250 ms after fixation onset, i.e., without the presaccadic and baseline intervals. For the FRP analysis, we calculated a test statistic between fixation categories of interest using a 2-tailed t-test for each electrode and time sample. Two or more data points adjacent in time and space and having p-values below 0.05 were clustered together. The *t*-statistics from each data point in a cluster were summed to get a cluster-level *t*-score. The t-scores were evaluated against a permutation distribution. A permutation distribution was generated from the largest cluster-level *t*-value obtained during each of a 1000 random assignment of data points to the two conditions. For each cluster, the probability of finding a cluster with its *t*-value was estimated as a *p*-value by finding its rank in the permutation distribution. The significance threshold for a cluster was 0.05. Such procedure penalizes small clusters, which mostly disappear when tested against the null hypothesis (Maris and Oostenveld, 2007).

For the time-frequency analyses, the frequency dimension was added to the algorithm described above. Here the clusters were considered in the conjoint time-electrode-frequency space. Data points were clustered if their p-values were below 0.05 and if they were contiguous in all three dimensions. The obtained clusters were large, often involving almost all electrodes and frequencies. To get a finer resolution of the effects we reduced sizes of the time-frequency clusters by choosing a more restrictive significance threshold of $p = 0.01$ compared to the initial cluster definition of $p = 0.05$, as the cluster extent depends on it (Sassenhagen and Draschkow, 2019).

Results

Eye movement results

Before applying the data exclusion criteria necessary for EEG analyses, we ran repeated measures ANOVAs on saccade duration and fixation duration, with the factor Fixation category (Precursor Fixation, Ordinary Fixation, Refixation). The effect of Fixation category on saccade duration was highly significant ($F(2, 40) = 49$, $p < 0.001$, $\varepsilon = 0.79$); saccades were longer in the Precursor Fixation than in the Refixation category, and longer in the Refixation than in the Ordinary Fixation category (all post-hoc $p < 0.001$) (Fig. 1C). The effect of Fixation category on fixation duration was also highly significant ($F(2, 40) = 36$, $p < 0.001$, $\varepsilon = 0.65$), with longer fixations in the Refixation category than in both the Ordinary Fixation and Precursor Fixation categories (both post-hoc $p < 0.001$), whereas there was no difference between the latter ($p = 0.3$) (Fig. 1C).

EEG results

Precursor fixations vs. ordinary fixations

To analyze the amplitude of fixation-related potentials in 8 ROIs (Fig. 2A) we ran a repeated measures ANOVA with factors: Fixation category (Precursor Fixation, Ordinary Fixation), ROI (frontal, central, parietal, occipital), and Hemisphere (left, right) for two intervals (70-110 ms and 110-250 ms) separately. For the interval 70-110 ms, we found effects of ROI ($F(3, 60) = 86$, $p < 0.001$, $\varepsilon = 0.43$) and Hemisphere ($F(1, 20) = 8.4$, $p = 0.009$), and an interaction between the Fixation category and Hemisphere ($F(1, 20) = 4.7$, $p = 0.04$) (Fig. 2B). For the interval 110-250 ms, we found an effect of ROI ($F(3, 60) = 96$, $p < 0.001$, $\varepsilon = 0.67$) and an interaction between Fixation category and Hemisphere ($F(1, 20) = 7.4$, $p = 0.01$). The post-hoc test revealed a higher FRP amplitude for the Precursor Fixation than the Ordinary Fixation category for the right hemisphere ($p = 0.049$) but no difference between the two categories for the left hemisphere (Fig. 2C). Thus, FRPs were distinct between the Precursor Fixation and Ordinary Fixation categories in both intervals.

The cluster-based permutation test of FRPs showed a significant difference between the Precursor Fixation and Ordinary Fixation categories (Fig. 2D-F). The effect involved an 81-electrode cluster (Fig. 2D, F) and was most pronounced over the posterior areas and over the right hemisphere. FRP amplitude was higher in the Precursor Fixation category than in the Ordinary Fixation category and persisted for the entire duration of the postsaccadic interval (Fig. 2E). The persistence and the predominant right-hemisphere lateralization of the cluster corresponded to the result of the ROI analysis.

