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Dynamics of Visibility, Confidence, and Choice During Eye Movements

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We study the dynamics of objective and subjective measures of visibility and choice in brief presentations occurring within a fixation during free eye-movements. We show that brief presentations yield homogeneous levels of performance in a window that extends almost throughout the entire fixation. Instead, confidence judgments vary for presentations occurring at different moments of the fixations. When the target occurs close to the onset of the fixation, it is reported accurately but with lower values of confidence; when it occurs close to the end of the fixation, it is reported with high confidence (Experiments 1 and 2). Consistently, in experiments in which participants can freely choose to report items, we observe a report bias toward the end of the fixation, where the maximum of confidence occurs for experiments with a single target (Experiments 3 and 4). Hence, these results suggest that confidence is not merely a measure of accumulated stimulus energy but instead varies reflecting an endogenous integration process by which later stimuli are assigned greater confidence.

Keywords: choice, confidence, decision-making, eye movements, visibility

We move our eyes three times per second, producing a sequence of fixations, separated by ballistic eye-movements or saccades (Yarbus, 1967). Saccades produce a displacement of the retinal image, but perception of the world remains continuous and stable (Burr, 2004). This is achieved by a selective suppression of the magnocellular visual pathway (i.e., saccadic suppression; Burr, Morrone, & Ross, 1994), and as a consequence, the temporal window of visibility is narrowed to discrete windows within periods of fixations. Delimiting the precise boundaries of this window and how information is integrated within this window to lead to reports of visibility and subjective confidence is the main aim of this work.

Sperling first addressed the problem of what can be seen in a single exposure (Sperling, 1960). However, these experiments were done while participants sustained fixation and the results are likely to change during free viewing because saccades initiate a complex machinery which actively suppresses and regulates vision. For instance, the visual system uses information from the upcoming eye movement to prepare the expected consequences of that movement (i.e., “saccadic remapping,” for a review see Burr & Morrone, 2011). This compensation is accompanied by profound changes in the perception of space (Ross, Morrone, & Burr, 1997), time (Morrone, Ross, & Burr, 2005), and number (Burr, Ross, Binda, & Morrone, 2010), and is correlated to neurophysiological responses in the lateral intraparietal cortex (LIP) (Duhamel, Colby, & Goldberg, 1992). Backward-masking manipulations of perceptual awareness are ineffective when the target is presented before an eye-movement (De Pisapia, Kaunitz, & Melcher, 2010), while the effectiveness of the mask is recovered when it is placed in the target’s remapped position (Hunt & Cavanagh, 2011). Similarly, classic limitations of the attentional system such as the Attentional Blink (Raymond, Shapiro, & Arnell, 1992; Shapiro, Caldwell, & Sorensen, 1997) change drastically when occurring during free eye-movements (Kamienkowski, Navajas, & Sigman, 2012).

The minimum time that a stimulus has to be present in the fovea to gain conscious access depends of course on many factors, including low-level features such as contrast, luminance, its relevance (e.g., emotional, semantic, learning), and top-down modulations (Kawahara, Di Lollo, & Enns, 2001; Naccache, Blandin, & Dehaene, 2002). Despite this broad variability, in a time scale of 50 to 100 milliseconds a foveated stimulus can be consciously perceived (for a review see Enns & Di Lollo, 2000). Electrophysiological studies suggest that this delay is partially explained by the retina-brain lag (i.e., the time required for retinal stimulation to

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propagate to the first steps of the cortical visual system; Reichle & Reingold, 2013). Based on this evidence, we hypothesize that the visual system needs at least several tens of milliseconds to render a stimulus visible after the onset of a fixation. Here, we aim to empirically test this hypothesis and measure the dynamics of visibility during fixations occurring in a task involving eye-movements (Experiments 1 and 2).

To map the time course of visibility, previous studies have used participant's introspection or confidence in their responses (Graziano & Sigman, 2009; Hurlburt & Heavey, 2001; Kotowicz, Rutishauser, & Koch, 2010; Marti, Sackur, Sigman, & Dehaene, 2010; Sergent, Baillet, & Dehaene, 2005). Kotowicz and collaborators previously showed that in a visual search task, confidence but not accuracy increases along with the time that they were allowed to fixate in the target (Kotowicz et al., 2010). Building up on the results of this study, here we test for a possible dissociation between the dynamics of confidence and visibility across saccadic eye movements (Experiments 1 and 2).

Distilling the time-course of confidence has strong implications for theories of decision making. In fact, it was argued that confidence signals the evidence toward a decision (Insabato, Pannunzi, Rolls, & Deco, 2010; Pleskac & Busemeyer, 2010; Vickers, 2001; Vickers & Smith, 1985), following the firing dynamics of neurons in the parietal cortex (Kiani & Shadlen, 2009). Zylberberg and collaborators used a classification image technique to show that integration of motion and luminance in the periphery (while subjects sustain fixation) has distinct dynamics for choice than for subjective reports of visibility (Zylberberg, Barttfeld, & Sigman, 2012). Using a RSVP paradigm resembling more the stimuli presented in this experiment, Shalom and collaborators also showed a regime in which increasing presentation time could increase choice without affecting subjective estimates that the chosen stimuli had been presented for more time and hence forced (Shalom et al., 2013). In this study, we set out to investigate whether visibility and confidence progress with different dynamics within a single fixation (Experiment 2). We then inquire how confidence may condition choice by comparing the selected item within a fixation when there are multiple options presented in time within a single fixation. (Experiments 3 and 4).

To address the issues mentioned above, we designed a set of gaze-contingent experiments in which the fixation duration was under control of the participants, but constrained to a distribution similar to fixations in natural tasks (Henderson, 2003; Kamienskowski et al., 2012; Otero-Millan, Troncoso, Macknik, Serrano-Pedraza, & Martinez-Conde, 2008; Rayner, 1998). By presenting a stream of letters in Rapid Serial Visual Presentation (RSVP) in a fixation point, we study visibility, confidence, and choice for items presented at different times relative to the fixation onset and offset.

Experiment 1: Temporal Kernel of Visibility During Eye Movements

The goal of this experiment is to provide quantitative evidence about the temporal limits of visibility relative to the fixation boundaries. Previous studies have shown that saccadic suppression confines visibility to the fixations (Burr, 2004; Burr et al., 1994). We hypothesize that the retina-brain lag delays the recovery of visibility by several tens of milliseconds relative to fixation onset (Reichle & Reingold, 2013). To this aim, we obtained objective

and subjective measures of visibility in a RSVP task embedded in a gaze-contingent experiment.

Method

Participants. Participants ($n = 10$; 3 female, mean age 22.3 years, SD 2.6 years) were undergraduate and graduate students. All of them were naïve with the only exception of author J.N. and had normal or corrected to normal vision. Participants completed 300 trials successfully.

Apparatus. Eye movements were recorded with a video-based eye tracker SR Research Eyelink 1000 (<http://www.sr-research.com/>) at a sampling rate of 1000 Hz. All eye movements were labeled as fixations, saccades, and blinks by the eye-tracker software using the default thresholds for Psychophysics experiments (30 deg/sec for velocity, 9500 deg/sec² for acceleration, and 0.15 deg for motion; Cornelissen, Peters, & Palmer, 2002). All stimuli were presented in a 19-inch ViewSonic CRT Screen at 1024 by 768 pixels resolution and a refresh rate of 100 Hz. The viewing distance was always 57 cm.

