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The bimodality of saccade duration during the exploration of visual scenes

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ABSTRACT
Eye movement parameters are consistently investigated, and the distribution of these parameters are well known. Whereas saccade duration has been studied along with saccade amplitude , the distribution of saccade duration has not yet been reported. We aim to investigate the distribution of saccade duration in several eye movement datasets from the literature and from our own data to confirm the common, but never reported, observation that the distribution of saccade duration is bimodal. We consistently observed the bimodality of saccade durations, not task- or stimuli-dependent. We created two groups of saccades based on the saccade duration distribution. Our results suggest that short duration saccades could be partly linked to bottom-up processes and long duration saccades to top-down processes. This study highlights the importance of reporting the distribution of eye movement data, in addition to means, which do not allow a correct and representative analysis in the case of bimodal distributions.

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In everyday life we move our eyes continuously and make a succession of saccades and fixations. These eye movements are crucial for many aspects of human behaviour like visual recognition, spatial orientation, and action control. In most studies, only a few eye movement parameters and the cognitive factors that influence them are analyzed. Several studies have reported main characteristics such as the position and duration of fixations (or the latency of saccades when the task allows access to it), and the amplitude of saccades. However, the duration of saccades, and more specifically the distribution of saccade duration, to our knowledge has never been reported nor discussed.

Saccades are stereotyped movements characterized mainly by amplitude, orientation, peak velocity and duration. The temporal profile of saccades is very standard: it shows a single progressive acceleration towards the peak velocity, followed by a single deceleration. In laboratory experiments, the peak velocity of saccades is generally between 200 and 600°/sec (Kauffmann et al., 2019). Average saccade duration is between 30 and 120 ms (van Beers, 2007). The most common results show that saccade amplitudes are usually below 15° with a majority of the amplitudes between 5 and 10° when recorded during scene exploration in laboratory conditions with the head fixed in place (Bahill et al., 1975; Ho-Phuoc et al., 2012). Saccade amplitudes follow a positively skewed, long-tailed distribution (Ho-Phuoc et al., 2012; Tatler et al., 2006). During scene exploration, saccades are mostly horizontal and to a lesser extent vertical (Moeller et al., 2004; Ossandón et al., 2010; Tatler & Vincent, 2008). However, even if the parameters of saccades are fairly stereotypical, there are some intra- and inter-individual variability (Bollen et al., 1993).

The saccade parameters (amplitude, duration and velocity) are linked in what is called the *main sequence* (Bahill et al., 1975; Murthy et al., 2007). The first association was defined between amplitude and duration by $D = 21 + 2.2A$, where D is the saccade duration and A the saccade amplitude (Carpenter, 1988). This linear relationship between saccade duration and saccade amplitude has been reaffirmed recently (Duchowski et al., 2017). It has also been shown that there is a positive correlation between amplitude and peak velocity and a negative correlation

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between duration and peak velocity (van Beers, 2007). Although the association between saccade amplitude and duration/peak velocity was initially described as linear, further studies suggest a nonlinear model (Dai et al., 2016; Reppert et al., 2015).

As far as we know, other studies that analyzed saccade durations have reported either the mean of saccade duration per experimental condition or saccade duration as a function of amplitude through the main sequence. No study has analyzed the duration of saccades and reported the distribution of saccade duration. However, it is common knowledge in the eye-movement research community that saccade duration shows a bimodal distribution. In a study from Nyström and Holmqvist (2010), a figure (Figure 8 of the paper) shows the distribution of saccade duration with two modes, but this is not further discussed. Similarly, we can observe the saccade duration distribution in Figure 10 of Duchowski et al. (2017) that could be bimodal, but this is neither discussed nor statistically tested.

Contrary to the distribution of saccade duration, the distribution of saccade latency has been extensively studied and reported as bimodal (Boch & Fischer, 1986; Cavegn & d'Ydewalle, 1996; Fischer & Weber, 1993; Weber & Fischer, 1994). Saccade latency is the time delay between the appearance of a target and the initiation of an orienting saccade to this target. This delay can only be measured in a controlled protocol in which the target of the saccade and its timing is known. This finding, first observed by Fischer and Boch (1983), has shown that saccadic latencies to singly appearing visual targets can yield a bimodal distribution in both humans and monkeys (Fischer & Ramsperger, 1984; Pare & Munoz, 1996; Rohrer & Sparks, 1993; Schiller & Haushofer, 2005; Schiller, Haushofer et al., 2004; Schiller, Slocum et al., 2004; Sommer, 1994). The first mode, which peaks at a latency of about 100 ms, has been termed express saccades; the second mode, which peaks around 160 ms, has been termed regular saccades. The frequency with which express saccades were generated has been shown to be greatly affected by the moment in time when the fixation spot was terminated relative to the onset of the target stimulus. If the fixation spot remained on the screen the entire time or was terminated right when the target appears, relatively few express saccades were generated. It has been suggested that termination of the fixation spot disengages inhibitory processes that assure fixation maintenance, thereby facilitating the generation of express-saccades (Carpenter, 2001; Fischer & Boch, 1983; Kingstone & Klein, 1993).

The first aim of this research was to report the distribution of saccade duration for a large number of eye movement data recorded under various experimental conditions and for various types of visual stimuli. We computed the distributions of saccade duration from several eye movement datasets to assess whether the bimodality has always existed. To ensure that the bimodality is genuine and not the product of artifacts, we tested different algorithms to extract saccade and fixation information from the data. We used several eye movement experiments recorded during different experimental protocols, for various types of stimuli (natural scene, noise, and artificial stimuli such as fractals) and different visual tasks (free exploration, visual search, and memorization). The nature of this study was exploratory, so we intentionally based part of the analysis on existing data in order to address replicability. We performed analyses on two different sets of data. In the first dataset (called Dataset 1, DS1), we reanalyzed existing datasets of eye movements; these eye movements were recorded by our lab and other research teams (Wilming et al., 2017). DS1 was created from data recorded on different groups of participants for different stimuli and tasks, leading to a between-subjects analysis. The second dataset (called Dataset 2, DS2) was recorded specifically for this research, with the same group of participants viewing different types of visual stimuli, for a within-subjects analysis. Under the hypothesis that the bimodality of the distribution of saccade duration is systematic, we should observe the phenomenon for all experimental conditions of DS1 and DS2. If the bimodality is linked to bottom-up factors (i.e., driven by the stimuli and related to the visual properties of the stimuli itself such as contrast or saliency), it might not be systematically observed for simple stimuli like gray background or noise. Conversely, if it is linked to top-down factors (i.e., to prior knowledge, wilful plans and current goals), we might primarily observe the bimodality when subjects are given a specific task.

The second aim was to study whether saccade bimodality can be related to known factors that affect visual exploration such as ambient and focal modes (Pannasch et al., 2008). Ambient and focal modes are two exploratory modes defined by the joint analysis of saccade amplitude and fixation duration (Frost & Pöppel, 1976; Unema et al., 2005; Velichkovsky et al., 2005). Ambient mode is present at the beginning of exploration, with shorter fixation durations and longer saccade amplitudes. Focal mode will progressively take over with longer fixation durations and shorter saccade amplitudes (Antes, 1974). Classification of ambient and focal modes can be performed based on saccade amplitude, with small amplitude saccades (4-5° in Unema et al., 2005 and Pannasch et al., 2008; 2–3° in Follet et al., 2011) attributed to focal mode and large amplitude saccades attributed to ambient mode. It was also demonstrated that focal mode was more bottom-up than ambient mode, and that focal-ambient dichotomy was not scene-dependent (Follet et al., 2011). Finally, we conducted analyses to further understand the nature of the two underlying processes by analyzing the properties of the two eye movement data subsets created from the bimodal saccade duration distributions. Each saccade was classified as either short duration or long duration, and then we analyzed the effects of saccade duration on eye movement context, orientation, time course, and saliency properties, which are known to play important roles during the exploration of visual stimuli.

Methods

In this study, we created two different datasets of eye movements: Dataset 1 (DS1) and Dataset 2 (DS2). DS1 was composed of eye movements recorded in several experiments (from our lab and other research teams). DS1 consisted of eye movements recorded with various viewing conditions: three visual tasks (free exploration, object search and memorization) and different types of stimuli (gray uniform backgrounds, complex natural scenes, noise and fractal images). The data contained in this set corresponds to different groups of participants. To run repeated measures ANOVA with a between-subject factor, we only extracted one experimental condition for each participant from already existing eye movement data. This was intentional due to the exploratory nature of the paper, in order to investigate the bimodality of saccade duration and assess its replicability across different conditions and participants. In DS2, we investigated the bimodality of saccade duration distributions for several types of visual stimuli which were viewed by the same participants. This led us to perform a repeated measures ANOVA with a single within-subject factor. The use of two separate datasets allowed us to explore the bimodality of saccade duration distributions for several eye movements recorded by our lab and other research teams, using different types of visual stimuli and different visual tasks. This allowed us to ensure robustness and replicability across conditions and participants. The utilization of different datasets also provided eye movements recorded for visual stimuli of various sizes, which ensured that the bimodality of saccade duration was not only due to stimuli size.

Tables 1 and 2 summarize information on the stimuli and participants for both datasets.

Dataset 1 (DS1)

We analyzed five experimental conditions, with different stimuli and different tasks. Examples of stimuli for each condition can be seen in Figure 1. The conditions were chosen with different task difficulty and stimulus complexity. Stimulus complexity was defined by the stimuli themselves and can be seen as a measure of visual complexity based on the quantity of task-relevant objects in the scene. Task difficulty referred to the task itself and how many cognitive processes needed to be involved to solve the task.

Table 1. Stimuli information for the two datasets DS1 and DS2 (number of stimuli, stimuli size in pixels, visual angles and recording setup).

		Number of stimuli	Stimuli size (pixel)	Visual angle (°)	Eye tracker	Sampling rate (Hz)
DS1	MemInCo	176	1024×768	30×24	Eyelink 1000	1000
	ObjSearch	240	1024×768	40×30	Eyelink 1000	1000
	FENS	60	1280×960	28×21	Eyelink II	500
	Fractal	64	1280×960	29×22	Eyelink II	500
	PN	64	1280×960	29×22	Eyelink II	500
DS2		10 for each of the 6 conditions	300×300	12×12	Eyelink 1000	1000

Table 2. Participant information for the two datasets DS1 and DS2.

		Number of participants	Number of trials per participant	Stimulus duration (ms)	Age (yo)	Gender (# F)
DS1	**MemInCo**	28	88	4000	21.7 (18–29)	11
	ObjSearch	39	60	4000	24.7 (20–36)	22
	FENS	22	60	6000	22.0 (19–28)	unknown
	Fractal	42	64	6000	23.1 (19–28)	unknown
	PN	48	64	6000	23.1 (19–28)	unknown
DS2		23	60	3000	24.4 (20 - 29)	10

- MemInCo: exploration of natural scenes in order to memorize the objects that are present. In this condition, half of the stimuli contained an object incongruent with the gist of the scenes (for example, a pan in a bathroom).
- ObjSearch: exploration of natural scenes in order to localize two easy-to-find objects
- FENS: free exploration of natural scenes
- Fractal: free exploration of fractal images
- PN: free exploration of pink noise images

Meminco

Data were recorded at the University of Colorado Boulder. Participants received monetary compensation for their participation. All participants were right-handed native English speakers and had normal or corrected-to-normal vision. Informed consent was obtained from each participant, and the study conformed to the Institutional Review Board guidelines. We recorded the eye-movements of 28 participants during the exploration of 88 different images which contained an object either congruent or incongruent with the gist of the scene (Figure 1). The pictures used in this experiment were taken in the personal places of colleagues, friends, and family in Boulder, Colorado, as well as in France. Each trial started with a white fixation cross presented for 1000 ms on a gray screen. This fixation cross was located at the centre of the screen. After 1000 ms, if the gaze had stabilized for 100 ms (gaze contingent display), the scene was displayed. If the participant did not gaze at the cross, the scene was still displayed after 5000 ms, but the trial was considered invalid and the recorded data were not analyzed. The scene was then presented for 4000 ms followed by a gray screen presented for 1000 ms. Every 11 trials, participants were presented with five recognition probes: one object was shown in each probe and subjects had to answer yes or no to the question "Have you seen this object?" Half of the objects came from images presented within the

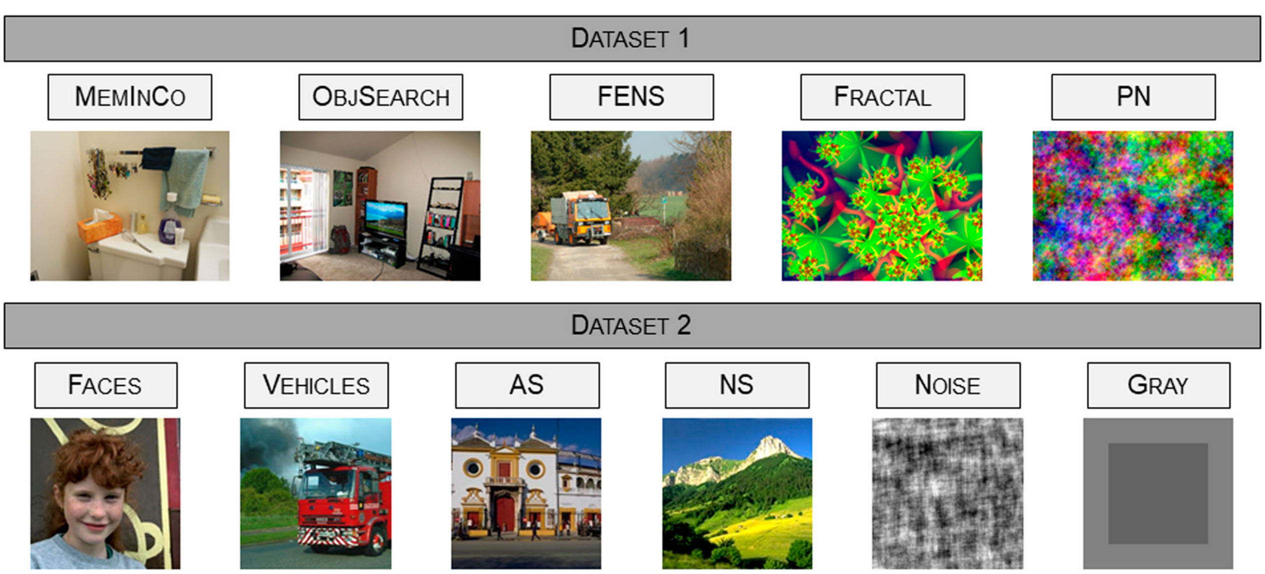

Figure 1. Examples of stimuli for the five different conditions from DS1 (MemInCo, ObjSearch, FENS, Fractal and PN) and the six different conditions from DS2 (Faces, Vehicles, artificial scenes (AS), natural scenes (NS), Noise and Gray).

last 11 trials and the other half were not previously observed.