The cluster-based permutation test of EEG power showed a significant difference between the Precursor Fixation and Ordinary Fixation categories (Fig. 2G, H). The cluster persisted for the entire duration of the postsaccadic interval, was prominent for frequencies between 5 and 16 Hz, and was most pronounced over the right frontal area, involving 19 electrodes (Fig. 2H). The EEG power was mostly lower in the Precursor Fixation than in Ordinary Fixation category, in contrast to the FRP amplitude.

The cluster-based permutation test of inter-trail coherence did not reveal any significant results.

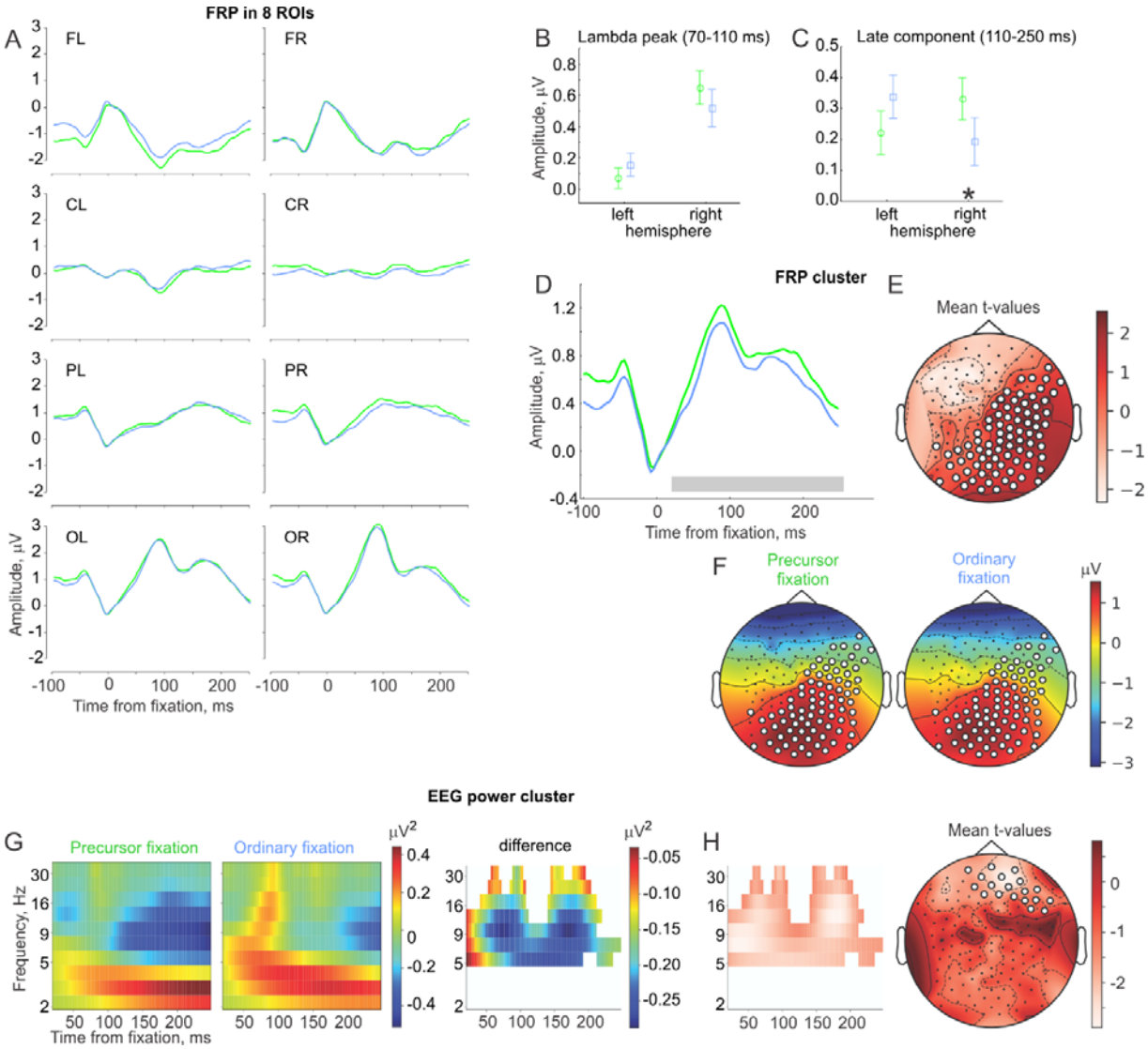

Fig. 2. Fixation-related EEG for Precursor Fixation and Ordinary Fixation categories. The results of the ROI analysis are shown in A-C; the results of the cluster based permutation tests are shown in D-H. A: The grand-averaged fixation-related potential, baseline-corrected at 0-20 ms from the fixation onset for 8 ROIs. B, C: The mean amplitude in the lambda (70-110 ms) and late (110-250 ms) intervals. The asterisk indicates the hemisphere with a significant difference between the Precursor Fixation and Ordinary Fixation categories. Error bars indicate standard errors of the means across 21 participants. D: The grand-averaged fixation-related potentials for electrodes with a significant difference shown in E. The grey bar indicates the interval of significant difference (here, the entire postsaccadic interval minus a baseline interval). E: The *t*-value map averaged across *t*-values in the significant interval (see D). F: The grand-averaged amplitude represents the interval of significant difference indicated as a grey bar in D. White circles indicate electrodes with a significant difference obtained in the cluster based permutation test. G: The grand-averaged time-frequency plots of EEG power, baseline-corrected at 0-20 ms from the fixation onset for electrodes with a significant difference shown in H and the plot of the difference between conditions. H: The time-frequency plot of *t*-values for the intervals and frequencies with a significant difference, and the *t*-value map averaged across *t*-values in time points and frequencies with a significant difference.