Stimuli. All stimuli were presented on the horizontal meridian of the screen. A *begin trial fixation square* (size: 0.8 degrees of visual angle) was located 19.2 degrees to the left from the center of the screen. Letters (Font: Arial, Size: 20) were presented in light gray in the center of the screen (size: 0.7 degrees of visual angle) over a dark gray background (see Figure 1). An *end trial fixation square* was presented on the right side of the screen (size: 0.8

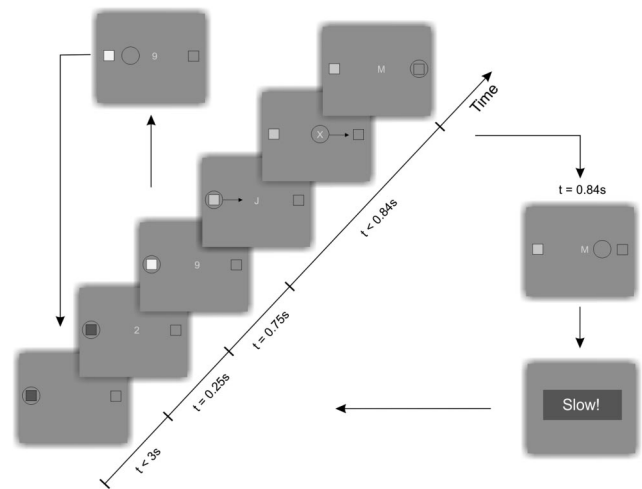


Figure 1. Structure of each trial: gaze-contingent design. Participants were instructed to maintain fixation to the left (red) square while numbers are presented in the center of the screen, updated every 80 ms. After 250 ms, the red square turned yellow and, after another 750 ms, it turned green. If participants break their fixation during this period, the trial was aborted and a new trial automatically began. If not, the left square turned green and the center point was switched to letter presentations. The green square was a cue to perform a single fixation in the center of the screen, and to rapidly move the eyes to the right square, yielding a saccade-fixation-saccade complex. If they did not complete this sequence before 840 ms, a "Slow" sign appeared in the center of the screen, the trial was aborted, and a new trial automatically began. Otherwise, the letter presentation stopped, and a response screen appeared where participants were requested to report about the content of what was presented in the center of the screen.

degrees of visual angle; position: 19.2 degrees to right on the horizontal meridian). Each letter was presented during 70 ms with an Inter-Stimulus Interval (ISI) of 10 ms, therefore resulting in a Stimulus Onset Asynchrony (SOA) of 80 ms. Experiments were implemented in Matlab, using the Psychophysics Toolbox extensions (Brainard, 1997). Sequences of letters were generated by randomly sorting all letters in the Latin alphabet. Only one letter was presented at each time, and within each trial no letter was presented twice.

Structure of each trial: Gaze-Contingent design. Each trial involved the following sequence of steps (see Figure 1):

Step 0. Participants direct their gaze to a red square in the left side of the screen. Eye movements are analyzed on real-time and when a fixation to the red square is detected the trial proceeds to Step 1.

Step 1. Participants maintain fixation on the red square. In the center of the screen, single digit numbers (instead of letters) are presented in RSVP, updated every 80 ms. After completing the experiment none of the participants reported seeing numbers. After 250 ms of sustained fixation, the square turns yellow and after 750 ms, it turns green. If during this period participants break their fixation (i.e., if the distance of the gaze to the center of the fixation square is greater than 0.4 degrees), then the trial is aborted.

Step 2. The left square turns green. The RSVP switches to letters updated at the same pace (80 ms per item). Participants are asked to move their eyes rapidly, performing a single fixation to the center of the screen, where letters are presented in RSVP, and then again another fixation to the square situated in the right point of the screen. If they do not complete this sequence in 840 ms, the trial is aborted. Otherwise, the trial proceeds to Step 3.

Step 3. If participants fixate in time and accurately (less than 0.4 degrees) to the *end trial fixation square*, a response screen is presented. In the response screen, participants report whether they saw a target (the letter X) and the confidence in their response in the RSVP.

Task. We randomly inserted the letter 'X' between positions 2 and 11 within the sorted sequence of letters (i.e., with an onset time of 80 ms to 800 ms from the beginning of Step 3). We generated 290 target trials (29 trials in each of the 10 positions of letter 'X') and 10 'catch trials' (where letter 'X' was absent), giving a total number of 300 trials.

Participants reported whether or not they had seen the letter 'X' by clicking the mouse in a "No" or "Yes" button. Following this binary response, participants responded their confidence in a graded scale (a continuous line). If they were 100% sure about having seen the letter 'X,' they were asked to enter their answer on the right-most point of the line. Conversely, if they were 100% sure of not having seen the target letter, they were asked to enter their answer on the left-most point of the continuous line. Participants were asked to use the line to report intermediate values of confidence of having seen the target. We scaled this answer to the interval $[-1, 1]$.

The experiment was divided in two sessions of 150 trials, separated by a 5 minutes resting break. All trials in which the distance of the fixation to the center of the RSVP exceeded 0.4 degrees or in which participants made more than one fixation within the central RSVP were rejected. The rejection procedure was very strict and resulted in the rejection of a high fraction of

the trials (61.3%, range: [37%, 83%]). Overall, the experiment lasted approximately 1 hour.

Data analysis.

Quantifying the temporal variations of visibility and confidence. We analyzed the data locking all times to the fixation onset and fixation offset. Trials were sorted by the time of presentation of letter 'X' (relative to the locked variable) assigning a true value (1) to that time if the target was reported as seen, and a false value (0) otherwise. For the analysis locked to the fixation onset, all the calculations were done using the offset of the target. When locking all the times to the fixation offset, we used the onset of the letter (Figure 2A). To quantify the temporal variations of visibility, we segmented the time in nonoverlapping bins of 10 milliseconds, and calculated the fraction of trials in which the target was presented in each bin, that is, $T_{Presented}(t)$, which varied from trial to trial since the onset of the saccade was not under experimental control. We also computed for each bin the fraction of trials in which the target was presented at this given bin and reported as seen, that is, $T_{Reported}(t)$. The ratio between these two variables reflects the participant's visibility as a function of time (see Table 1). Next, we studied the dynamics of confidence on correct identifications of the target following the procedure described above. Time was segmented in nonoverlapping bins of 10 milliseconds, and for each bin we computed the mean $Confidence(t)$.

Determining the temporal kernel of visibility. For each individual participant, we defined the onset of the temporal kernel of visibility as the time from fixation onset in which participants began reporting the target with a probability significantly different from zero. Similarly, the offset of the temporal kernel of visibility was defined as the time relative to fixation offset in which the participant stopped reporting the target with a probability significantly larger than zero. This procedure was performed by adapting a robust method taken from the statistical quality control literature (Roberts, 2000), also implemented to filter fast guesses in the Ratcliff Diffusion Model (Ratcliff & McKoon, 2008), and to compute minimum RTs in ultrafast decision-making tasks (Milosavljevic, Madsen, Koch, & Rangel, 2011).