Objsearch

The data were extracted from an unpublished condition reported in Devillez et al. (2015). Participants completed four sessions that had 60 randomly chosen scenes displayed for 4000 ms. Participants were asked to perform one specific task for each session (free-viewing, categorization, visual search task or spatial organization). For the purpose of the current analysis, we only analyzed data from the spatial organization task, where participants were asked to localize two objects. The eye-movements of 39 participants were recorded during the exploration of 60 colour images (over a total of 240) that represented both indoor and outdoor scenes (Figure 1). Each trial began with a screen that showed a question that asked whether an object was to the left or right of another object (e.g., "Is the backpack to the left or right of the television?" [Figure 1]). This screen was displayed until the participants pressed one of the mouse buttons (or for 5000 ms maximum if no response was registered). This was followed by a gray screen with a white central fixation cross that was displayed for 800–1200 ms. If the gaze had stabilized for 100 ms, a scene was displayed for 4000 ms (gaze contingent display). After this scene, the initial question was shown again with the two possible answers: left or right. Participants gave their answer by pressing the mouse button that corresponded to one of the two proposed responses. The response screen was displayed until the participant answered.

Data for the three following conditions came from Wilming et al. (2017) and are available online.[1] We chose three different conditions from three different studies reported in their paper.

FENS

The eye movements of 24 participants were recorded during free viewing of 120 images in two different categories: natural scenes (e.g., landscapes) and urban scenes (e.g., street views or cities). Images were presented for 6000 ms in a randomized order. A gap of 0, 300, 600 or 900 ms (a gray screen) was introduced between the fixation dot and the appearance of the image. Participants did not receive any instructions about the existence of a gap and were all right-handers. For the purpose of the current paper, we only analyzed eye movement data recorded for urban images (Figure 1).

Fractal

The eye movements of 43 participants were recorded during free viewing of 255 different images in four different categories (natural, urban, fractal, pink noise). Images were presented for 6000 ms in a randomized order. All right-handed participants explored either the original version of each image or a mirror-reversed version of it. For the purpose of the current analysis, we only analyzed eye movements recorded for fractal images (Figure 1) (note that the eye movements recorded for the original and mirror-reversed conditions were merged in this analysis).

PN

The eye movements of 48 participants were recorded during free-viewing of 255 different images in four different categories (Natural, Urban, Fractal, Pink noise). Images were presented for 6000 ms in a randomized order and participants were instructed to study the images carefully. For the current paper, we only analyzed the eye movements recorded for pink noise images because other categories were already analyzed in other conditions in this paper (Figure 1).

Dataset 2 (DS2)

We recorded the eye movements of 23 participants, students of the University of Grenoble Alpes, France, during the free-viewing of various images, which included vehicles, natural scenes (NS; images with landscapes such as mountains, rivers, beaches), artificial scenes (AS; images containing buildings, streets etc.), faces, noise and gray background (mean gray level of 50 cd/m^2) (Figure 1). In order to maintain frequency properties of the natural scenes, noise stimuli were created by adding a phase spectrum of white noise to the average amplitude spectrum created from the image (Torralba & Oliva, 2003; Wichmann et al., 2006). Images were 300 × 300 pixels and were pasted onto a background of 1024 × 768 pixels set to a mean gray level (68 cd/m^2). Each trial started with a central white fixation cross presented for 1000 ms on a mean gray value adjusted screen. After 1000 ms, if the gaze had stabilized for 100 ms (gaze contingent display), the scene was displayed for 3000 ms. If the participant did not gaze at the cross, the scene was still displayed after 5000 ms, but the trial was considered invalid and the recorded data were not analyzed. Participants performed a total of 60 trials, 10 trials for each stimulus category. Finally, at the end of each trial, a mean gray screen appeared for 1000 ms. Categories were chosen with different stimulus specificities. We defined specificity as the amount of common features between different stimuli from the same category. For example, faces are very specific stimuli since all faces have the same features (eyes, nose, and mouth) and are known to elicit particular eye movement patterns over the eyes and the mouth (Vatikiotis-Bateson et al., 1998).

Analysis and results

All of the conditions used the Eyelink system from SR-research (Eyelink 1000 and Eyelink II, see Table 1). Therefore, events were automatically detected using the SR-research default parameters (cognitive configuration); saccades were defined as events with an acceleration threshold of 8000° per sec^2, a velocity threshold of 30° per sec, and a deflection threshold of 0.1°. Fixations were defined as time periods without saccades.

To ensure the results reported in the paper that concern the bimodality of the distributions of saccade duration are not only due to the saccade detection algorithm used, we tested three other algorithms on the datasets for which raw data were available: two conditions from DS1 (MemInCo and ObjSearch) and all conditions from DS2 (for DS2, we gathered all conditions and computed the distributions of saccade duration). Results are presented in the Appendix: Eye movement detection algorithms. The first algorithm is the R package "saccades" that uses the velocity-based algorithm for saccade detection (Engbert & Kliegl, 2003). The second algorithm is the adaptive algorithm for fixation, saccade, and glissade detection (Nyström & Holmqvist, 2010). This algorithm is also a velocity-based algorithm endowed with a noise-dependent velocity threshold which allows for the identification of glissades as a separate class of eye movements. A glissade is a wobbling movement at the end of a saccade and can either be a rapid (Kapoula et al., 1986) or a slower postsaccadic movement (Weber & Daroff, 1972). The third algorithm is the modified DBSCAN algorithm (Li et al., 2016). This algorithm is designed to identify fixations in eye-tracking data, combining advantages from dispersion-based algorithms (such as resilience to noise and intuitive fixational structure) and velocity-based algorithms (such as the ability to deal appropriately with smooth pursuit movements). The distributions of saccade duration, for the saccades detected either with the Eyelink software or with the three other tested algorithms are in Figure A1. The bimodality of the saccade duration distributions was observed both for the different experimental conditions and for whatever algorithm was used to detect saccades.

Fixations that occurred around eye blinks or outside the display were discarded. Fixations and saccades were preprocessed to keep only fixations with a duration higher than 50 ms but lower than 1500 ms, and saccades with a duration lower than 200 ms. This preprocessing method has been performed in other eye movement papers (Devillez et al., 2017; Tatler & Vincent, 2008).

In the following analysis, we first investigated saccade duration distributions; whereby we provided a theoretical distribution based on the main sequence and reported the actual saccade duration distributions. We also looked at individual distributions of saccade duration. Different measures relative to short and long duration saccades were computed to further understand the nature of the bimodality of saccade durations. We reported fixation duration and saccade amplitude, duration of previous and subsequent eye movements, as well as orientation and probability of occurrence of short and long duration saccades. Finally, we quantified the similarity between eye movements and saliency maps to investigate whether saliency can be predicted by saccade duration.

To quantify the bimodality of saccade duration, we based our analysis on Hartigan's dip statistic (HDS) (Hartigan & Hartigan, 1985), and the bimodality coefficient (BC), (Sas Inst., 1990). The HDS measure is meant to test the null hypothesis of unimodality against the alternative hypothesis of multimodality, although it has also been widely utilized in the bimodal context (Freeman & Dale, 2013; Knapp, 2007). The *dip* value is the maximum distance between the empirical distribution and the best fitting unimodal distribution. Dip test statistics increase when the distribution differs from a unimodal distribution. HDS *p* values less than .05 indicate significant bimodality, and values between .05 and .10 suggest bimodality with marginal significance (Freeman & Dale, 2013). BC is a coefficient to assess multimodality using information from the third and fourth statistical moments of the data (Sas Inst., 1990). If $BC \leq 0.555$ (BC value for uniform distribution), the data are considered to follow a unimodal distribution. In this paper, we decided to implement a method proposed in a recent study that combines the BC and the HDS (Kang & Noh, 2019). For each condition, we reported the BC value and its associated significance level (α) for the HDS with BC (or *HDSw/BC*), as well as the *dip* and *p* values that correspond to Hartigan's dip statistic. Distributions were considered bimodal if the *p* value was smaller than the significance level (α).

Data were analyzed in a mixed-design analysis of variance (ANOVA) with condition as a between-subject factor for DS1 (MemInCo, ObjSearch, FENS, Fractal and PN) or as a within-subject factor for DS2 (Faces, Vehicles, AS, NS, Noise and Gray). When applicable, saccade duration (short and long) and/or orientation (horizontal and vertical) were used as within-subject factors. Multiple comparisons were assessed with Bonferroni post-hoc tests (reported with p_{Bonf}). For clarity, only significant results are reported. We do not report nor discuss main effects of condition. Because we are mainly interested in the differences between short and long duration saccades, we only report effects related to duration and orientation, when applicable.

Distributions

"Theoretical" saccade duration distribution

Under the assumption that saccade duration is linked to saccade amplitude, through the "main sequence" we generated a "theoretical" distribution of saccade durations for a range of saccade amplitudes classically observed in eye tracking studies and observed in our two datasets. The distribution of saccade amplitude is known to be positively skewed with a long-tailed distribution and can be modelled by a gamma distribution (Ho-Phuoc et al., 2012; Tatler et al., 2006). We generated data that corresponded to saccade amplitudes from a gamma distribution with a shape parameter of 1.41 and a scale parameter of 4.87 (Ho-Phuoc et al., 2010; Ho-Phuoc et al., 2012) (Figure 2A). The average saccade amplitude for this distribution was 6.90°. In parallel, we plotted saccade duration as a function of saccade amplitude for MemInCo (Figure 2B); similar results were obtained for the other conditions of DS1[2] and for all conditions of DS2 (Figure 2C). The literature reported a linear relationship between saccade duration and saccade amplitude (Carpenter, 1988; Duchowski et al., 2017). However, visual inspection of data showed that the relationship between saccade amplitude and duration could also be modelled by an exponential function (Figure 2B,C). To model the main sequence we used either a linear association defined by $D = 13.97 + 3.66A$ or an exponential association defined by $D = 10^{1.16} \times A^{0.55}$, where D is the saccade duration and A the saccade amplitude. The exponential association was obtained by fitting a linear function to the log transformed data. Finally, we used the two different functions obtained from the main sequence (from Figure 2B) to generate

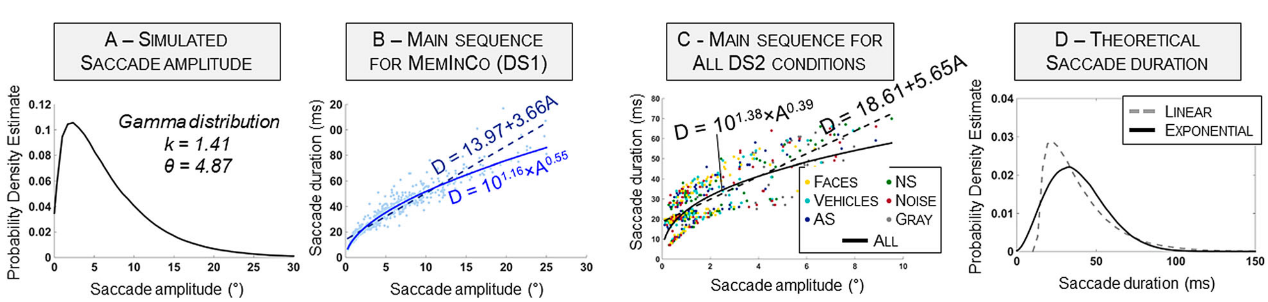

Figure 2. (A) Probability density estimates of saccade amplitude generated from a gamma law. (B) Main sequence from one participant in the MemInCo condition (for a linear and an exponential model of the main sequence). (C) Main sequences for one participant in each condition of DS2 (for a linear and an exponential model of the main sequence). (D) Theoritical saccade duration distributions computed using the main sequence and the saccade amplitude range from MemInCo.

theoretical distributions of saccade duration (Figure 2D) from the simulated saccade amplitude values obtained previously (shown in Figure 2A). As expected, since these two functions were monotonically increasing functions, the theoretical distributions were unimodal (both non-significant when running *HDSw/BC*).

Observed saccade duration distribution

The distributions of saccade duration showed a bimodality for both datasets (Figure 3B). Bimodality statistics are reported in Table 3 and confirm the bimodality for all conditions (all $p < .001$). Mode and local minimum are also reported. For all conditions, the two modes and the local minimum are very similar. The local minimum L_m is used in the following analysis to create two groups of saccades: short ($\leq L_m$) and long ($>L_m$) saccades, and to compare different parameters between the two groups of saccades. We also reported the distributions of saccade amplitude (Figure 3A). For DS1, distributions of saccade amplitude showed a single mode at 2.62° for MemInCo, 1.26° for ObjSearch, 1.91° for FENS, 0.90° for Fractal, 0.75° for PN and 1.28° overall for DS2 (1.17° for Faces, 1.18° for Vehicles, 1.44° for AS, 1.68° for NS, 1.79° for Noise and 1.79° for Gray). We observed a positive correlation between saccade duration and saccade amplitude, even though the distributions of saccade duration were bimodal (Figure 2B,C).

Because saccade duration and saccade amplitude are closely linked by the main sequence (Figure 2B, C), we were interested in the influence of saccade amplitude on saccade duration. To further investigate, we plotted saccade duration distributions for different saccade amplitudes. This is shown in Figure 4 for one condition from DS1 (ObjSearch) and collapsed over the six conditions from DS2.[3] The *HDSw/BC* statistics are reported directly in the figures. We observed that distributions were bimodal for all ranges of saccade amplitude for all conditions. When we considered only small amplitude saccades, we observed *de facto* more short duration saccades, and the bimodality was not obvious to see on the plots but was still present. When we added more large amplitude saccades, the bimodality became more visible on the plots. For DS2, even if the saccade duration distributions do not look bimodal the bimodality is statistically significant.