Refixation vs. Ordinary Fixation categories

To compare the FRP amplitude between Refixations and Ordinary Fixations in 8 ROIs (Fig. 3A) we ran a repeated measures ANOVA with factors of Fixation category (Refixation, Ordinary Fixation), ROI (frontal, central, parietal, occipital), and Hemisphere (left, right) for two intervals (70-110 ms and 110-250 ms) separately. For the interval 70-110 ms, we found significant effects of ROI ($F(3, 60) = 62$, $p < 0.001$, $\varepsilon = 0.41$) and Hemisphere ($F(1, 20) = 5.8$, $p = 0.026$), and an interaction between Fixation category and ROI ($F(3, 60) = 9.5$, $p < 0.001$) (Fig. 3B). The post-hoc test revealed a difference between the Refixation and Ordinary Fixation categories for frontal, parietal, and occipital ROIs (all $p < 0.004$). For the interval 110-250 ms, we found only a significant effect of ROI ($F(3, 60) = 72$, $p < 0.001$, $\varepsilon = 0.48$). Thus, the difference between conditions was limited to the lambda (70-110 ms) interval.

The cluster-based permutation test of FRPs showed a difference between the Refixation and Ordinary Fixation categories (Fig. 3C-E). The cluster was most pronounced over the parieto-occipital areas, involving 55 electrodes (Fig. 3C, E) and persisted from approximately 20 to 116 ms (Fig. 3D). The predominant posterior lateralization of the cluster and its latency signal a relation to lambda activity.

The cluster-based permutation test of EEG power also showed a significant difference between the Refixation and Ordinary Fixation categories (Fig. 3F, G). The cluster extended from approximately 20 to 200 ms, was prominent for frequencies below 5 Hz, and was most pronounced over the right frontal area, involving 18 electrodes (Fig. 3G).

The cluster-based permutation test of inter-trail coherence showed a difference between the Refixation and Ordinary Fixation categories (Fig. 3H, I). A cluster persisted from approximately 80 to 170 ms, was prominent for frequencies between 9 and 16 Hz, and was most pronounced over the right parieto-occipital area, involving 31 electrodes (Fig. 3I). The latency of the cluster, the frequency of the maximal difference, and the posterior lateralization confirm its relation to the lambda activity.