The method consists in calculating an exponentially weighted moving average (EWMA) of the participants' responses ($1 = \text{seen}$, $0 = \text{unseen}$) after ordering the data according to its time of presentation:

$$EWMA_i = \lambda X_i + (1 - \lambda)EWMA_{i-1} \quad (1)$$

with $i \geq 1$, where λ indicates the amount of weight given to past observations, and X_i is the response of the i th observation. When all times are aligned to the fixation onset, the first observations will correspond to presentations occurring during the previous saccade and though $EWMA_0$ is defined as 0 (no visibility). To measure time relative to fixation offset, all times are multiplied by a factor of -1 , and the procedure is identically repeated.

The upper boundary of the confidence interval for the EWMA statistic under the null hypothesis of no visibility is as follows:

$$UB_i = \mu + N\sigma \sqrt{\frac{\lambda}{2 - \lambda} (1 - (1 - \lambda)^{2i})} \quad (2)$$

where $\mu = \text{mean}(X_i) = 0$, and $\sigma = \text{std}(X_i) = 0.5$ are the mean and

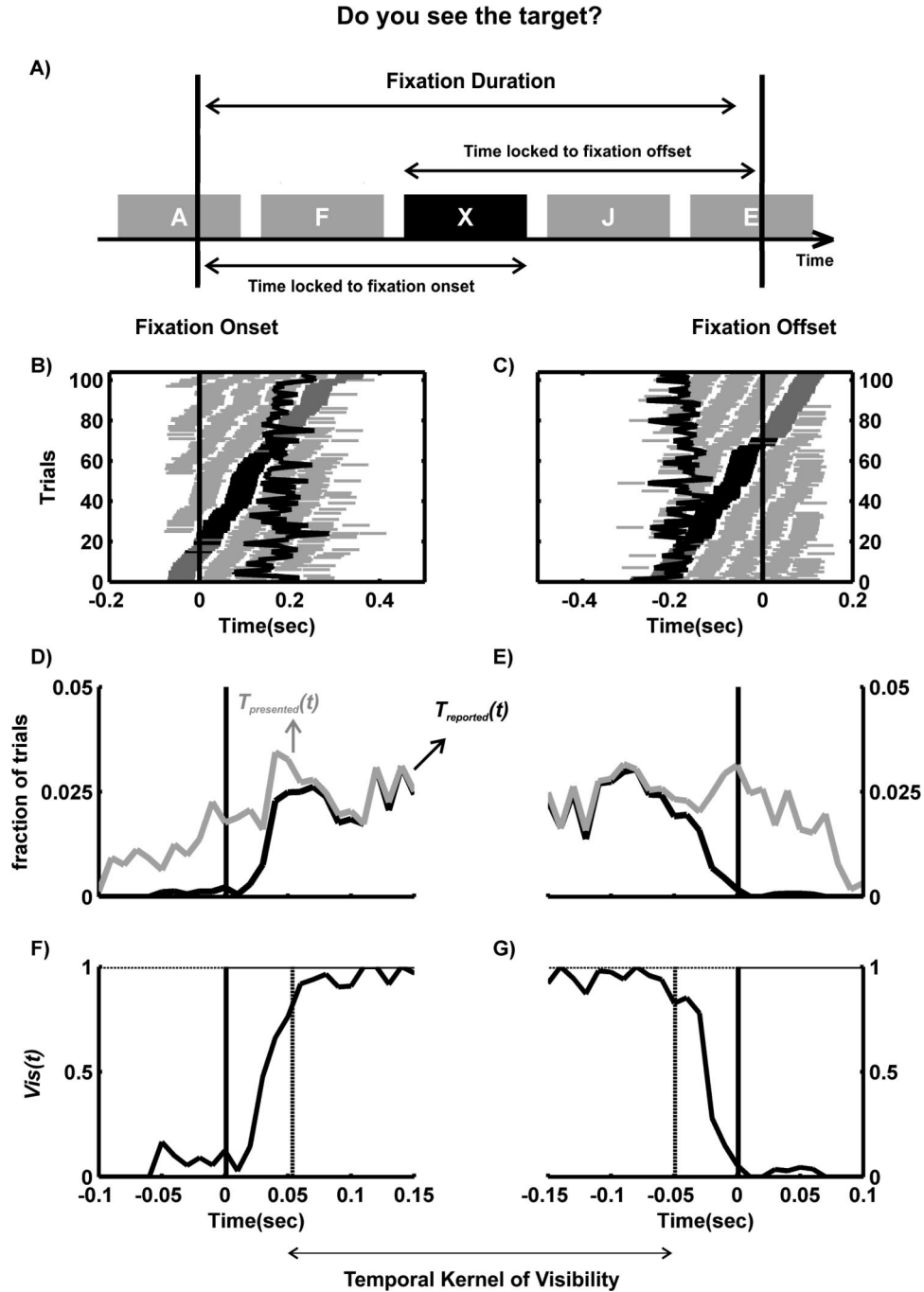


Figure 2. Temporal kernel of visibility during eye movements. In Experiment 1, participants were instructed to report the presence/absence of letter 'X' within the sequence of presented letters. A) For each trial we computed the time of presentation of all distractor letters (light gray), the time of onset and offset of the central fixation (black lines) and the time of presentation of the target letter (black). B) These times relative to fixation onset for all considered trials of a typical participant. Trials are sorted by the time of presentation of the target letter (black if seen, dark gray if not). C) The same as B but relative to fixation offset. D) Fraction of trials in which the target letter was presented as a function of time relative to fixation onset (gray line), and fraction of trials in which the target was presented and reported as seen (black line) as a function of its time of presentation relative to fixation onset (black vertical line). E) The same as D but relative to fixation offset (black vertical line). F) Probability to report the target as a function of its time of presentation relative to fixation onset. The gray dotted line shows the onset of the temporal kernel of visibility ($Konset$). G) The same as F but relative to fixation offset. The gray dotted line shows offset of the temporal kernel of visibility ($Koffset$).

Table 1

Summary of Variables Used to Estimate the Dynamics of Visibility and Choice During Eye Movements: Description and Definition of the Variables Used Along the 4 Experiments Presented in the Current Study

Variable	Description	Definition	Experiment
$T_{Presented}(t)$	Fraction of trials in which the target was presented, as a function of its time of presentation.		Exp. 1–2
$T_{Reported}(t)$	Fraction of trials in which the target was reported, as a function of its time of presentation.		Exp. 1–2
$Vis(t)$	Visibility as a function of time.	$Vis(t) = \frac{T_{Reported}(t)}{T_{Presented}(t)}$	Exp. 1–2
$MT(\mu)$	Minimum time at which a processing significantly larger than μ is achieved.	First time at which the EWMA statistic (Equation 1) permanently exceeds UB_i as defined by Equation 2.	Exp. 1–2
$Konset, (Koffset)$	Minimum time at which a processing significantly larger than 0 is achieved. $Konset$ ($Koffset$) is time relative to the fixation onset (offset).	First time at which the EWMA statistic (Equation 1) permanently exceeds UB_i as defined by Equation 2 with $\mu = 0$. (Equivalent to $MT(\mu = 0)$)	Exp. 1–2
$Confidence(t)$	Confidence on correct identification of the target, as a function of its time of presentation.		Exp. 1–2
$L_{Presented}(t)$	Fraction of trials in which a letter was presented, as a function of its time of presentation.		Exp. 3–4
$L_{Reported}(t)$	Fraction of trials in which a letter was reported, as a function of its time of presentation.		Exp. 3
$Choice(t)$	Choice of a single letter as a function of time.	$Choice(t) = \frac{L_{Reported}(t)}{L_{Presented}(t)}$	Exp. 3
NR	Number of Reported Letters		Exp. 4
$L_{Reported_{NR}}^i(t)$	Fraction of trials in which the i th of NR letters was presented, as a function of its time of presentation.		Exp. 4
$Choice_{NR}^i(t)$	Choice of the i th of NR letters, as a function of time.	$Choice_{NR}^i(t) = \frac{L_{Reported_{NR}}^i(t)}{L_{Presented}(t)} \text{ With } i \leq NR.$	Exp. 4

standard deviation of each observation under the null hypothesis, respectively. The other parameters used in this study were $n = 2$ and $\lambda = 0.01$. The onset (offset) of the temporal kernel of visibility is defined as the smallest time from fixation onset (offset) at which the EWMA measure permanently exceeds (falls below) UB_i . These times are referred to as $Konset$ and $Koffset$, respectively, throughout the article.