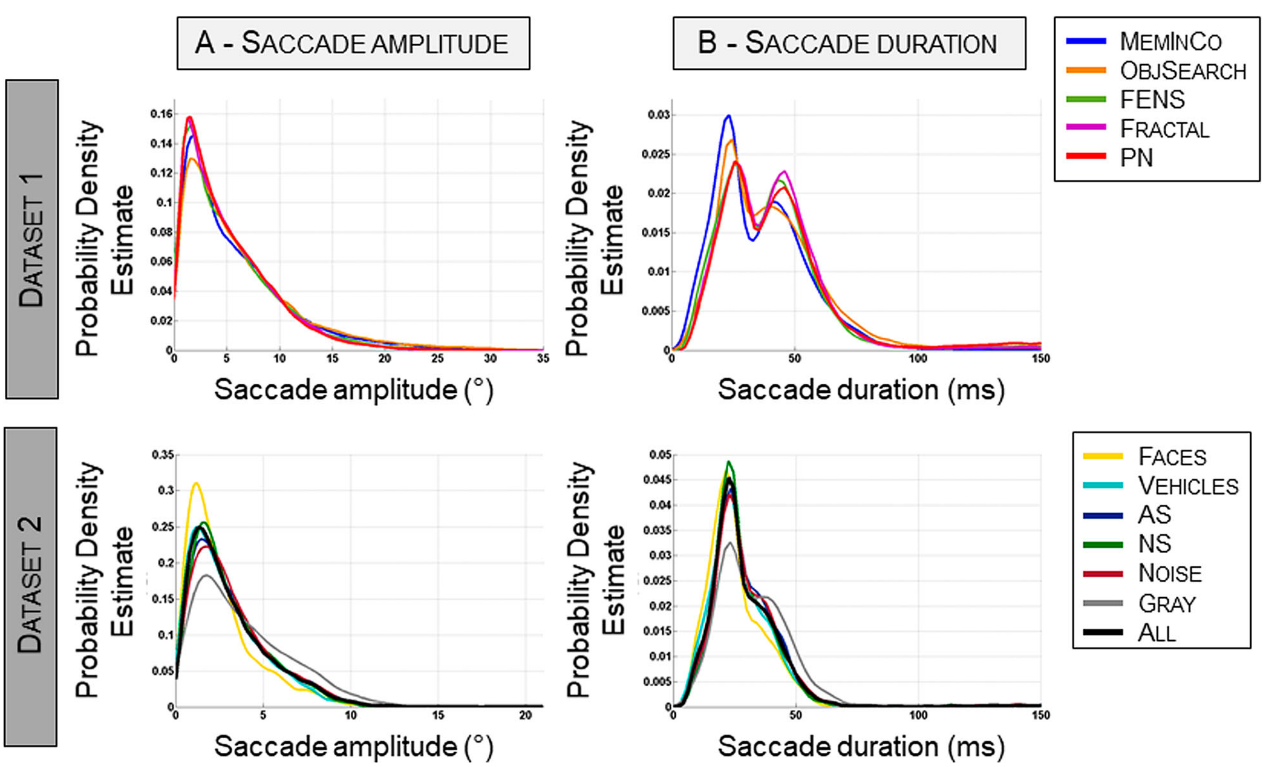

Figure 3. (A) Probability density estimates of saccade amplitudes and (B) saccade durations for the different conditions in DS1 (five conditions) and DS2 (six conditions seperately and all the saccades gathered across conditions).

Table 3. Modes (in ms), local minimum L_m (in ms) and *HDSw/BC* statistics (BC, *dip*, *p*-value and α) of the distributions of saccade duration computed for the different conditions of the two datasets.

		Mode 1	L_m	Mode 2	BC	*dip*	*p*	α
DS1	MemInCo	23	32	43	0.41	0.020	<.001	0.09
	ObjSearch	24	32	39	0.52	0.017	<.001	0.12
	FENS	26	35	42	0.70	0.051	<.001	0.18
	Fractal	26	36	46	0.60	0.053	<.001	0.15
	PN	26	35	46	0.74	0.051	<.001	0.20
DS2	Faces	22	32	34	0.71	0.025	<.001	0.28
	Vehicles	22	32	38	0.72	0.025	<.001	0.28
	AS	22	31	37	0.72	0.024	<.001	0.28
	NS	23	32	36	0.77	0.028	<.001	0.29
	Noise	23	31	36	0.77	0.024	<.001	0.29
	Gray	23	32	38	0.73	0.023	<.001	0.28
	ALL	23	32	37	0.74	0.025	<.001	0.28

Saccade duration for individual participants

In this section, we were interested in the distribution of saccade duration for each participant. This exploratory analysis was performed in order to confirm that the bimodality of saccade duration was not only due to some participants and to discern whether it is a systematic phenomenon observed for all eye movement data. Figures 5 and 6 show the distributions for individual participants (see more individual subject distributions in Figures A2–A8). We ran the *HDSw/BC* on the average distribution for the different conditions as well as on each individual participant. Overall, we observed a significant bimodality for all conditions in both datasets. In DS1, for MemInCo, we observed a unimodal distribution for only one participant; for ObjSearch, we observed a unimodal distribution for five participants and for FENS, Fractal and PN, we observed a significant bimodality for all participants. When each participant was analyzed over the six conditions in DS2, we observed a bimodal distribution for all participants, although unimodal distributions were observed for some individual subjects in individual conditions.

Eye movement properties for short vs. long duration saccades

In the second part of the analysis, we describe the properties and context of eye movements for two saccade groups (based on their durations). Eye movement context refers to the fixation and saccade properties of eye movements before (previous eye movements) and after (subsequent eye movements) the saccade of interest. Eye movement context is important as it is known that statistical dependencies exist between successive eye movements (Tatler & Vincent, 2008) and that exploration modes can be defined by fixation and saccade modes (Pannasch et al., 2008; Unema et al., 2005). This analysis aimed to give more information about systematic tendencies relative to short and long duration saccades as well as to control for any confounding factors that would potentially explain the bimodality of saccade duration distribution. The first group is called Short and is composed of saccades that have a duration shorter than the local minimum L_m (Table 3). The second group is called Long and is composed of saccades that have a duration longer than L_m. The classification of Short and Long duration saccades was done for each dataset of eye movements (and the same L_m value was used for all participants). For each group, we analyzed the proportion of saccades (number of saccades in each group) as well as mean fixation duration, mean saccade amplitude and mean saccade duration for previous and subsequent eye movements. Details with numbers for each condition are presented in Table A1 and results are summarized in Table 4. We observed fewer short duration saccades than long duration saccades for DS1 and the opposite was observed for DS2. Overall, we observed that the short duration saccades were preceded by longer fixations and saccades (longer duration and larger amplitude) and were followed by longer saccades (longer duration and larger amplitude) than the long duration saccades. We observed more significant difference in DS1 compared to DS2. This can be explained by the different design between the two datasets, with different subjects in DS1 and the same subjects in DS2.

Orientation of short vs. long duration saccades

In this section, we computed the orientation of short and long duration saccades (Figure 7). The distributions of saccade orientations were similar for the

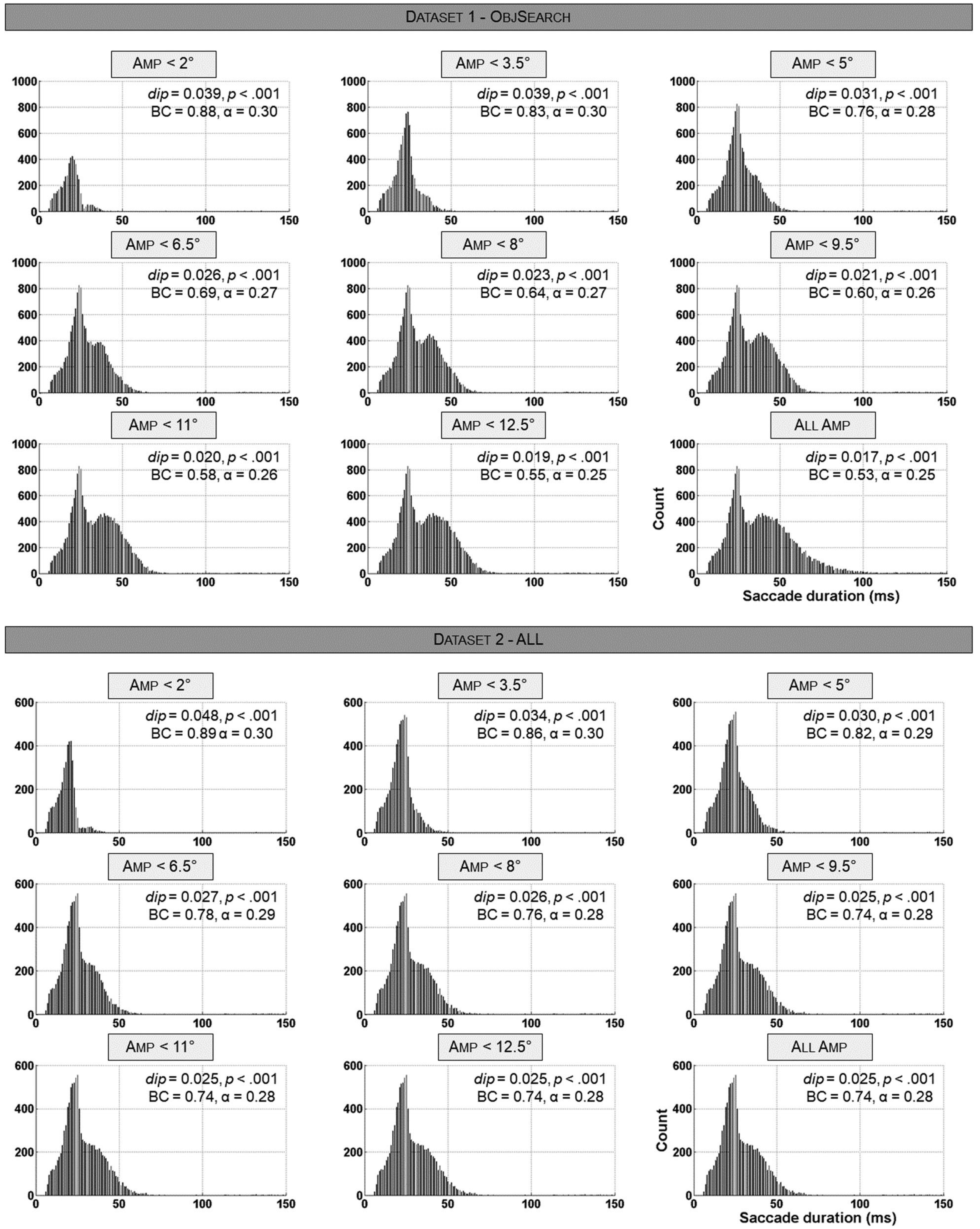

Figure 4. Distributions of saccade duration for different saccade amplitude ranges (<2°, <3.5°, <5°, <6.5°, <8°, <9.5°, <11°, <12.5° and all amplitudes) for the condition ObjSearch from DS1 and for all conditions collapsed from DS2. *HDSw/BC* statistics are reported.

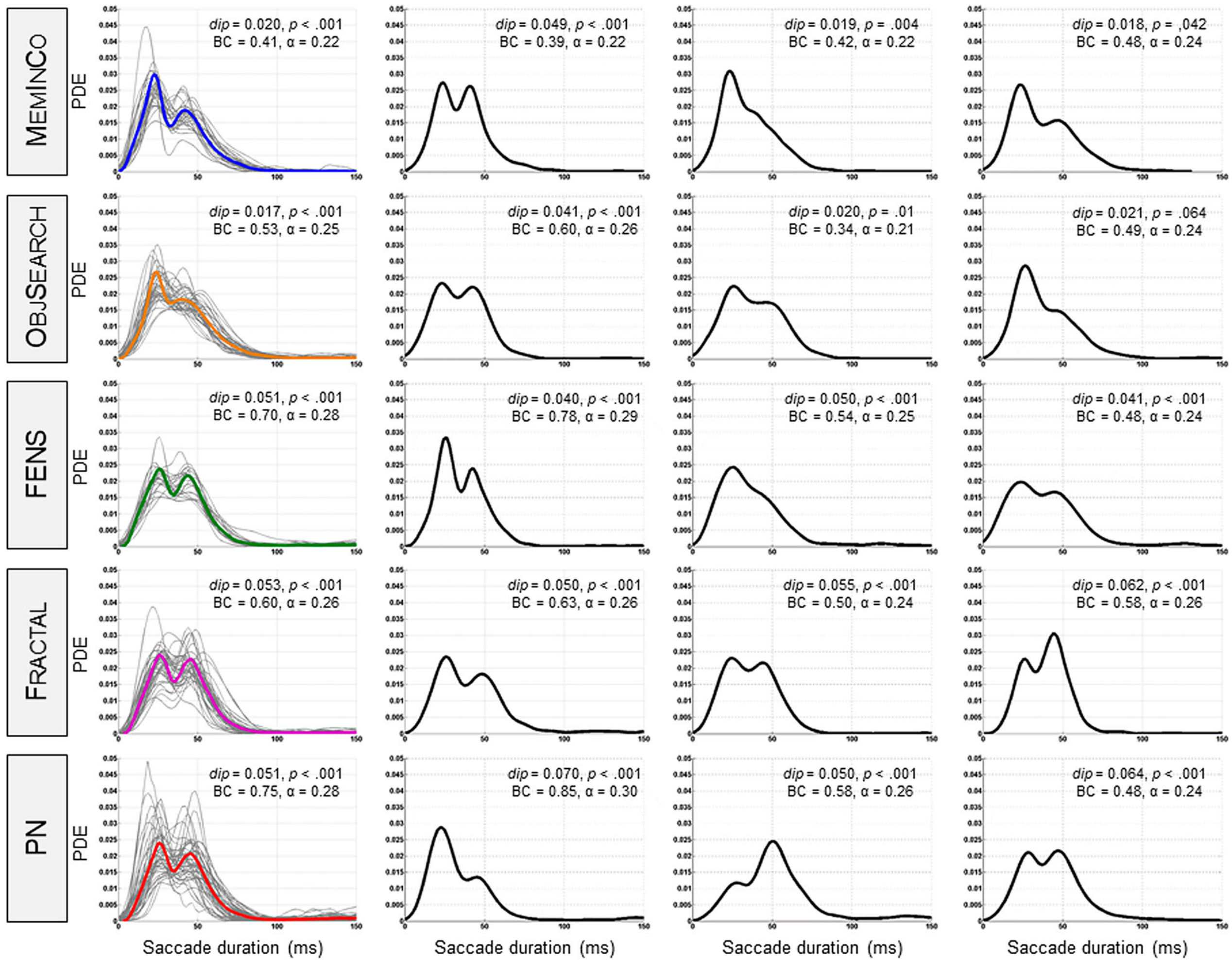

Figure 5. Left. Probability density estimates (PDE) of saccade durations for each condition of DS1. Each thick coloured line is the mean distribution and thin gray lines are individual participants. **Right**. Examples of the probability density estimates for three different participants for each condition. The probability density estimates for each individual participant are presented in the appendix section (Figure A2 for MemInCo, Figure A3 for ObjSearch, Figure A4 for FENS, Figure A5 for Fractal and Figure A6 for PN). *HDSw/BC* statistics are reported.

different conditions as well as for short and long duration saccades. We further analyzed these observations by comparing the mean number of vertical and horizontal saccades. Hence, vertical (all saccades with an orientation between 45° and 135° or between 225° and 315°) and horizontal (all saccades with an orientation between 0 and 45° or between 135° and 225° or between 315° and 360°) were counted, and then normalized by exploration time. For DS1, the significant effect of orientation, $F(1,174) = 1155.50$, $p < .001$, $\eta_p^2 = 0.87$, was qualified by a significant condition × orientation interaction, $F(4,174) = 36.76$, $p < .001$, $\eta_p^2 = 0.46$, a significant orientation × duration interaction, $F(1,174) = 131.54$, $p < .001$, $\eta_p^2 = 0.43$, and a condition × duration × orientation interaction, $F(4,174) = 7.75$, $p < .001$, $\eta_p^2 = 0.15$. It showed more horizontal saccades compared to vertical saccades for the five conditions (all $p_{Bonf} < .001$) and for both short and long duration saccades (all $p_{Bonf} < .001$). We also observed that the horizontal > vertical difference was larger for long than for short duration saccades. For DS2, the significant effect of orientation, $F(1,21) = 22.20$, $p < .001$, $\eta_p^2 = 0.51$, showed more horizontal saccades compared to vertical saccades. This was true for all conditions except for Faces and Noise, as revealed by the significant condition × orientation interaction, $F(5,105) = 5.36$, $p < .001$, $\eta_p^2 = 0.20$ ($p_{Bonf} < .001$). More horizontal than vertical movements were only observed for short duration saccades as revealed by the significant duration × orientation interaction, $F(1,21) = 7.79$, $p < .05$, $\eta_p^2 = 0.27$ ($p_{Bonf} < .001$).