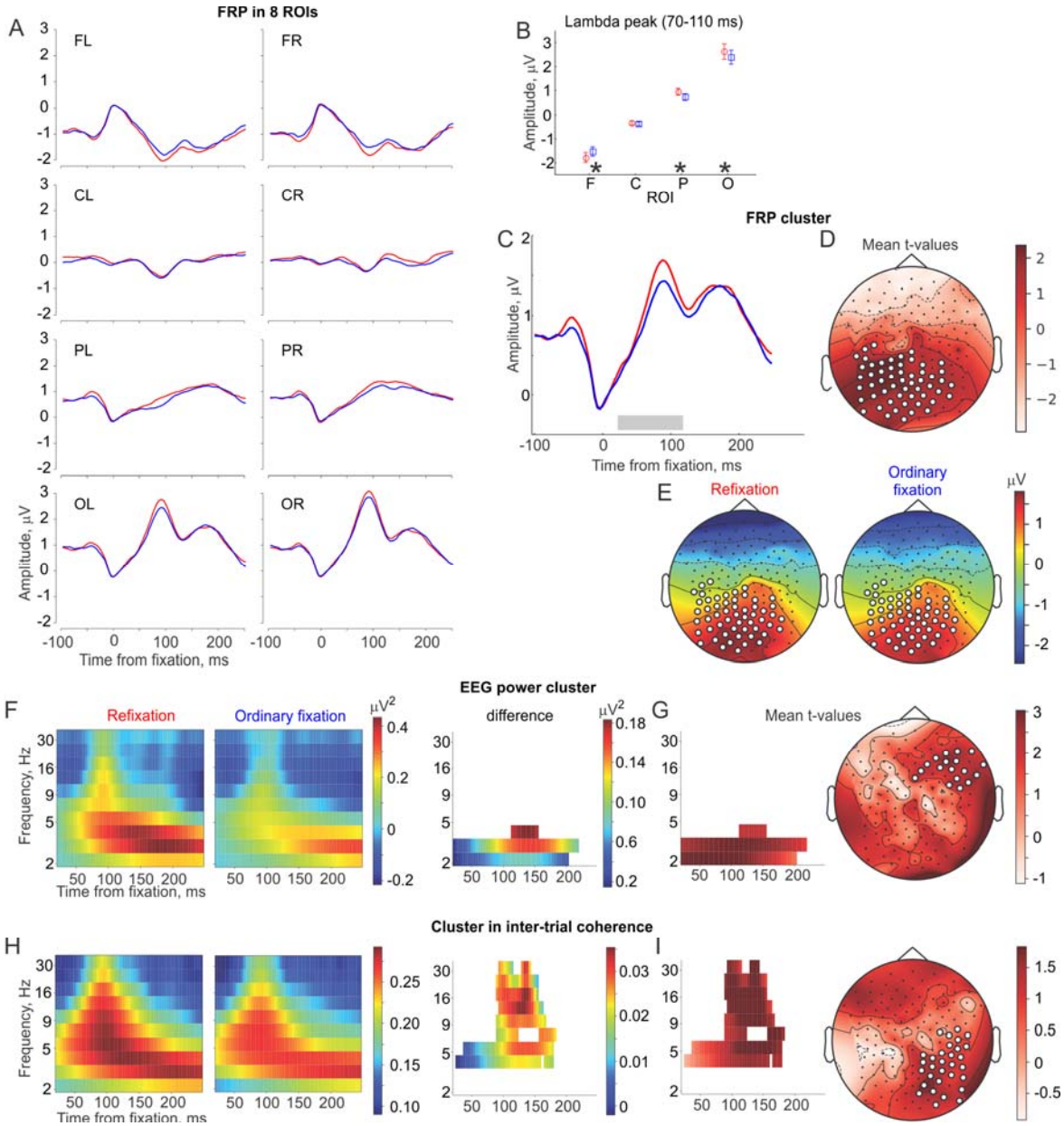

Fig. 3. Fixation-related EEG for the Refixation and Ordinary Fixation categories. Results of the analysis for 8 ROIs are shown in A-B; those of the cluster based permutation test in C-I. A: The grand-averaged fixation-related potentials, baseline-corrected at 0-20 ms from the fixation onset. B: The mean amplitude in the lambda (70-110 ms) interval. The asterisks indicate ROIs with significant differences between the Refixation and Ordinary Fixation categories. Error bars indicate standard errors of the means across 21 participants. C: The grand-averaged fixation-related potentials for electrodes with a significant difference shown in D. The grey bar indicates the interval of significant difference. D: The *t*-value map averaged across *t*-values in the significant interval (see C). E: Grand-averaged amplitude maps for the period of a significant difference between the Refixation and Ordinary Fixation categories, indicated as a grey bar in C. White circles indicate electrodes with a significant difference obtained in the cluster based permutation test. F: Grand-averaged time-frequency plots of EEG power, baseline-corrected at 0-20 ms from fixation onset for electrodes with a significant difference shown in G and the plot of the difference between conditions. G: The time-frequency plot of *t*-values for the intervals and frequencies with a significant difference, and the *t*-value map averaged across *t*-values in the significant time points and frequencies. H: The grand-averaged plots of inter-trail coherence for electrodes with a significant difference between Refixation and Ordinary Fixation shown in I and the plot of the difference between conditions. I: Time-

frequency plot of *t*-values for intervals and frequencies with a significant difference between Refixation and Ordinary Fixation, and the *t*-value map averaged across *t*-values in time points and frequencies with a significant difference.

Ordinary fixations for precursor fixations vs. ordinary fixations for refixations (a control analysis)