A similar approach was implemented to calculate the minimum time at which a processing significantly larger than μ can be achieved. We defined this variable as $MT(\mu)$. To calculate $MT(\mu)$, we found the smallest time from fixation onset (offset) that the EWMA statistic permanently exceeded (fell below) UB_i as defined by Equation (2), but using different values of μ . We used values of μ ranging from 0 to 0.75 in steps of 0.25. When using times relative to the fixation onset (offset), $MT(\mu = 0)$ is equivalent to $Konset$ ($Koffset$).

Results and Discussion

Eye movements. In spite of the time pressure imposed by the experiment, the distribution of fixation times was similar to the one observed in natural tasks, such as reading (R. Kliegl, Nuthmann, & Engbert, 2006; R. Kliegl, Risse, & Laubrock, 2007) and visual searches (Kotowicz et al., 2010). The mean saccadic latency from the *begin trial fixation square* was 363 ± 97 ms and the mean fixation duration in the central stream was 233 ± 13 ms.

Temporal kernel of visibility in single fixations. Because participants freely decided when to initiate and terminate the fixation, the time of target onset relative to fixation onset and

offset varied from trial to trial (Figure 2B and 2C). Participants did not see the target when it was presented during saccades, in agreement with an extensive literature supporting the fact that vision is actively suppressed during saccades, a phenomenon referred to as saccadic suppression (e.g., Burr et al., 1994). In contrast, participants could easily report the presence of the target when it was entirely presented during the fixation. Only in the trials in which the target was partly presented during the fixation and partly during the saccade did we observe a regime in which participants reported seeing the target with variable probability.

To quantify this observation, we measured for each time the fraction of trials in which the target was presented (i.e., $T_{Presented}(t)$), and the fraction of trials in which the target was reported (i.e., $T_{Reported}(t)$; Figure 2E and 2F). $T_{Reported}(t)$ was close to zero before the fixation onset and after the fixation offset (i.e., during any of the two saccades). To determine the precise onset and offset of visibility, we computed $Vis(t)$ defined as the ratio between $T_{Reported}(t)$ and $T_{Presented}(t)$; see Table 1) locked to fixation onset (Figure 2D), and to fixation offset (Figure 2E). Establishing a statistical criterion for visibility (described in Methods), we measured for each participant $Konset$ and $Koffset$, (see Table 2). Visibility differs significantly from zero when the target is presented at least during 54 ± 4 ms after the fixation onset and similarly, the target is visible if the saccade starts not earlier than 49 ± 5 ms after stimulus presentation. These symmetrical observations suggest that, in this experimental condition, the target has to be present at least 50 ms during a fixation to be reported.

Table 2

Limits of the Temporal Kernel of Visibility During Eye Movements: Individual Onsets and Offsets of the Kernel (Konset and Koffset, Respectively), Mean Fixation Duration, and Number of Trials Considered for Analysis in Experiment 1

Participant	Konset (ms)	Koffset (ms)	Fixation duration (mean \pm SEM) (ms)	n
1	62	68	177 \pm 4	103
2	54	56	260 \pm 4	63
3	59	32	223 \pm 7	113
4	45	38	210 \pm 4	82
5	57	62	303 \pm 9	53
6	33	67	286 \pm 5	167
7	38	47	220 \pm 4	189
8	72	23	245 \pm 5	179
9	51	50	206 \pm 4	136
10	65	48	196 \pm 3	139
Average (mean \pm SEM)	54 \pm 4	49 \pm 5	233 \pm 13	122 \pm 15

We then studied the amount of processing achievable at different times. This was done by increasing the parameter μ of Equation (2) from 0 to 0.75 (i.e., $MT(\mu)$; see Methods and first column of Table 3). We observed that $MT(\mu)$ increases alongside with μ both relative to the fixation onset (1-way rm-ANOVA with $\mu = \{0, 0.25, 0.5, 0.75\}$ as within-subject factor: $F_{(3,27)} = 6.6, p < .005$) and relative to the fixation offset (1-way rm-ANOVA with $\mu = \{0, 0.25, 0.5, 0.75\}$ as within-subject factor: $F_{(3,27)} = 8.4, p < .001$). These results are in line with a wide variety of physiological experiments summarized by Reichle and Reingold (2013), stating that the retina-brain lag is approximately 60 ms (similarly to our measure of *Konset*).

Dynamics of confidence in single fixations. The analysis of the previous section showed that when the target was entirely presented during the fixation, $Vis(t)$ was at ceiling, and participants very rarely failed to see it. With the confidence report we can investigate whether during this regime the feeling of confidence is

constant or whether instead, subjective confidence varies when the target is presented at different windows within the fixation (even if the target is always reported). To this aim, we measured the confidence report in the trials in which participants correctly identified the presence of the target (Figure 3). $Confidence(t)$ showed a slow monotonic increase reaching its maximum just before the offset of the kernel (i.e., 80 ms before the fixation offset). This monotonic growth continued even beyond the time when $Vis(t)$ saturated to values close to 1 (150 ms before fixation offset). This observation was quantified by a linear regression of the temporal dynamics of $Confidence(t)$ locked to fixation offset ($Confidence(t) = A + B * Time$; $A = (1.022 \pm 0.008)$, $B = (2.263 \pm 0.702)$, $F_{(1,7)} = 7.29, p < .05, R^2 = 0.51$).

The relation between *confidence* and $Vis(t)$ (Figure 3C) was poorly fitted by a linear regression ($Vis(t) = A + B * Confidence$, $A = (0.154 \pm 0.006)$, $B = (0.981 \pm 0.013)$, $df = 13, t = 1.93, p > .05$). Instead, a sigmoid regression fitted the relation between these

Table 3

Amount of Processing Achievable at Different Times: Minimum Fixation Time Needed to Render the Stimulus Visible With a Probability Significantly Larger Than μ (See Equation 2) After Fixation Onset (Upper Table) or Before Fixation Offset (Lower Table)