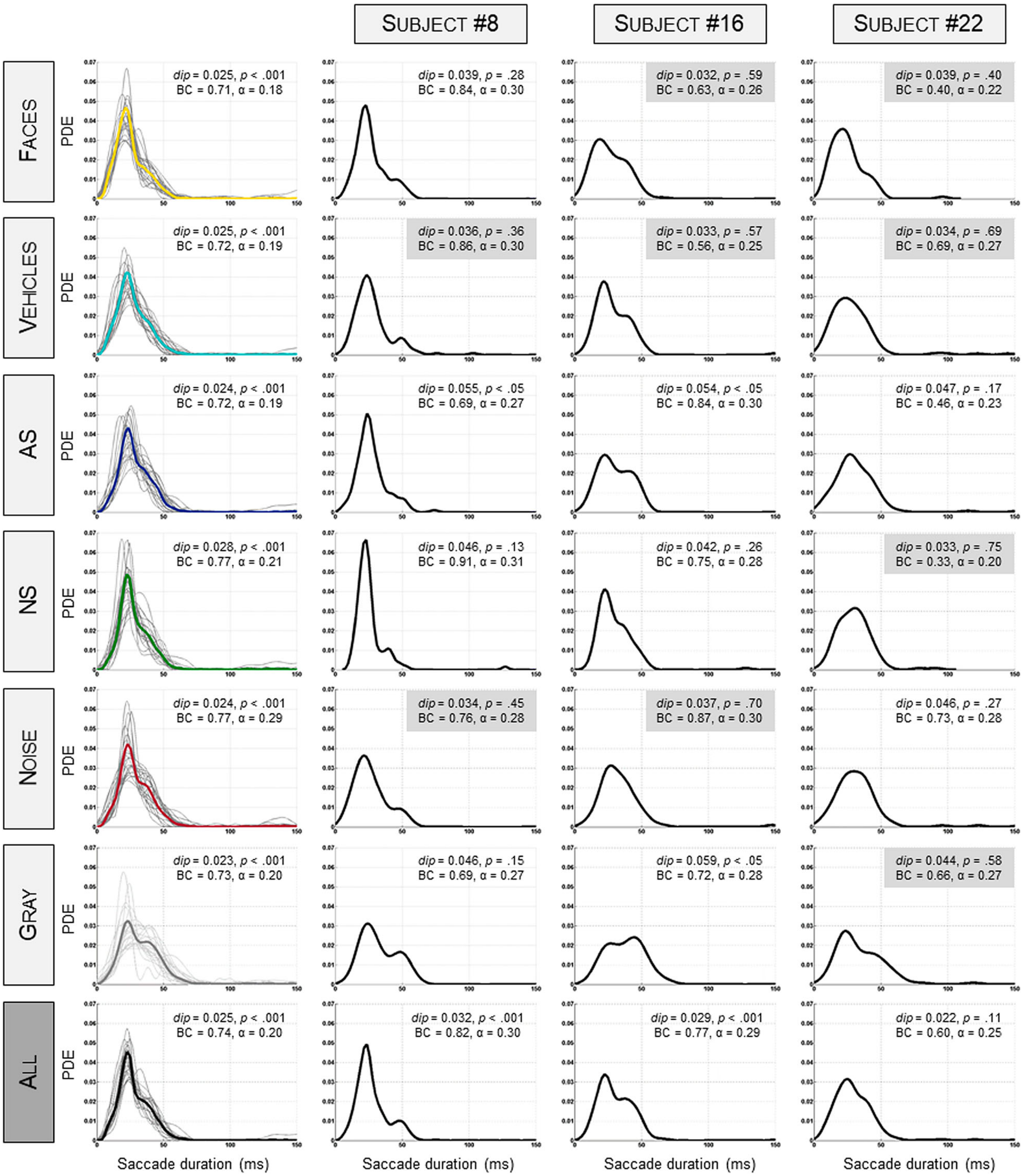

Figure 6. Left. Probability density estimates (PDE) of saccade durations for each condition of DS2. Each thick coloured line is the mean distribution and thin gray lines are individual participants. **Right**. Examples of the probability density estimates for three participants for each condition. The probability density estimates for each individual participant are presented in the appendix section (Figures A7 and A8). *HDSw/BC* statistics are reported.

Time course of short vs. long duration saccades

In this section, we are interested in the time course of short and long duration saccades. To address this, the probabilities of occurrence for short and long duration saccades were computed as a function of time. For each bin of 80 ms, we counted the number of saccades that have a duration included in the bin. Two probability density functions were

Table 4. Summary of the results that compare Short (S) and Long (L) duration saccade groups, for the five conditions of DS1 (PN, Fractal, FENS, ObjSearch and MemInCo) and the six conditions of DS2 (Faces, Vehicles, AS, NS, Noise and Gray). Red and blue signs denote signifcant difference between Short and Long duration saccades, *ns* stands for non significant.

			Duration	Condition × duration					
		Saccade duration	S L	S L	S L	S L	S L	S L	
Dataset 1				MemInCo	ObjSearch	FENS	Fractal	PN	
Proportion			<			*ns*			
Previous eye movements	Fixation duration		>	`*ns*	>	*ns*	>	*ns*	
	Saccade	Amplitude	>	>	<	>	>	*ns*	
		Duration	>	*ns*	*ns*	>	<	>	
Subsequent eye movements	Fixation duration		*ns*	<	>	*ns*	*ns*	<	
	Saccade	Amplitude	>	>	<	>	>	*ns*	
		Duration	>	*ns*					
Dataset 2				Faces	Veh.	AS	NS	Noise	Gray
Proportion			>	>	>	>	>	>	>
Previous eye movements	Fixation duration		*ns*			*ns*			
	Saccade	Amplitude	*ns*	*ns*	*ns*	*ns*	<	*ns*	<
		Duration	*ns*	*ns*					
Subsequent eye movements	Fixation duration		*ns*	*ns*	*ns*	*ns*	<	<	*ns*
	Saccade	Amplitude	*ns*	<	*ns*	*ns*	>	*ns*	*ns*
		Duration	>			*ns*			

obtained, one for short duration and one for long duration saccades. Figure 8 shows the probability density functions (pdf) for the short and long duration saccades in relation to viewing time. In order to detect when we observed more short duration saccades than long duration saccades or vice-versa, we used k-means, a method for finding clusters which aims to partition *n* observations into *k* clusters where each observation belongs to the cluster with the nearest mean.

We identified three time intervals for each condition that reflect periods of time when we observed (1) more long duration saccades than short (in red on Figure 8), (2) more short duration saccades than long (in blue on Figure 8), and (3) the same amount of short and long duration saccades (in white on Figure 8). For DS1, we observed that the probability of having short and long duration saccades was comparable across the exploration timeline for three conditions, but not for ObjSearch and Fractal. For ObjSearch (and to a lesser extent Fractal), we observed more long duration saccades at the beginning of the exploration and more short duration saccades at the end of the exploration. For the other three conditions, we mainly observed that the three possibilities interleaved during the whole exploration. For DS2, we observed that the probability of having short and long duration saccades was similar for all conditions. We observed more short duration saccades at the beginning of the exploration (between 240 and 590 ms on average) and more long duration saccades at the end of the exploration.

Saliency predicted by short vs. long duration saccades

To quantify the degree of similarity between predicted saliency maps and experimental fixations, a ROC (Receiver Operating Characteristic) analysis was conducted (Fawcett, 2006; Follet et al., 2011; Le Meur & Chevet, 2010). One computational model was chosen from the most common types used to compute saliency maps: the Multi-scale rarity-based saliency detection model (RARE2012) (Riche et al., 2013). This model was used with default parameters.[4] Additionally, a random model was also used; in this case, saliency maps were created that randomly attributed a saliency value to each pixel of the image. The random model was used to ensure that the fixation locations were not purely random. We analyzed both the previous and subsequent fixations, relative to short and long duration saccades, in order to see whether previous visual information can influence saccade durations or whether it is predictive of what will come next. The saliency maps obtained were converted into binary maps and thresholded to keep 20% of the most fixated areas of the images. Fixations following or preceding short duration saccades or long duration saccades were then labelled as fixated (or salient) or non-fixated (or non-salient). The ROC analysis provided a curve that plotted the false alarm rate (labelling a non-fixated location as fixated) as a function of the hit rate (labelling fixated locations as fixated). A perfect similarity between two curves would give an Area Under the Curve (AUC) equal to 1. An AUC of 0.5

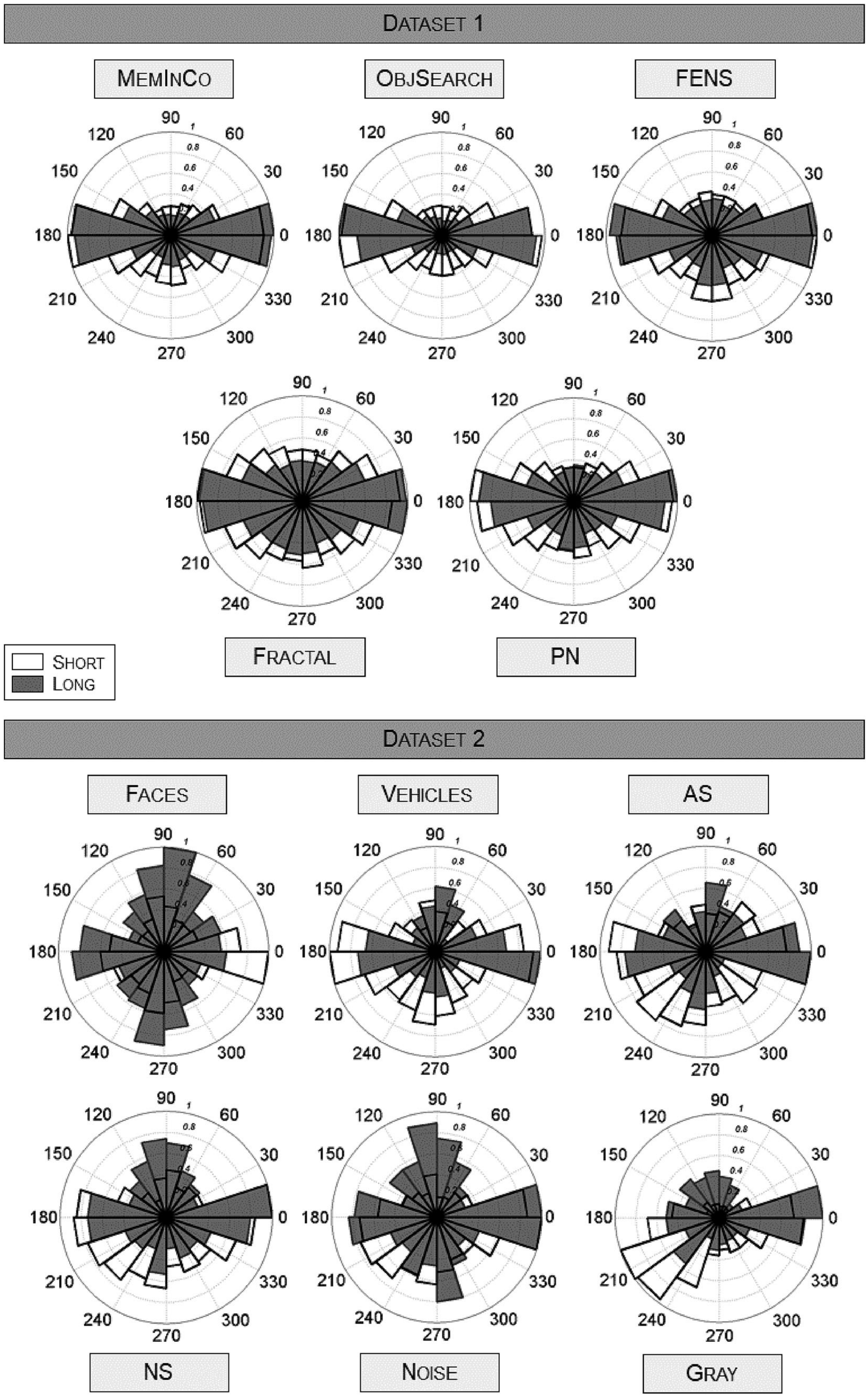

Figure 7. Orientation of saccades for short and long duration saccade groups for the five conditions of DS1 (MemInCo, ObjSearch, FENS, Fractal and PN) and the six conditions of DS2 (Faces, Vehicles, AS, NS, Noise and Gray).