In the EEG analyses above, precursor fixations and refixations were contrasted to ordinary fixations. The sets of ordinary fixations for each analysis were derived from the same distribution (Fig. 1B) by selecting ordinary fixations which match in saccade size and rank fixations in the conditions of interest. Since the two sets of ordinary fixations only partially overlapped, differences in saccade size and rank between them may be present. Therefore, the brain processes associated with these sets may differ, making the reference condition for the two main analyses inadequate. Therefore we compared EEG measures between the two sets of ordinary fixations with all the tests used in the main analyses (except inter-trail coherence because the number of epochs was substantially different between the two sets and consequently the comparison of this measure would not be reliable). None of the analyses showed a significant difference between the two sets of ordinary fixations, even though their saccade sizes and ranks were not matched (Fig. S1). This indicates that the two sets of ordinary fixations are qualitatively similar, and they provide an adequate reference condition for the comparisons of interest.

Discussion

Eye tracking research has shown that refixations account for updating or recovering information lost or missed during continued scanning of a scene (Gilchrist and Harvey, 2000; Tatler et al., 2005; Körner and Gilchrist, 2008; Zelinsky et al., 2011; Shen et al., 2014; Meghanathan et al., 2019). However, it is not clear to what extent revisits occur because information is lost during the scanning process or was missed initially. If the latter, was it initially ignored, or was there more than could be captured in an initial fixation

We investigated information acquisition at fixation locations revisited later (precursor fixations) in natural viewing conditions of a contour detection task. In EEG activity following fixation onsets, we considered the difference between precursor fixations and fixations to locations that do not receive later refixations (ordinary fixations). We found that EEG related to precursor fixations is distinct from ordinary fixations. The FRP amplitude was higher in the precursor than in ordinary fixations (Fig. 2A-F). The distinction persists across the entire duration of the postsaccadic interval and is found over posterior areas and over the right hemisphere. The widespread and extended character of this effect indicates involvement of both visual and encoding processes occurring at fixation onset. This is contrary to what would be expected if insufficient processing at precursor fixations gives rise to refixation behavior.