Condition	Experiment 1	Experiment 2		
	Main study	Main study	ISI	SOA
Amount of processing		Time relative to fixation onset		
$MT(\mu = 0)$ (<i>Konset</i>)	(54 \pm 4) ms	(52 \pm 9) ms	(45 \pm 6) ms	(45 \pm 9) ms
$MT(\mu = 0.25)$	(62 \pm 5) ms	(58 \pm 9) ms	(52 \pm 7) ms	(58 \pm 11) ms
$MT(\mu = 0.5)$	(75 \pm 10) ms	(82 \pm 5) ms	(81 \pm 11) ms	(85 \pm 12) ms
$MT(\mu = 0.75)$	(91 \pm 14) ms	(96 \pm 13) ms	(90 \pm 7) ms	(108 \pm 23) ms
		Time relative to fixation offset		
$MT(\mu = 0)$ (<i>Koffset</i>)	(-49 \pm 5) ms	(-55 \pm 5) ms	(-48 \pm 6) ms	(-27 \pm 5) ms
$MT(\mu = 0.25)$	(-60 \pm 6) ms	(-59 \pm 6) ms	(-53 \pm 5) ms	(-30 \pm 6) ms
$MT(\mu = 0.5)$	(-66 \pm 6) ms	(-73 \pm 6) ms	(-68 \pm 6) ms	(-56 \pm 8) ms
$MT(\mu = 0.75)$	(-81 \pm 11) ms	(-85 \pm 11) ms	(-96 \pm 16) ms	(-68 \pm 3) ms

Note. The tables display the mean \pm SEM across participants for each condition of Experiments 1 and 2. We compared Experiment 1 and ‘Main study’ condition of Experiment 2 using 2-way mixed effects ANOVA with experiment as between-subject factor and μ as within-subject factor. Relative to fixation onset, experiment: $F_{(1,9)} = 0.02, p = .88, \mu: F_{(3,54)} = 22.8, p < 10^{-8}$; relative to fixation offset, experiment: $F_{(1,18)} = 0.2, p = .65, \mu: F_{(3,54)} = 21.3, p < 10^{-8}$. The comparison within Experiment 2 was performed using a 2-way Rm-ANOVA with μ and condition as within-subject factors. Relative to fixation onset, $\mu: F_{(3,27)} = 52.1, p < 10^{-10}$; Condition: $F_{(1,18)} = 0.2, p = .82$; $\mu \times$ Condition: $F_{(3,27)} = 0.5, p = .80$. Relative to fixation offset, $\mu: F_{(3,27)} = 52.4, p < 10^{-10}$; condition: $F_{(1,18)} = 14.6, p < .001$; $\mu \times$ condition: $F_{(3,27)} = 5.3, p < .001$.

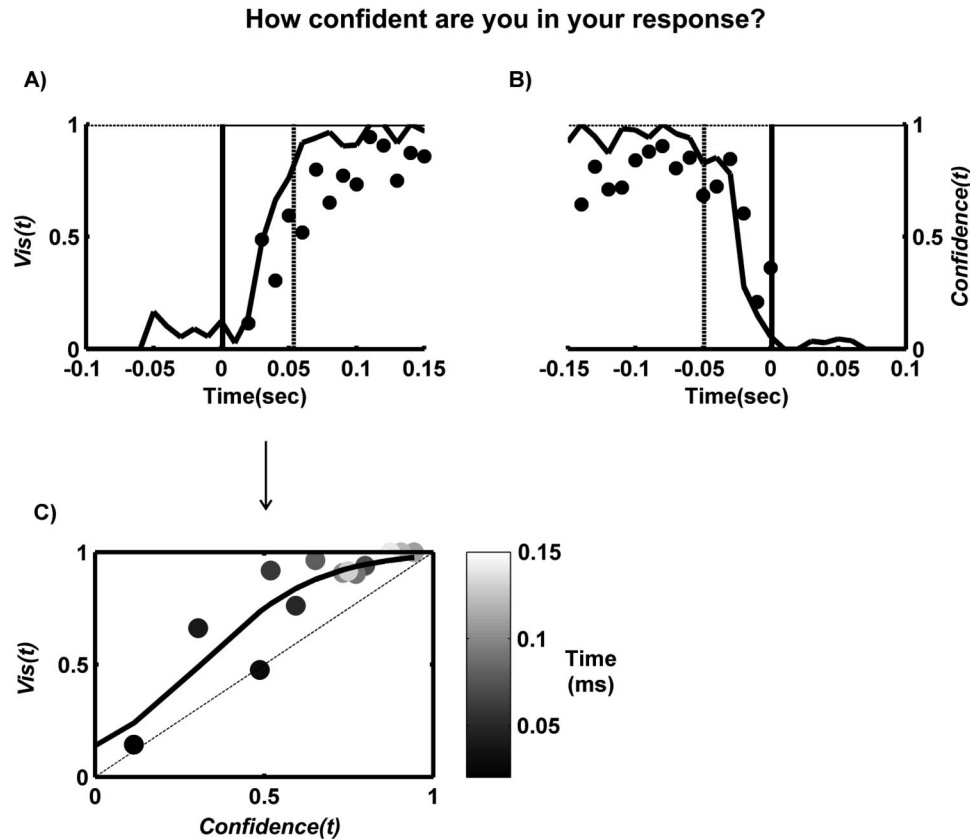


Figure 3. Dynamics of confidence during eye movements. In Experiment 1, participants were requested to report the *confidence* on their response on a continuous line. A) Probability to report the target (black line) and *confidence* on positive responses (black dots), as a function of the time of presentation of the target, relative to fixation onset (black vertical line). The dotted line shows the onset of the temporal kernel of conscious access. B) The same as A but relative to fixation offset (black vertical line). The dotted line shows the offset of the temporal kernel of conscious access. C) Probability to report the target as a function of *confidence*. The intensity of each dot codifies the time of presentation of the target letter relative to fixation onset. The identity (black dotted line) and a sigmoid regression (black solid line) are superposed to the data.

variables significantly better ($Vis(t) = 1/(1 + \exp(-B * (Confidence - A)))$), $A = (0.312 \pm 0.001)$, $B = (5.843 \pm 1.465)$, $df = 13$, $t = 9.89$, $p < .001$). The sigmoid relationship between these two variables suggests that $Vis(t)$ abruptly increases when $Confidence(t)$ crosses a threshold, after which it remains close to perfect (see General Discussion).

Experiment 2: Temporal Dynamics of Visibility Under Different Conditions of Visual Stimulation

In Experiment 1 we could derive a timescale of about 50 ms to render a stimulus visible in a single fixation. Moreover we showed that the window of visibility was homogeneous throughout the fixation, but confidence was not, ramping toward the end of the fixation. This experiment cannot distinguish whether these results are specific to the temporal properties of the stimuli or if, alternatively, they reflect intrinsic parameters of information processing during eye movements. In Experiment 2, we sought to disentangle these possibilities by studying the limits of the temporal kernel of visibility in a paradigm where we changed two temporal properties

of the visual stimulation: the stimulus onset asynchrony (SOA), and the interstimulus interval (ISI).

Method

Participants. Participants ($n = 10$, 3 female, mean age: 26.2 years, SD : 4.1 year) were undergraduate and graduate students. Two of these participants also performed Experiment 1, while the remaining eight were naïve. All participants had normal or corrected to normal vision.

Stimuli. This experiment had three different conditions, organized in a blocked design. In the first condition, we used exactly the same parameters of Experiment 1 ('Main Study' condition, stimulus duration = 70 ms, ISI = 10 ms, SOA = 80 ms). In the 'ISI changed' condition we modified the ISI by shortening the time of presentation (stimulus duration = 30 ms, ISI = 50 ms, SOA = 80 ms). In the 'SOA changed' condition we varied the SOA also by shortening the time of presentation (stimulus duration = 30 ms, ISI = 10 ms, SOA = 40 ms). These three experimental conditions are schematized in Figure 4A.