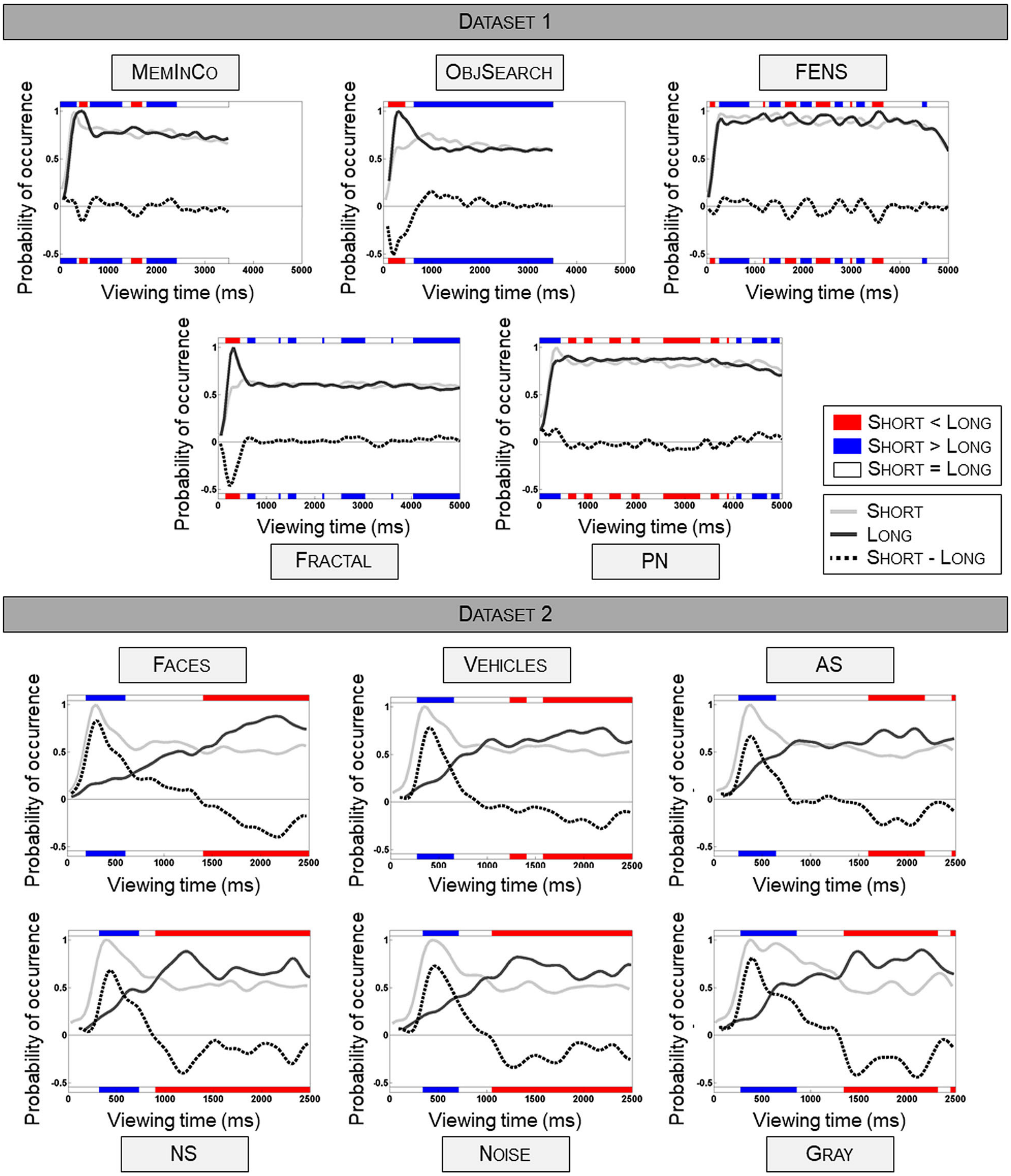

Figure 8. Probability of occurrence for short and long duration saccades according to viewing time for the five conditions of DS1 (MemInCo, ObjSearch, FENS, Fractal and PN) and the six conditions of DS2 (Faces, Vehicles, AS, NS, Noise and Gray). The probability obtained for each condition was rescaled between 0 and 1 to be able to compare between conditions. Red lines represent the time when more long duration saccades were observed, blue lines when more short duration saccades were observed, and white lines when the same proportion of short and long duration saccades were observed.

suggests that the similarity is at the chance level. No differences were observed between short and long duration saccades for the random model, for both the preceding and the following analyses. Note that the Gray condition of DS2 was not analyzed in this section, since saliency maps cannot be computed for gray background images. However, the data were tested on the random model. Results showed an AUC of 0.50 for Short and 0.49 for Long without a significant difference between groups (this data is not presented here).

Figure 9 shows the ROC analysis results for all conditions of DS1 and DS2 and the two models (RARE and random). The random model showed an AUC at chance level for all conditions. Since we were not interested in comparing models, it was not included in the ANOVAs. In DS1, for fixations both preceding and following the current saccade, we observed a significant main effect of duration (preceding: $F(1,588) = 59.25$, $p < .001$, $\eta_p^2 = 0.09$; following: $F(1,588) = 157.14$, $p < .00\ 1$, $\eta_p^2 = 0.21$), which showed that fixations preceding or following short duration saccades were better predicted by the saliency model than fixations preceding or following long duration saccades. The significant duration × condition interaction revealed that the effect varied across conditions (preceding: $F(4,588) = 3.79$, $p < .01$, $\eta_p^2 = 0.02$; following: $F(4,588) = 10.62$, $p < .001$, $\eta_p^2 = 0.07$, with $p_{Bonf} < .05$ except for FENS, Fractal and PN in the analysis of preceding fixations, and for FENS and Fractal in the analysis of following fixations where p_{Bonf} were not significant). In DS2, for both fixations preceding and following the current saccade, we observed a significant main effect of duration (preceding: $F(1,75) = 18.58$, $p < .001$, $\eta_p^2 = 0.19$; following: $F(1,75) = 54.27$, $p < .001$, $\eta_p^2 = 0.38$), which revealed that fixations preceding or following short duration saccades were better predicted by saliency models than the ones preceding or following long duration saccades.

General discussion

In this paper, we aimed to investigate the properties of saccade duration and the bimodality of its distribution during visual exploration. We chose different conditions (five in the first dataset and six in the second) with different tasks (such as memorization or visual search) and different stimuli (such as gray background, noise, faces or natural scenes) to answer two questions: (1) is the bimodality of the distribution of saccade duration a systematic phenomenon, and (2) is the bimodality of the distribution of saccade duration linked to any exploration strategies?

A systematic phenomenon, not scene- or task-dependent

A primary result of this study is the observation of a bimodality in saccade duration distributions for all the conditions studied, even though a hypothesis based on the saccade amplitude distribution and the main sequence would have predicted a unimodal distribution. This bimodality was observed for a large majority of subjects, which suggests a systematic phenomenon, not an artefact linked to subgroups of participants displaying only short– or long–duration saccades and not scene- or task-dependent. Aside from different participants and fewer trials in the experiment that was used for the second dataset, the biggest difference between the data used in DS1 and DS2 was the size of the stimuli. Even though the screen was around the same size for the data used in the first dataset, the stimuli themselves were smaller (visual angle of 12 × 12 compared to visual angles of 29 × 22, 40 × 30 and 30 × 24 for the different conditions of DS1) and only fixations within the stimuli were taken into account. This shows that the bimodality of saccade duration is not an artefact of the experimental set-up, which is also confirmed by the distributions of saccade durations obtained from different datasets recorded in different labs with different protocols. By studying the properties of the two groups of saccades that were created based on saccade duration (short and long duration), we observed different patterns between conditions, but some overall tendencies can also be reported. We summarize the main findings of DS1 in the following paragraph followed by a paragraph on the main findings of DS2 (also see Table 4). We will discuss the results later in regard to ambient vs. focal exploration modes and top-down vs. bottom-up processes.

For DS1, no difference was observed in the probability of occurrence for short and long duration saccades during exploration (see Figure 8), with the exception of ObjSearch (and to a lesser extent, for Fractal). For these conditions, we observed more long duration saccades at the beginning of the exploration. For ObjSearch, this difference can be explained by the task itself. Participants were asked to search for two objects and localize them relative to each other; they may have had an exploration strategy where they first broadly explored the scene to

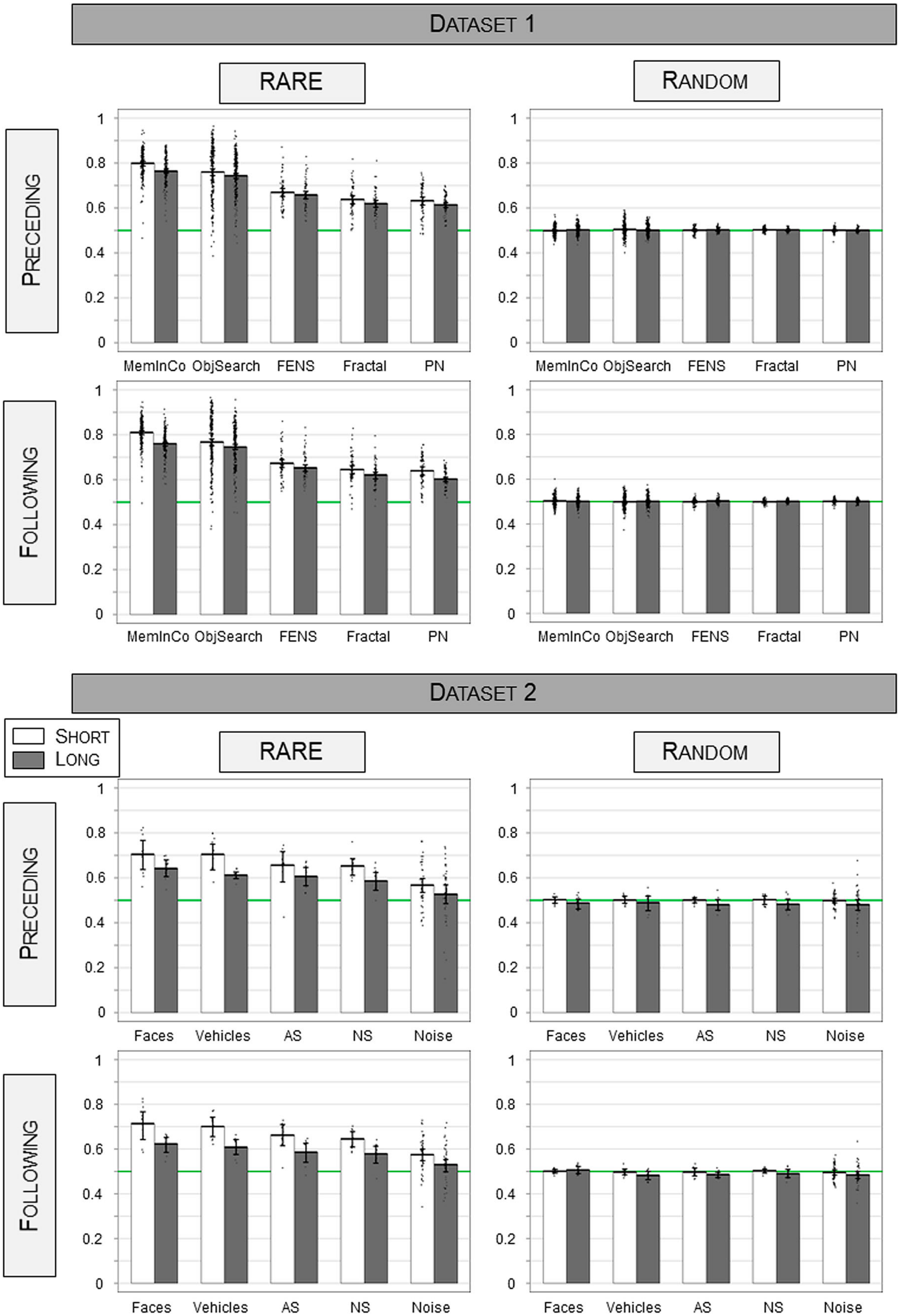

Figure 9. AUC values indicate the difference between computational saliency maps (RARE and random), and maps created from fixations preceding (***top row***) and following (***bottom row***) short and long duration saccades for the five conditions of DS1 (MemInCo, ObjSearch, FENS, Fractal and PN) and the six conditions of DS2 (Faces, Vehicles, AS, NS, Noise and Gray). A value of 0.50 indicates random performance whereas 1 denotes perfect performance. Means are plotted with the 95% between-subjects confidence intervals. Individual data points represent the mean for each participant.

answer the question before they explored the scene "normally." Furthermore, they may have made eye movements between the two objects in the scene, which were 8.34° apart on average. However, no task based explanation can be found for the Fractal condition with free exploration. The phenomenon seems to last for a shorter period of time and might be coming from participants or other uncontrolled variables. Previous and subsequent eye movements showed the same patterns for short and long duration saccades: longer eye movements (saccades and fixations) before short duration saccades compared to long duration saccades as well as longer eye movements after short duration saccades than long duration saccades. Orientation results replicated previous studies that have shown more horizontal than vertical saccades (Moeller et al., 2004; Ossandón et al., 2010; Tatler & Vincent, 2008).

For DS2, opposite results were observed in proportion. We observed a larger amount of short compared to long duration saccades, and short duration saccades occurred earlier in the exploration. These results seem to be directly related to the smaller size of the stimuli. We did not observe any notable effects on the properties of previous and subsequent eye movements. However, the Faces condition seemed to show some differences when compared to other conditions (short fixations and saccades, more vertical saccades) consistent with the existence of a specific eye movement pattern during the exploration of faces (Coutrot et al., 2016; Yarbus, 1967). The presence of the bimodality for the Gray condition suggests that the control of saccades was the same during both the exploration of unicolor background and during the exploration of more complex stimuli. For the Gray condition, we could also make the assumption that the participants who explored other stimuli with more informative content, would continue to explore gray backgrounds in the same way as the other stimuli, since gray backgrounds were interspersed with other conditions. In this condition, the stimuli and the background were similar, even though there was a difference in the gray used for both, so it can be considered one big stimulus that shared a similar visual angle with stimuli from DS1. This suggests that the size of the stimuli might play a role in the bimodality of the distribution of saccade durations, even though it was observed, but less evident, for all conditions of DS2.