Higher FRP amplitude over posterior areas for precursor fixations is accompanied by lower EEG power over frontal areas, mostly in the alpha frequency band (Fig. 2G-H). Low alpha power is associated with high activity of local cortical regions (Klimesch et al., 2007). Thus, alpha reduction indicates activation of frontal control regions, such as, posterior medial frontal cortex, lateral prefrontal cortex, and the frontal eye fields (Clayton et al., 2015). These regions imply both the involvement of eye movement planning and executive function. The alpha effect starts before sensory information reaches the visual cortex (Maunsell and Gibson, 1992), i.e. right after fixation onset. This may reflect anticipation in top-down control of visual processing,

for instance involving the presaccadic shift of attention to the next fixation target. The maximal reduction of alpha power occurs after 100 ms from fixation onset (Fig. 2G), indicating increased top-down control over processing at precursor fixations.

Taken together, the FRP and EEG power results provide evidence for enhanced information processing at precursor fixation locations. Refixation behavior is therefore unlikely to have resulted from ignoring relevant information during the initial examination of a scene. Enhanced processing suggests that the precursor fixation locations are of such strategic interest that a single initial fixation does not exhaust the information acquisition, despite the best efforts. To complete the process a refixation is needed.

The combination of the decreased frontal alpha and elevated FRP amplitude over the posterior areas provides evidence for interaction between the frontal lobe and visual cortex, which is crucial for target selection in goal-oriented viewing behavior (Medendorp et al., 2011; Schall, 2013). These observations indicate that at precursor fixations, enhanced visual processing and saccade planning go hand in hand. This may involve decision making about the further scanning strategy, or, in other words, about laying down a prospective scanpath based on prior knowledge and experience. By marking locations for later refixations to return to, precursor fixations may set landmarks for subsequent visual exploration.

The current eye movement results revealed that saccade size is largest in precursor fixations, which tend to occur at the beginning of visual exploration, and fixation duration is longest in refixations, i.e., towards the end of exploration. This is in line with the well-known observation that early free viewing behavior after the appearance of a visual scene is characterized by large saccades and short fixations, which indicate exploration of the spatial organization of the display. Later behavior is characterized by small saccades and long fixations, which indicate scrutiny of local details (Unema et al., 2005; Pannasch et al., 2008).

The key step in our analysis was matching eye movement characteristics between the fixation categories. The matching eliminates possible confounding effects of eye movement characteristics on EEG (Nikolaev et al., 2016). In the current study, in addition to eye movement characteristics (saccade size), we matched the within-trial fixation rank. Previous EEG-eye movement co-registration research showed that the fixation rank affects FRP amplitude: if a trial lasts several second (e.g., 5-10 s), the amplitude is higher for later fixations than earlier ones in a trial (Fischer et al., 2013; Kamienkowski et al., 2018; Nikolaev et al., 2018). Since fixation ranks in our study were matched between fixation categories, the effects of FRP amplitude and EEG power in the precursor fixations cannot be attributed to the position of a fixation in a trial.

In addition to comparing precursor fixations and ordinary fixations, our study also compared refixations and ordinary fixations (Fig. 3). FRP amplitude was higher for refixations than for ordinary fixations only in a short interval over posterior areas, corresponding to lambda activity. Lambda activity is indicative of early perception at fixation (Thickbroom et al., 1991; Kazai and Yagi, 1999; Dimigen et al., 2009). The association of this effect with lambda activity is further supported by the occurrence of a previously-observed, transient increase in inter-trail coherence at the typical lambda frequencies, right after the lambda peak (Nikolaev et al., 2016). Moreover, we recently found that the large-scale phase change after fixation onset is manifested as a traveling wave spreading from the posterior-inferior to anterior-superior

direction, which may reflect feedforward propagation of information at fixation (Giannini et al., 2018). Thus, the current findings indicate enhanced visual processing at refixations.

Similarly to FRP amplitude, EEG power is also higher at refixations than at ordinary fixations. This difference is observed in the delta frequency band (2-5 Hz) during almost the entire postsaccadic interval (note that the temporal resolution of wavelets at such frequencies is low, so the duration can only be coarsely estimated). Although this difference is also observed over the frontal areas as that between precursor and ordinary fixations, the distinct frequency of the differences suggests involvement of distinct brain processes in precursor fixations and refixations.