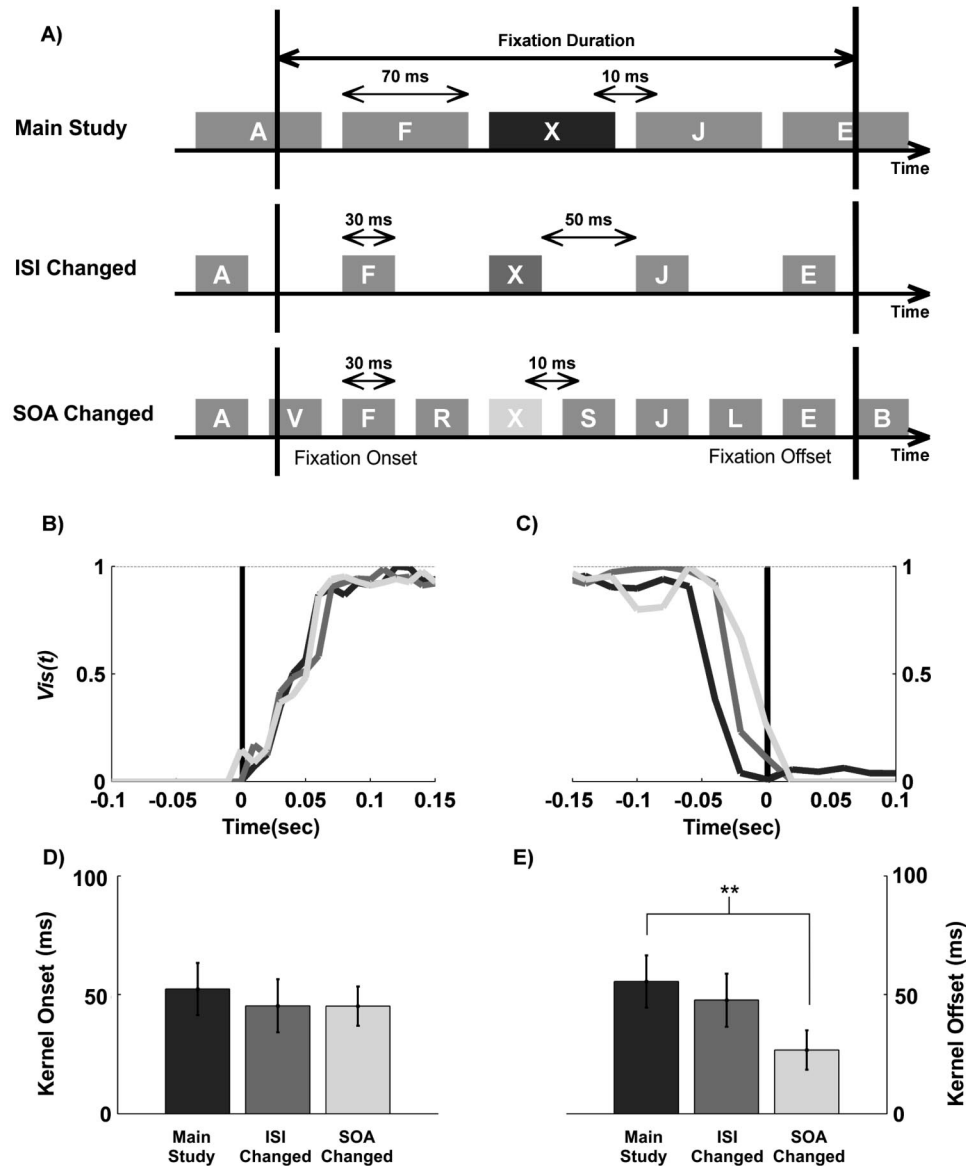


Figure 4. Temporal kernel of visibility under different conditions of visual stimulation. In Experiment 2, participants were instructed to report the presence/absence of letter 'X' within the sequence of presented letters, for three different conditions of visual stimulation. A) Stimuli presentation: 'Main Study' condition: SOA = 80 ms, ISI = 10 ms (black); 'ISI changed' condition: SOA = 80 ms, ISI = 50 ms (dark gray); 'SOA changed' condition: SOA = 40 ms, ISI = 10 ms (light gray). B) Probability to report the target letter as a function of its time of presentation relative to fixation onset. The black vertical line shows the time of onset of the central fixation. C) The same as B but relative to fixation offset. The black vertical line shows the time of offset of the central fixation. D) Mean and SEM of the onset time of the temporal kernel of conscious access (*Konset*). E) Mean and SEM of the offset time of the temporal kernel of conscious access (*Koffset*). Only significant comparisons were marked in the figure. ** $p < .01$.

Task. Task instructions were identical to Experiment 1. In this experiment, each participant performed two sessions of 140 trials for each of the three conditions. All participants completed the six sessions in less than 3 hours separated in two days. The process of trial rejection was identical to Experiment 1, and resulted in the rejection of a significant proportion of trials ('Main Study': $M = 49.2\%$, range = [6%, 74%]; 'SOA changed': $M = 51.8\%$, range = [4% - 71%]; 'ISI changed': $M = 48.1\%$ range = [16%, 80%]).

Results and Discussion

The mean fixation duration was (300 ± 1) ms for the 'Main Study' condition, (317 ± 2) ms for the 'ISI changed' condition, and (331 ± 2) ms for the 'SOA changed' condition. A repeated-measures analysis of variance (rm-ANOVA) revealed that the mean fixation duration exhibited a significant effect of condition ($F_{(2,18)} = 4.31$, $p = .03$). Pairwise multiple comparison tests

showed that the only significant difference was between the ‘Main Study’ condition compared with the ‘SOA changed’ ($p < .05$).

Next, we measured $Vis(t)$ for the three conditions (Figure 4B and 4C) and $Konset$ and $Koffset$ (Figure 4D and 4E). $Konset$ was largely unaffected by the temporal parameters of visual stimulation (Figure 4B and 4D, rm-ANOVA: $F_{(2,18)} = 0.33, p = .72$). Instead, $Koffset$ varied with the update frequency of the RVSP (Figure 4C and 4E; rm-ANOVA: $F_{(2,18)} = 12.4, p < .001$; Pairwise Multiple Comparison Test: ‘Main Study’ vs. ‘SOA changed’: $p < .001$; ‘Main Study’ vs. ‘ISI changed’: $p = .34$; ‘SOA changed’ vs. ‘ISI changed’: $p < .01$).

We then calculated for each condition the minimum time at which a processing significantly larger than μ is achieved, that is, $MT(\mu)$, for $\mu = \{0, 0.25, 0.5, 0.75\}$. This analysis shows in the first place that Experiment 1 and the ‘Main Study’ condition of Experiment 2 yielded virtually identical results both from the onset and the offset of the fixation (see Table 3, column 1 and 2; *Relative to fixation onset*: $F_{(1,19)} = 0.02, p = .88$; *Relative to fixation offset*: $F_{(1,19)} = 0.2, p = .65$). Given that these two conditions are the same, this finding confirmed the robustness and reproducibility of our experimental design. For all conditions, $MT(\mu)$ increased along with μ both relative to the fixation onset (see Table 3, column 2 to 4; $F_{(1,9)} = 52.1, p < .001$), and relative to the offset of fixation (see Table 3, column 2 to 4; $F_{(1,9)} = 52.4, p < .001$). Interestingly, there were no significant differences between conditions in Experiment 2 when looking from the onset of fixation (see Table 3, column 2 to 4; $F_{(1,9)} = 0.2, p = .82$). In turn, when calculating $MT(\mu)$ relative to the fixation offset, the SOA condition was significantly closer to the fixation offset than the other two conditions (see Table 3, column 2 to 4; $F_{(1,9)} = 14.6, p < .001$; Bonferroni post hoc tests: Main Study vs. ISI: $p > .05$, Main Study vs. SOA: $p < 10^{-10}$, ISI vs. SOA: $p < 10^{-10}$).