Bimodality revealed the presence of dual exploration mechanisms

Analysis of a distribution's modality is crucial in the detection of the presence of dual processes (Freeman & Dale, 2013; Murphy, 1964). In the following, we discuss the bimodality of saccade duration in relation to well-known dual exploration modes: (1) focal and ambient exploration modes (Pannasch et al., 2008) and (2) top-down and bottom-up processing.

Previous studies used saccade amplitude (< 5° or ≥5°) to identify focal and ambient exploration modes (Pannasch et al., 2008). They reported a larger proportion of focal fixations (short amplitude saccades). Another study proposed an automatic classification method relying on the previous saccade amplitudes to separate these two exploration modes (Follet et al., 2011). They reported an average of 70% focal and 30% ambient visual fixations in each cluster respectively. DS1 shows more long duration saccades than short, and DS2 shows more short duration saccades than long. Previous research on focal and ambient exploration modes showed that either the ambient mode appeared at the beginning of the exploration with a later contribution of focal mode (Norman, 2002; Pannasch et al., 2008; Unema et al., 2005) or there was a dominance of focal fixations just after stimulus onset and the focal mode became more important over time (Follet et al., 2010). Results from DS1 suggest that they occurred equally during the whole exploration and results from DS2 suggest a predominance of short duration saccades at the beginning of the exploration, which can be explained by the size of stimuli. Under the hypothesis that our two saccade groups are related to focal and ambient modes, we could make the prediction that more short duration saccades would be followed by longer duration fixations than long duration saccades. This effect was not observed overall, only for MemInCo and PN in the first analysis and NS and Noise in the second analysis. The opposite effect was observed for ObjSearch. Overall, our results seem partly inconsistent with previous studies on focal and ambient modes.

Our saliency analysis showed that fixations following and preceding short duration saccades were better explained by bottom-up saliency models than fixations following and preceding long duration saccades. These results suggest that the role of short duration saccades might be to move the eyes in order to accurately process areas of interest in the scene, with the eyes making short saccades in the most salient areas of the scene. On the contrary, large saccades might be used to broadly explore the scene, perhaps driven by more top-down influences. This is supported by additional observations. First, the observation of more horizontal saccades for long than short duration saccades observed in DS1 suggests that short duration saccades are used to explore a specific area of the scene by moving the gaze all around. Second, longer fixations before short duration saccades observed in DS1 suggests that the area fixated on is "of interest" and needed more time to be fully analyzed. From DS2, the fact that more short duration saccades occurred at the beginning of the exploration and more long duration saccades occurred at the end is also supportive of short duration saccades being more bottom-up, because the beginning of exploration is mostly driven by bottom-up information. Taken together, our results suggest that the two groups we observed can potentially be linked more to bottom-up and top-down process than to focal and ambient modes.

However, independently of this association between long duration saccades and top-down processing on one side, and short duration saccades and bottom-up processing on the other, the fact that the bimodality of saccade duration distribution was observed even in the absence of complex visual stimuli (i.e., with gray background) suggests that top-down processes played a role in the distinction between short and long duration saccades. Similarly, the bimodality of saccade duration distribution was also observed when no specific visual task was given to participants, which suggests that some low-level mechanisms took part in the observation of the bimodality, even though subjects can always make up their own top-down goals. Overall, the association between the bimodality of saccade duration distributions and top-down vs. bottom-up processing remains weak and difficult to further investigate in the context of free exploration conditions as used in our study, and would benefit from further investigation with exploration conditions more explicitly controlled by top-down and bottom-up manipulations. Nevertheless, our study revealed that saccade duration can be used to detect two different attention modes that are involved during scene exploration, which needs to be further understood.

Association with saccade latency

A parallel might be drawn between the bimodality observed in the distribution of saccade latency found in the literature (Boch & Fischer, 1986; Cavegn & d'Ydewalle, 1996; Fischer & Weber, 1993; Weber & Fischer, 1994) and the bimodality observed in our study during free exploration of various visual scenes. The distribution of saccade latency can show a sub-population called express saccades forming an additional peak with a much shorter latency (Carpenter, 2001; Fischer & Boch, 1983; Fischer & Ramsperger, 1984). It is sometimes assumed that express saccades are due to a faster pathway in parallel with the main one (Schiller et al., 1987). This has been modelled by a neural network where a random dichotomizer first decides whether a trial is express or not, and then a separate stochastic process generates different latencies (Fischer et al., 1995). The same mechanism could potentially be happening for saccades during free exploration of visual stimuli, where short duration saccades would be generated by a parallel and faster pathway.

Another explanation is that the bimodality of saccade latency was a consequence of the way in which saccadic experiments are normally conducted (Carpenter, 2001). Using a two-gap task (i.e., the target position changed two times while participants were instructed to follow it), the authors showed that the latency of the second saccade falls into the faster category if it is in the same direction as the one that immediately preceded it. This may be the result of both the oculomotor system predicting target direction and saccades in the expected direction having a shorter latency. Even though there is no gap effect in free exploration of visual stimuli, short duration saccades could be hypothesized as being the prolongation (in the same direction) of the preceding saccade, which results in a corrective saccade to reach the desired target of this preceding saccade. Again, corrective saccades were mainly studied during controlled eye movement paradigms, where saccade targets were modified or moved while participants performed the saccade, which cannot happen during free exploration of visual stimuli (Ray et al., 2004). Further analysis and experimental manipulations are needed to examine whether short duration saccades (or possibly a part of them) can be assimilated to fast corrective saccades in the context of free exploration of visual stimuli.

Limitations

The results of this study, which to our knowledge are the first to explore the role of saccade duration and the bimodality of its distribution during the viewing of scenes, need to be interpreted with caution due to some limitations, mainly related to other eye movement types. For example, it would be interesting to consider microsaccades, or fixational eye movements, which are small and involuntary eye movements (Martinez-Conde et al., 2004; Otero-Millan et al., 2008). It has been shown that saccades and microsaccades have comparable spatiotemporal characteristics and a common oculomotor generator (Otero-Millan et al., 2008). Thus, they are most likely to be part of the fixations, so they might not have a strong influence in the results of this study.

Another type of eye movement is a glissade, which is a wobbling movement at the end of a saccade that can either be a rapid (Kapoula et al., 1986) or a slower postsaccadic movement (Weber & Daroff, 1972). Glissades occur in about half of the saccades during scene perception and have an average duration of about 24 ms (Nyström & Holmqvist, 2010). Nyström and Holmqvist (2010) argue that when using algorithms that are not explicit about glissade detection, their durations will randomly spill over to the fixation or the saccade and add more than 25% to the average saccade duration and about 5% to the average fixation duration. The SR Eyelink detection algorithm, according to both the algorithm description in their manual and to a study from Stampe (1993), may be better with the way they treat glissades than most algorithms are, with the intent to remove glissades by filtering and assigning their durations to the fixation. We also tested other saccade detection algorithms, including the one from Nyström and Holmqvist, and still observed a bimodality in saccade duration distribution.

Finally, a last type of eye movement is smooth pursuit, where express saccades have been observed as a catch-up saccade preceding smooth pursuit (Korentis & Enderle, 2016). In our study, we do not specifically have predicted targets, except for Obj-Search where participants have to find target objects in the scene, but without knowing the object's position in advance and using static images. For these reasons, we do not expect smooth pursuit even though it still occurred, probably more as drifts of the gaze, which would result in the detection of slow and long duration saccades. This would not influence the bimodal distribution, as they will be on the queue of the distribution.

Conclusion

The main results of this study are that the bimodality of saccade durations is not scene- or task-dependent, which suggests a systematic phenomenon at least for the exploration of various types of visual stimuli. The bimodality of saccade duration did not seem to be clearly related to the focal/ambient dichotomy during exploration of natural scenes. It seems to be partially related to top-down and bottom-up processes, with short duration saccades linked to bottom-up processes and long duration saccades linked to top-down processes. However, since the bimodality was observed even when no stimulus was presented (i.e., gray background), this raises the question of the role of a systematic oculomotor control of saccades. We can also hypothesize that since gray backgrounds were interspersed with other stimuli, participants kept the same exploration strategies even when nothing was presented. This study suggests future investigations into the bimodality of saccade duration, to further examine the systematic nature of the phenomenon. For example, by studying more specific and stereotyped exploration types like reading. It also reiterates the importance of studying and reporting the distribution of eye movement measures (not just the means of eye movement measures), since in saccade duration the mean is not representative of a bimodal distribution. Finally, saccade durations should be taken into account in saliency models, at the same level as saccade amplitudes (which are implicitly used behind fixation locations). The bimodality of saccade duration observed in this paper opens up new opportunities to study dual exploration modes during free exploration of visual stimuli, in order to better understand the exact physiological processes involved for these two types of saccades as well as their relationship to well know dual processes that are top-down and bottom-up.

Availability of data and materials

The data are available on the Open Science Framework: https://osf.io/48bkq/?view_only=78be244957834e7caaa7b69bb5187438.

Notes

1. Wilming et al., Dryad https://doi.org/10.5061/dryad.9pf75 (2017).
2. More data for DS1 are available online: https://osf.io/48bkq/?view_only=78be244957834e7caaa7b69bb5187438.
3. Plots for the other conditions are shown online: https://osf.io/48bkq/?view_only=78be244957834e7caaa7b69bb5187438.
4. The model was downloaded from this website http://saliency.mit.edu/results_mit300.html.

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Disclosure statement

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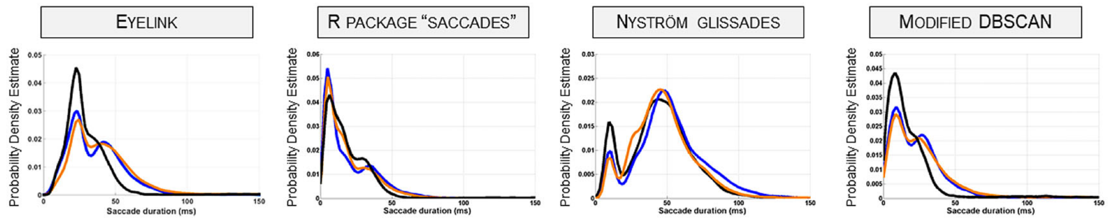
Appendix

Eye movement detection algorithms



	Eyelink	R package "saccades"	Nyström glissades	Modified DBSCAN
MemInCo	*nb sacc = 23266* *dip* = 0.020, *p* < .001 BC = 0.41, α = 0.22	*nb sacc = 53055* *dip* = 0.034, *p* < .001 BC = 0.46, α = 0.23	*nb sacc = 32266* *dip* = 0.023, *p* < .001 BC = 0.32, α = 0.20	*nb sacc = 22423* *dip* = 0.018, *p* < .001 BC = 0.62, α = 0.28
ObjSearch	*nb sacc = 24093* *dip* = 0.017, *p* < .001 BC = 0.53, α = 0.13	*nb sacc = 42232* *dip* = 0.030, *p* < .001 BC = 0.59, α = 0.26	*nb sacc = 30352* *dip* = 0.018, *p* < .001 BC = 0.32, α = 0.20	*nb sacc = 25139* *dip* = 0.016, *p* < .001 BC = 0.68, α = 0.27
All – Analysis II	*nb sacc = 11051* *dip* = 0.025, *p* < .001 BC = 0.74, α = 0.28	*nb sacc = 15907* *dip* = 0.026, *p* < .001 BC = 0.67, α = 0.27	*nb sacc = 12369* *dip* = 0.042, *p* < .001 BC = 0.27, α = 0.19	*nb sacc = 8332* *dip* = 0.022, *p* < .001 BC = 0.79, α = 0.29

Figure A1. Probability density estimates of saccade duration for MemInCo and ObjSearch (DS1) and all conditions (DS2); saccades were automatically detected by the Eyelink software (cognitive configuraion) and three different saccade detection algorithms were also used on the same eye movement data: the R package saccades (Engbert & Kliegl, 2003), the detection algorithm from (Nyström & Holmqvist, 2010) and the modified DBSCAN (Li et al., 2016). Hartigan's dip statistic with corresponding *p* values are also reported.

Saccade duration distributions for individual participants

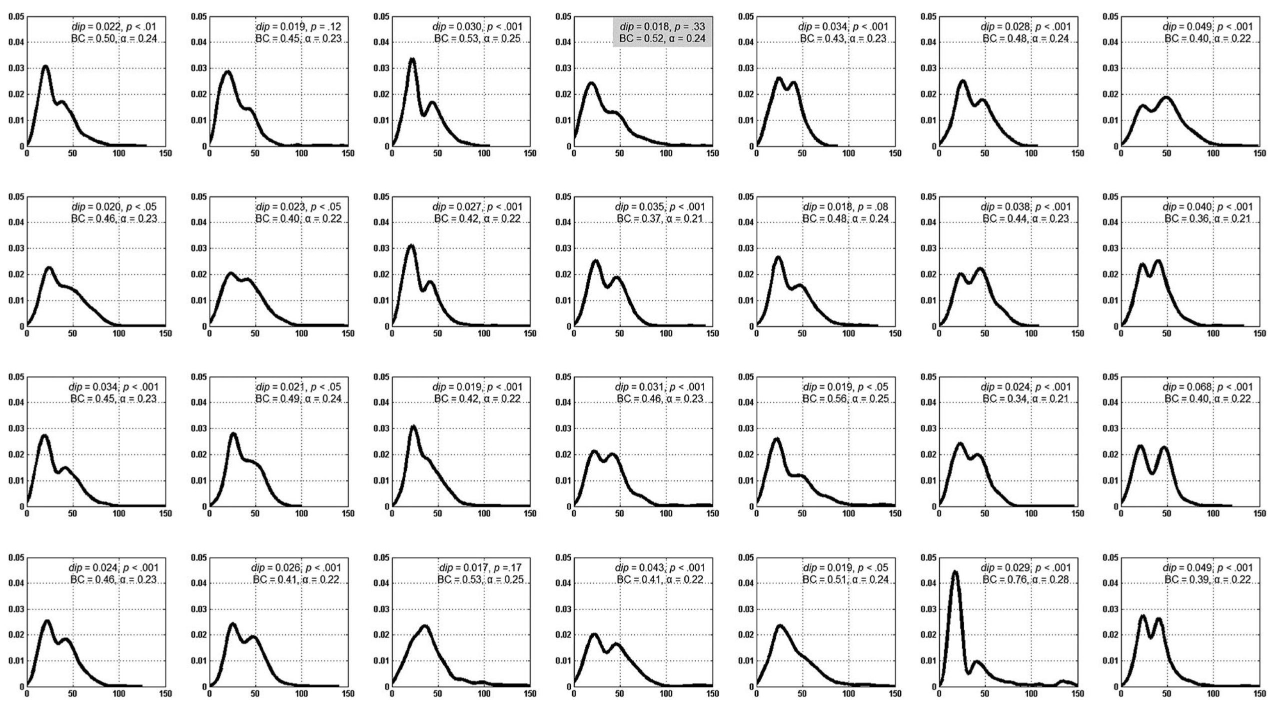


Figure A2. Probability density estimates of saccade duration for each participant for MemInCo condition. *HDSw/BC* statistics are reported; statitics not showing a bimodality are highlighted in gray.