In general, refixation behavior does not seem to be uniform, i.e., refixations may serve for different functions. For example, there may be distinct types of refixations, ones for recovering lost information and ones for scrutinizing locations of interest marked earlier for later exploration. There may even be a third type, in which both functions are combined. Distinct refixation types were described in previous research (Li et al., 2010; Klein and Hilchey, 2011; Meghanathan et al., 2019). In our recent eye-tracking study we distinguished three types of refixations that were defined by size of the preceding saccade (Meghanathan et al., 2019). “Continued refixations” and “continued revisits” occur within a foveal boundary of the item region and preceded by small saccades. In contrast, “revisits” are refixations of the item region after leaving it at least one time; consequently they are preceded by large saccades. The three refixation types have distinct dynamical properties within a trial, and they are differently associated with the target or distractor identity of fixated items and with change detection accuracy depending on the load on working memory. In the current study, we removed continued refixations and continued revisits, which are preceded by small saccades and consequently may be used for visual scrutiny, and focused on revisits, which are preceded by large saccades and therefore can relate distant areas of the entire display. Future research should be able to classify revisits into ones for compensating memory deficiencies and ones setting landmarks for a following exploration.

In sum, in natural viewing behavior, the perceptual, encoding and top-down control processes are elevated at fixation locations that are revisited later. This finding indicates that these locations contain important task-relevant information in need of returning to later.

ACKNOWLEDGMENTS

The authors were supported by an Odysseus grant (G.0003.12) from the Flemish Organization for Science (FWO) to Cees van Leeuwen. We thank Nathalie Van Humbeeck and Johan Wagemans for permission to use the jointly collected data in the current analysis.

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Supplementary figure

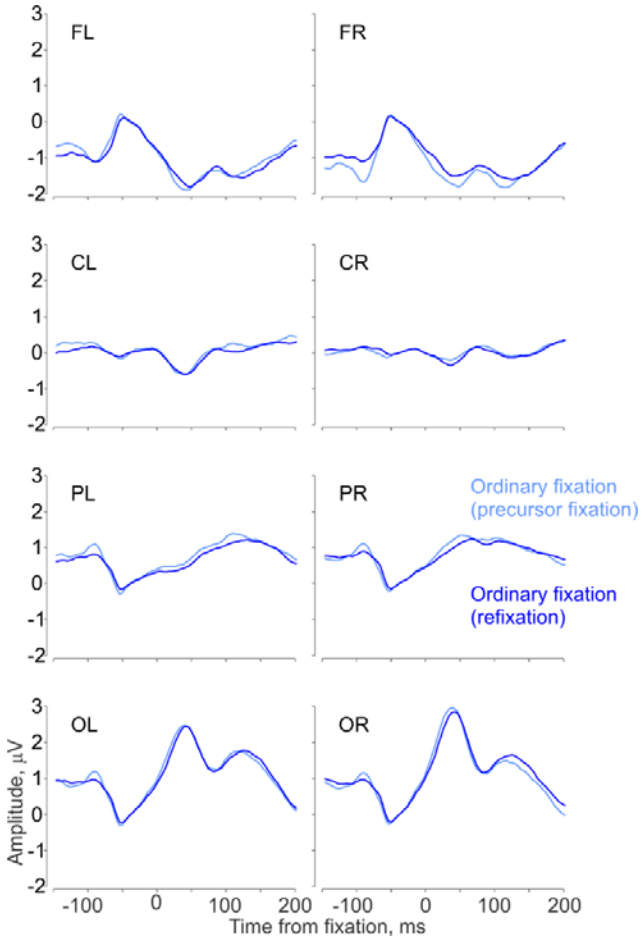

Fig. S1. The grand-averaged fixation-related potentials for the two Ordinary Fixation categories used for comparison with the Precursor Fixation and Refixation categories in the previous analyses. The potentials are baseline-corrected at 0-20 ms from the fixation onset.