This experiment demonstrates that the temporal window of visibility is not symmetric, that is, the total time of presentation required to render a stimulus visible is not the same when it is just after a saccade than when it is just before. In the light of this observation, we reanalyzed the data of Experiment 1 to determine whether in a participant by participant basis, there was a correlation between $Konset$ and $Koffset$. Analysis showed that these variables were uncorrelated with each other ($r = -0.38, p = .27$), suggesting that they reflect independent processes. Interestingly, the window of visibility was wider in the ‘SOA changed’ condition, where one may have expected visibility to be more impaired because the presentation time is shorter and the number of items (and hence of masks) is maximal (Enns & Di Lollo, 2000). A very influential theory of visual perception suggests that perception is structured in episodes (Dehaene, Sergent, & Changeux, 2003). In the framework of this theory (Dehaene et al., 2003) or similarly in Posner’s description of engagement and disengagement of attention (Posner, 1980), our results suggest that the initiation of an episode (or the engagement of attention) is relatively insensitive to the temporal properties of the stimuli. Instead, the closing of an episode (disengagement) seems to be entrained by the temporal frequency of the stimuli.

As in Experiment 1, confidence increased linearly from $Konset$, reaching its maximum just before $Koffset$. ($Confidence(t) = A + B * Time$; ‘Main Study’: $A = (0.241 \pm 0.018)$, $B = (0.007 \pm 0.002)$, $F_{(1,7)} = 10.09, p < .05, R^2 = 0.62$; ‘ISI changed’: $A = (0.112 \pm 0.004)$, $B = (0.004 \pm 0.001)$, $F_{(1,7)} = 48.27, p < .001$,

$R^2 = 0.89$; ‘SOA changed’: $A = (0.218 \pm 0.001)$, $B = (0.003 \pm 0.001)$, $F_{(1,7)} = 6.67, p < .05, R^2 = 0.52$). As in Experiment 1, we also observed a dissociation between $Confidence(t)$ and $Vis(t)$ for the three conditions, and a sigmoid regression accurately fitted the data ($Vis(t) = 1/(1 + \exp(-B * (Confidence(t) - A)))$); ‘Main Study’: $A = (0.421 \pm 0.002)$, $B = (4.806 \pm 0.695)$, $df = 13, t = 2.49, p < .05$; ‘ISI changed’: $A = (0.328 \pm 0.002)$, $B = (5.543 \pm 1.091)$, $df = 13, t = 5.89, p < .001$; ‘SOA changed’: $A = (0.345 \pm 0.002)$, $B = (8.398 \pm 1.409)$, $df = 13, t = 3.64, p < .01$).

In summary these results show that a) the ignition of visibility is independent of the dynamics of the RSVP, and b) the temporal limit of visibility relative to the offset of the fixation varies with stimulus properties. This is not simply explained by masking because the visibility of targets extends closer to the fixation in the more masked conditions (with faster rhythm of presentation). These results are consistent with a rhythmic organization of attention which can be entrained by stimulus properties, regulating the closure of an attentional episode (Wyble, Nieuwenstein, & Bowman, 2009) or disengagement of attention (Posner, 1980). In all conditions confidence varies within the regime in which visibility is constant, showing maximal confidence when the stimulus is presented in the later segments of the window of visibility compared with the earlier segments of the window of visibility. This result is independent of the number of distractors following the target (which varies in different conditions) and hence does not seem to be a direct consequence of masking.

Experiment 3: Temporal Dynamics of Choice of a Single Item

In Experiment 1 and Experiment 2, we measured visibility based on the probability to report a predefined target. However, in natural vision, target selection results from the interaction from bottom-up and top-down saliency mechanisms by which we freely select the relevant information (the target) through different parameters of saliency. Here we set to investigate whether a) there is a temporal selection bias when more than one target is presented within a fixation, and b) whether this bias may be determined by the dynamics of confidence. To this aim, in Experiment 3, we investigated this issue by asking the participants to freely report a single item from the array of letters.

Method

Participants. Ten participants (2 female, mean age: 23.7 years; SD : 2.4 years) of Experiment 1 also performed Experiment 3. All of them were naïve with the only exception of author J.N., and had normal or corrected to normal vision. Participants completed 300 trials successfully.

Task. Participants were required to report a single letter from the array. At the end of the trial, an image of a QWERTY keyboard appeared over a black screen and participants were instructed to select the chosen letter simply by clicking on it with the mouse. In the case of seeing more than one letter, participants were encouraged to report the one on which they were most confident about its presentation. Responses had to be imputed in less than 3.5 seconds. Immediately, a feedback was given on whether or not the selected letter was present in the array. After clicking on the mouse, a new trial began.

Data analysis. The procedure to compute the probability to choose a single item (i.e., $Choice(t)$, see Table 1) was analogous to the one used to compute $Vis(t)$ in Experiment 1 and Experiment 2. First, we estimated the fraction of trials in which any letter was presented for each time bin (i.e., $L_{Presented}(t)$). We then computed the fraction of trials in which we presented the reported letter (i.e., $L_{Reported}(t)$). The ratio between these two curves reflects the probability of to choose a letter as function of time (i.e., $Choice(t)$). As in Experiment 1, we performed the analysis locked to fixation onset separately from the analysis locked to fixation offset.

Results and Discussion

In this experiment participants were asked to freely report one item from the array of letters. The objective is to determine whether the probability of reporting one letter (when more than one is presented during a fixation) correlates with the perceived confidence observed in Experiments 1 and 2 in which participants reported a fixed target. For each trial we computed the time of presentation of each letter, the time of onset and offset of the fixation in the center of the screen, and the response (Figure 5A). Figure 5B shows the data for a typical participant locked to fixation offset, for each trial sorted by time of presentation of the selected letter. The fixation duration, (188 ± 21) ms, was shorter than the one observed for Experiment 1 (paired t test $df = 5$, $t = 3.56$, $p < .01$). This is expected because in this experiment participants do not need to wait for the target and can just proceed

when they have seen a letter. However, as exemplified in Figure 5A, in many trials more than one letter was presented during the fixation, which can be then used to investigate the dynamics of free choice. We also note that 188 ms constitutes an upper bound for participants to begin the fixation, identify a target, and proceed to the next fixation. This time is very short compared with most response time experiments and is in line with views of very rapid extraction of object information (Crouzet, Kirchner, & Thorpe, 2010; Kirchner & Thorpe, 2006; Milosavljevic et al., 2011).