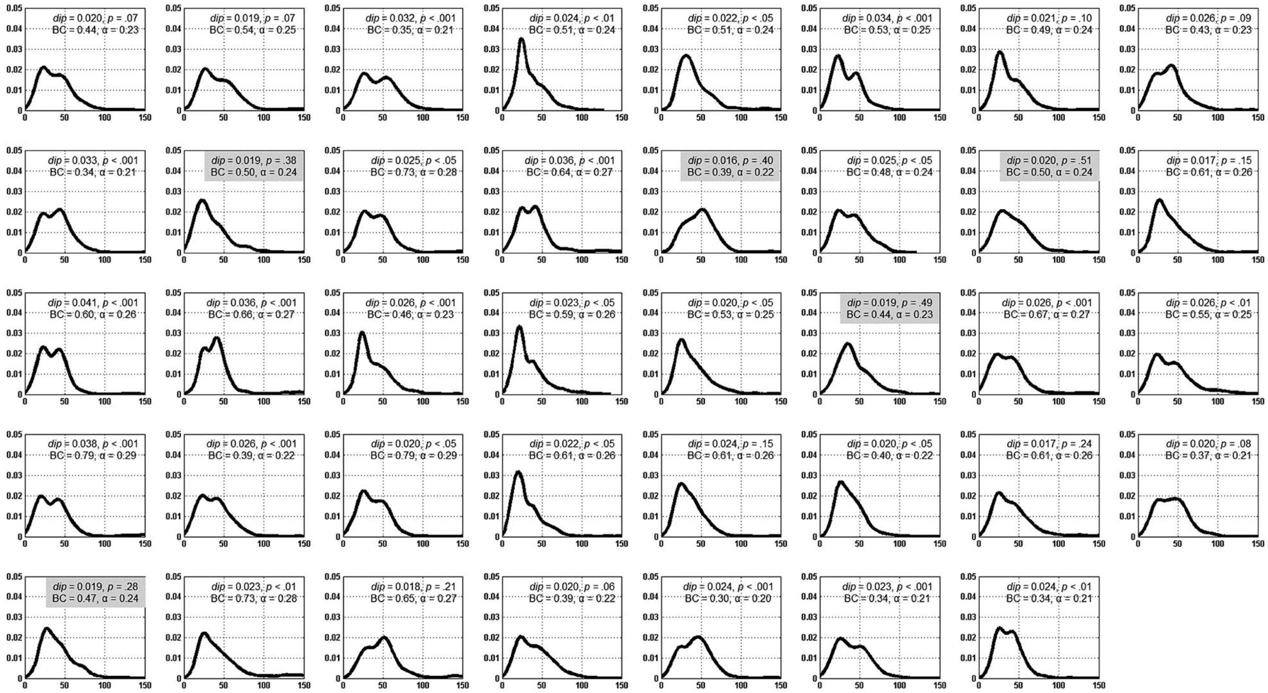


Figure A3. Probability density estimates of saccade duration for each participant for ObjSearch condition. *HDSw/BC* statistics are reported; statitics not showing a bimodality are highlighted in gray.

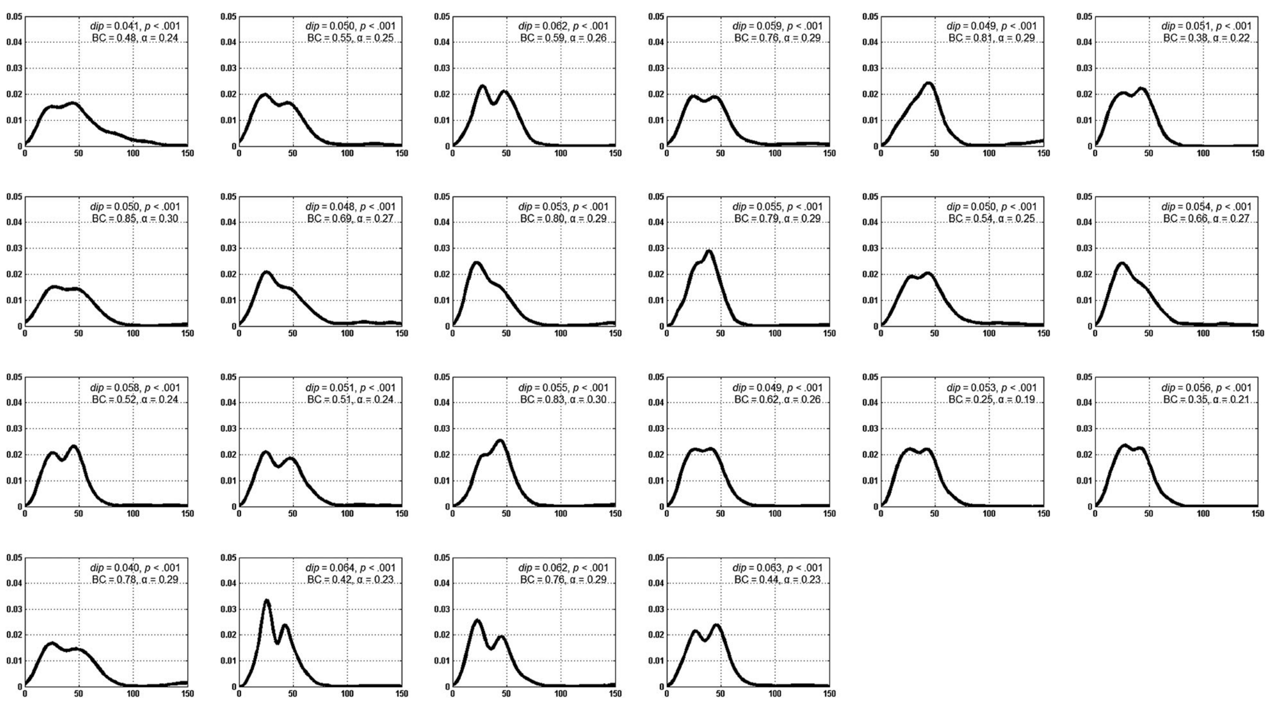


Figure A4. Probability density estimates of saccade duration for each participant for FENS condition. *HDSw/BC* statistics are reported.

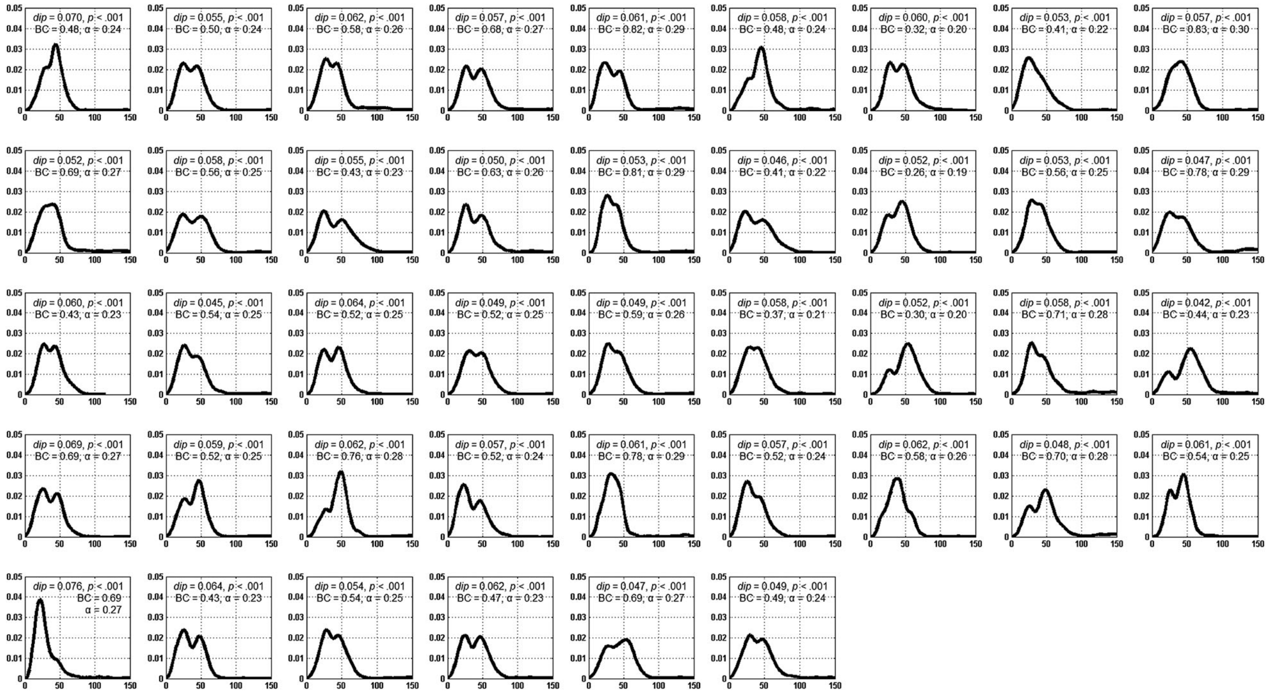


Figure A5. Probability density estimates of saccade duration for each participant for Fractal condition. *HDSw/BC* statistics are reported.

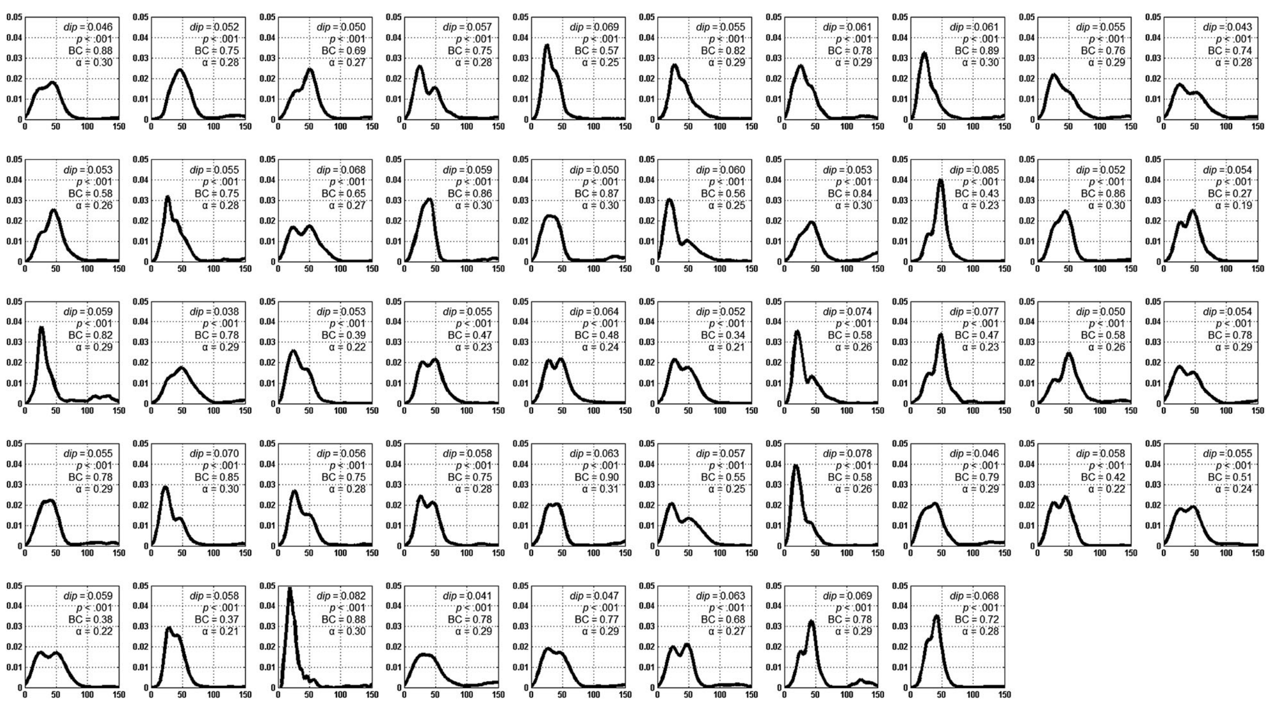


Figure A6. Probability density estimates of saccade duration for each participant for PN condition. *HDSw/BC* statistics are reported.

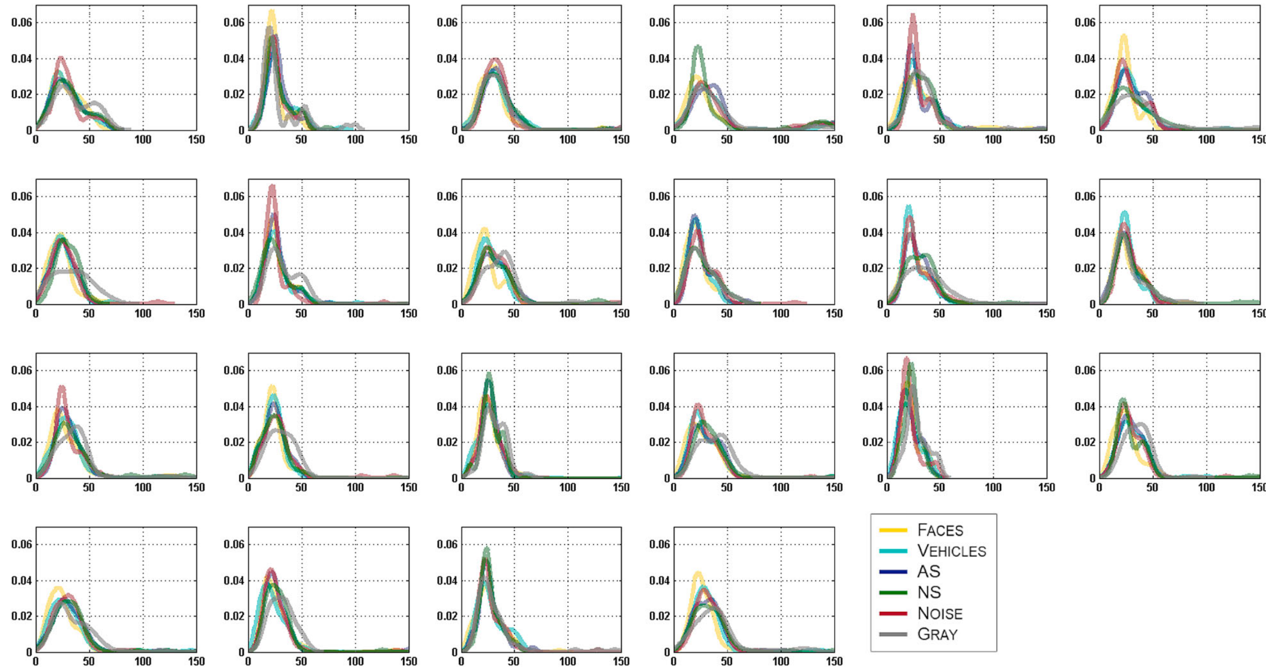


Figure A7. Probability density estimates of saccade duration for each participant for the 6 conditions of DS2.

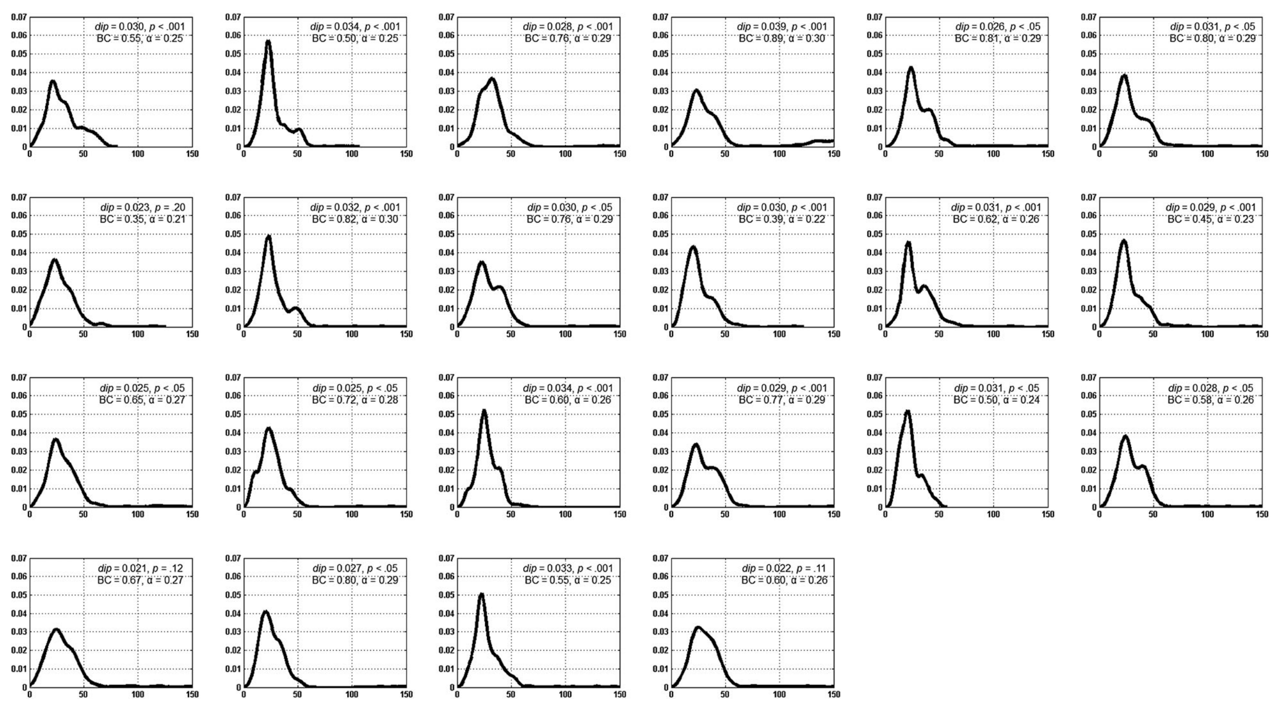


Figure A8. Probability density estimates of saccade duration for each participant for all conditions (Faces, Vehicles, AS, NS, Noise and Gray). *HDSw/BC* statistics are reported.

Eye movement properties for short vs. long duration saccades

Dataset 1

Conditions: MemInCo (exploration of natural scenes in order to memorize the objects that are present, $N = 28$), ObjSearch (exploration of natural scenes in order to localize two easy-to-find objects, $N = 39$), FENS (free exploration of natural scenes, $N = 22$), Fractal (free exploration of fractal images, $N = 42$) and PN (free exploration of pink noise images, $N = 48$).

Previous eye movements. Fixation duration. The significant effect of duration, $F(1,174) = 76.10$, $p < .001$, $\eta_p^2 = 0.30$, revealed that fixations were longer when they preceded short rather than long duration saccades. The significant condition × duration interaction, $F(4,174) = 6.06$, $p < .001$, $\eta_p^2 = 0.12$, showed that short duration saccades were preceded by longer fixations than long duration saccades for only MemInCo, ObjSearch, Fractal and PN (all $p_{Bonf} < .05$).

Saccade amplitude. The main effect of duration, $F(1,174) = 66.41$, $p < .001$, $\eta_p^2 = 0.28$, was qualified by a condition × duration interaction, $F(4,174) = 28.18$, $p < .001$, $\eta_p^2 = 0.39$. For MemInCo, FENS and Fractal, current short duration saccades were preceded by smaller amplitude saccades than current long duration saccades (all $p_{Bonf} < .001$).

Saccade duration. The main effect of duration $F(1,174) = 6.33$, $p < .05$, $\eta_p^2 = 0.04$, was qualified by a significant condition × duration interaction, $F(4,174) = 6.70$, $p < .001$, $\eta_p^2 = 0.13$. For PN, current short duration saccades were preceded by longer duration saccades than current long duration saccades ($p_{Bonf} < .05$).

Subsequent eye movements. Fixation duration. The significant condition × duration interaction, $F(4,174) = 18.64$, $p < .001$, $\eta_p^2 = 0.30$, showed that short duration saccades were followed by longer fixations than long duration saccades for ObjSearch ($p_{Bonf} < .001$).

Saccade amplitude. The significant effect of duration, $F(1,174) = 30.53$, $p < .001$, $\eta_p^2 = 0.15$, was qualified by a significant condition × duration interaction, $F(4,174) = 19.62$, $p < .001$, $\eta_p^2 = 0.31$. Current short duration saccades were followed by higher amplitude saccades than current long duration saccades for MemInCo, FENS and Fractal (all $p_{Bonf} < .001$) and current short duration saccades were followed by smaller amplitude saccades than current long duration saccades for ObjSearch ($p_{Bonf} < .001$).

Saccade duration. The significant effect of duration, $F(1,195) = 16.39$, $p < .01$, $\eta_p^2 = 0.08$, showed that current short duration saccades were followed by longer duration saccades than current long duration saccades.

Table A1. Eye movement properties for Short and Long duration saccades. Short saccades had their duration shorter than the local minimum L_m (Table 3) and long saccades had their duration longer than L_m.

MemInCo		Short saccades	Long saccades
Previous Saccade	Amplitude (°)	6.30 (±0.21)	5.12 (±0.17)
	Duration (ms)	37.86 (±0.73)	34.05 (±0.75)
Previous fixation duration (ms)		239.84 (±4.80)	226.18 (±5.17)
Subsequent Saccade	Amplitude (°)	6.30 (±0.21)	5.46 (±0.19)
	Duration (ms)	37.78 (±0.72)	35.08 (±0.81)
Subsequent fixation duration (ms)		227.57 (±5.17)	240.57 (±5.52)
ObjSearch		Short saccades	Long saccades
Previous Saccade	Amplitude (°)	6.05 (±0.13)	6.31 (±0.11)
	Duration (ms)	48.44 (±1.50)	47.39 (±1.02)
Previous fixation duration (ms)		240.31 (±4.13)	213.44 (±3.75)
Subsequent Saccade	Amplitude (°)	6.01 (±0.13)	6.41 (±0.11)
	Duration (ms)	50.32 (±1.56)	48.89 (±1.48)
Subsequent fixation duration (ms)		235.53 (±4.57)	216.41 (±3.38)
FENS		Short saccades	Long saccades
Previous Saccade	Amplitude (°)	5.69 (±0.16)	4.89 (±0.12)
	Duration (ms)	49.62 (±3.06)	44.95 (±2.19)
Previous fixation duration (ms)		242.00 (±5.11)	234.27 (±5.54)
Subsequent Saccade	Amplitude (°)	5.60 (±0.16)	4.99 (±0.12)
	Duration (ms)	48.92 (±2.67)	45.01 (±2.27)
Subsequent fixation duration (ms)		239.09 (±5.17)	237.00 (±5.11)
Fractal		Short saccades	Long saccades
Previous Saccade	Amplitude (°)	5.59 (±0.17)	4.93 (±0.13)
	Duration (ms)	57.04 (±1.47)	61.94 (±2.14)
Previous fixation duration (ms)		253.05 (±4.12)	242.68 (±5.87)
Subsequent Saccade	Amplitude (°)	5.52 (±0.18)	4.86 (±0.14)
	Duration (ms)	45.83 (±1.08)	43.37 (±0.87)
Subsequent fixation duration (ms)		249.57 (±5.21)	248.87 (±4.72)
PN		Short saccades	Long saccades
Previous Saccade	Amplitude (°)	4.98 (±0.21)	5.16 (±0.17)
	Duration (ms)	58.74 (±3.13)	53.28 (±1.77)
Previous fixation duration (ms)		325.02 (±9.08)	292.79 (±7.84)
Subsequent Saccade	Amplitude (°)	5.07 (±0.23)	5.19 (±0.17)
	Duration (ms)	56.60 (±2.71)	53.84 (±1.83)
Subsequent fixation duration (ms)		294.29 (±8.70)	314.71 (±7.96)

Dataset 2

Conditions: free exploration of Faces, Vehicles, artificial scenes (AS), natural scenes (NS), Noise and Gray, with $N = 23$.

Previous eye movements.

Fixation duration. No significant effects were observed.

Saccade amplitude. The significant condition × duration interaction, $F(5,105) = 5.14$, $p < .001$, $\eta_p^2 = 0.20$, showed shorter saccade amplitude for short duration saccades compared to long duration saccades, for NS and Gray.

Saccade duration. No significant effects were observed.

Subsequent eye movements.

Fixation duration. The significant condition × duration interaction, $F(5,105) = 2.57$, $p < .05$, $\eta_p^2 = 0.11$, showed shorter fixation duration for short duration saccades compared to long duration saccades, for NS and Noise.

Saccade amplitude. The condition × duration interaction was significant, $F(5,105) = 2.89$, $p < .05$, $\eta_p^2 = 0.12$. For Faces, we observed lower saccade amplitude for short duration saccades compared to long duration saccades. The opposite was observed for NS.

Saccade duration. The significant effect of duration, $F(1,21) = 5.84$, $p < .05$, $\eta_p^2 = 0.22$, revealed longer saccade duration for short duration saccades compared to long duration saccades.

Table A2. Eye movement properties for Short and Long duration saccades. Short saccades had their duration shorter than the local minimum L_m (Table 3) and long saccades had their duration longer than L_m.

Faces		Short saccades	Long saccades
Previous Saccade	Amplitude (°)	2.52 (±0.13)	2.68 (±0.12)
	Duration (ms)	28.47 (±2.11)	28.18 (±0.83)
Previous fixation duration (ms)		250.05 (±5.94)	270.48 (±13.26)
Subsequent Saccade	Amplitude (°)	2.65 (±0.13)	2.97 (±0.12)
	Duration (ms)	28.76 (±1.77)	29.70 (±1.13)
Subsequent fixation duration (ms)		274.61 (±9.68)	264.05 (±14.07)
Vehicles		Short saccades	Long saccades
Previous Saccade	Amplitude (°)	2.92 (±0.12)	2.75 (±0.15)
	Duration (ms)	31.42 (±1.92)	29.02 (±1.80)
Previous fixation duration (ms)		256.09 (±6.23)	261.66 (±10.99)
Subsequent Saccade	Amplitude (°)	3.10 (±0.13)	2.86 (±0.17)
	Duration (ms)	32.30 (±2.15)	30.37 (±1.86)
Subsequent fixation duration (ms)		256.36 (±7.44)	264.07 (±13.05)
AS		Short saccades	Long saccades
Previous Saccade	Amplitude (°)	3.21 (±0.15)	3.00 (±0.16)
	Duration (ms)	33.59 (±2.36)	30.35 (±1.40)
Previous fixation duration (ms)		262.25 (±8.30)	255.41 (±11.92)
Subsequent Saccade	Amplitude (°)	3.42 (±0.16)	3.21 (±0.16)
	Duration (ms)	32.51 (±1.37)	32.26 (±1.96)
Subsequent fixation duration (ms)		255.43 (±9.05)	272.95 (±12.43)
NS		Short saccades	Long saccades
Previous Saccade	Amplitude (°)	3.15 (±0.15)	2.82 (±0.14)
	Duration (ms)	33.85 (±2.31)	30.62 (±1.23)
Previous fixation duration (ms)		273.07 (±8.45)	270.41 (±15.04)
Subsequent Saccade	Amplitude (°)	3.33 (±0.14)	3.07 (±0.17)
	Duration (ms)	34.17 (±1.89)	31.28 (±1.35)
Subsequent fixation duration (ms)		271.05 (±10.82)	295.14 (±10.57)
Noise		Short saccades	Long saccades
Previous Saccade	Amplitude (°)	3.24 (±0.14)	3.01 (±0.13)
	Duration (ms)	35.69 (±2.27)	33.60 (±2.09)
Previous fixation duration (ms)		300.84 (±10.90)	286.93 (±11.76)
Subsequent Saccade	Amplitude (°)	3.43 (±0.12)	3.32 (±0.17)
	Duration (ms)	38.02 (±2.96)	36.03 (±2.76)
Subsequent fixation duration (ms)		281.25 (±8.82)	320.57 (±17.46)
Gray		Short saccades	Long saccades
Previous Saccade	Amplitude (°)	3.49 (±0.18)	3.84 (±0.17)
	Duration (ms)	37.54 (±2.55)	39.79 (±2.84)
Previous fixation duration (ms)		320.75 (±21.40)	344.73 (±23.89)
Subsequent Saccade	Amplitude (°)	4.00 (±0.21)	4.05 (±0.21)
	Duration (ms)	44.18 (±4.84)	42.09 (±2.88)
Subsequent fixation duration (ms)		323.11 (±20.95)	338.34 (±23.76)