We computed the probability to select an item as a function of time, $Choice(t)$ (see Table 1). Compared with $Vis(t)$ measured in Experiments 1 and 2, $Choice(t)$ was more closely locked to fixation offset, reaching its maximum just before $Koffset$. A joint analysis of the dynamics of $Choice(t)$ (Experiment 3), $Vis(t)$ and $Confidence(t)$ (Experiment 1) showed that the maximum of choice (when more than one target is presented in a fixation and participants freely choose) coincides with the peak in the confidence (when only one target is predefined and participants assign the confidence of having seen it). A t test comparing the peaks of $Confidence(t)$ and $Choice(t)$, obtained in independent experiments for each individual participant, revealed that these values were not significantly different (paired t test: $df = 5$, $t = 0.91$, $p = .4$). This shows that although an item may be visible in a broad temporal window extending almost throughout the entire fixations, when let free to choose participants opt for the letter which was presented just before the saccade. This coincides quantitatively with the

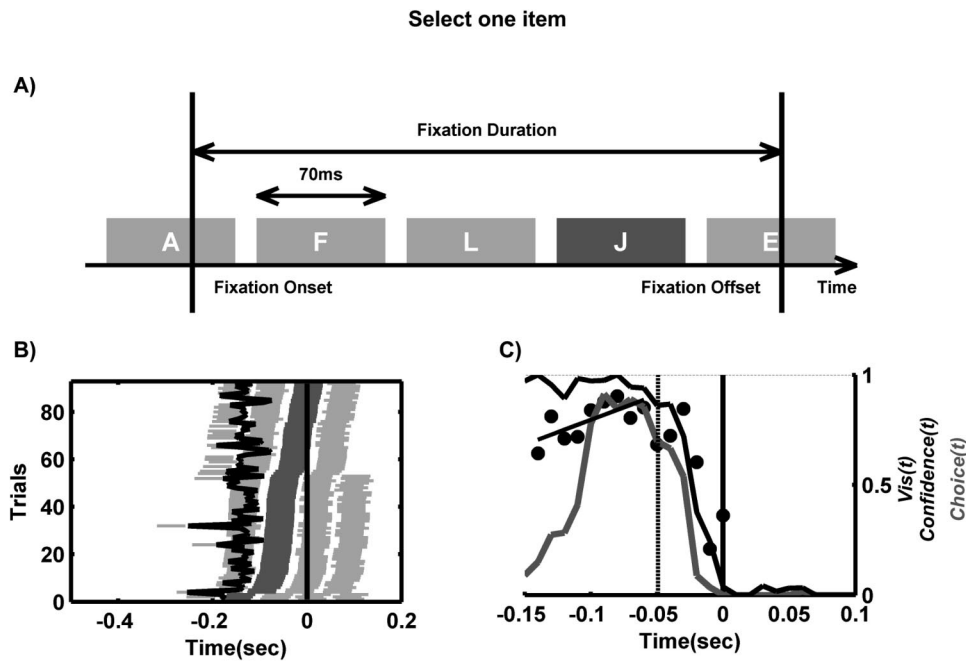


Figure 5. Dynamics of selection of a single item. In Experiment 3, participants were instructed to select one letter. A) For each trial we computed the time of presentation of all letters (dark gray if it is the reported letter, light gray if not) and the time of onset and offset of the central fixation (black). B) These times relative to fixation offset for all considered trials of a typical participant. Trials are sorted by the time of presentation of the selected letter. C) Probability to report a target (black line, Experiment 1), *confidence* (black dots, Experiment 1), and probability to select an item (gray line, Experiment 2) as a function of time relative to fixation offset (black vertical line). Data is superposed to a linear regression for the temporal dynamics of *confidence* (black straight line) prior to *Koffset* (dotted line).

moment in which a participant assigns greater confidence when asked to look for a fixed target which may be presented at different times within the fixation.

Experiment 4: Temporal Dynamics of Choice of Multiple Items

Experiments 1, 2 and 3 coherently show that a) a target is visible if presented in a wide range covering almost the entire fixation, b) despite this uniform distribution of visibility, confidence grows monotonically, and hence targets presented closer to the end of the fixation are perceived with greater confidence, and c) when more than one target is available and participants are asked to report one freely, the same bias toward the last segment of the fixation is systematically observed.

In Experiment 4, we ask whether it is possible to report more than one of the items presented in a single fixation. To do so, we investigate the number of items that participants can choose and study the temporal dynamics of selection across eye movements.

Method

Participants. Participants ($n = 9$; 6 female, mean age 24.4 years; SD 2.1 year) were undergraduate and graduate students. All of them had normal or corrected to normal vision and were naïve with the only exception of author J.N. Author J.N. is the only participant who performed previous experiments. Participants completed 300 trials successfully.

Task. Participants were required to report all the perceived items from the array of letters. At the end of the trial, an image of a QWERTY keyboard appeared over a black screen and participants were instructed to select the chosen letters simply by clicking on it with the mouse. In the case of seeing more than one letter, participants were asked to report them in the correct order of presentation. Participants had up to 3.5 seconds to enter their answer after which the keyboard disappeared. Immediately, the experiment gave participants a feedback on their response (i.e., whether or not all the selected letters were present in the array).

Data analysis. Trials were grouped according to the number of responses entered by the participants (i.e., NR). Similarly to Experiment 3, we measured for each time bin the fraction of trials in which a letter was presented. Also, for further analysis, here we measure distinctively the fraction of trials in a given bin in which the presented letter was the first, second or the third in the fixation. This enabled us to calculate the probability to identify the i th of NR letters (i.e., $Choice_{NR}^i(t)$, see Table 1).

Results and Discussion

Participants were instructed to report all the perceived items from the array of letters periodically updated in the center of the screen (Figure 6A). This instruction led spontaneously to longer fixation times than the ones observed in Experiment 3, 263 ± 19 ms, ($df = 13$, $t = 2.65$, $p = .01$), although task instructions did not impede participants to maintain the same procedure of rapid fixations and report one or at most two letters. On average, 3.78 ± 0.27 letters were presented within each fixation (compared with 3.05 ± 0.31 in Experiment 3) and participants reported a maximum of three letters (One letter: $11.2 \pm 0.8\%$, Two Letters:

$45.3 \pm 17.1\%$, Three Letters: $43.4 \pm 22.3\%$). Figure 6B shows an example of a participant who reported more frequently two letters.

We separated our analysis according to the number of responses ($nr = 1, 2, 3$), and calculated for each value of nr the probability to select the i th letter as a function of time locked to the fixation onset and offset (i.e., $Choice_{NR}^i(t)$, with $nr = 1, 2, 3$ and $i \leq Nr$, see Table 1). This is a natural extension of the analysis of Experiment 3 to several choices. We first focused on the distributions of $Choice_2^i(t)$, and $Choice_3^i(t)$, locked to the fixation offset (Figure 6C), which are the temporal distributions corresponding to the last reported letter regardless of the total number of reported letters. Following the same argumentation described in Experiment 3, we hypothesized that these distributions would not be homogeneous but, instead, be sharply locked to the fixation offset and in coincidence with the peak in confidence measured in Experiments 1 and 2. To test this hypothesis, we measured for each participant the peaks of the distributions of $Choice(t)$ (Experiment 3), $Choice_2^i(t)$, and $Choice_3^i(t)$ (Experiment 4). A one-way ANOVA confirmed that these values were not significantly different ($F_{(2,19)} = 1.6$, $p > .1$). Interestingly, the times at which we observed a maximum in $Confidence(t)$ in Experiment 1 did not differ to the maximum of $Choice_2^i(t)$ ($df = 13$, $t = 1.3$, $p = .1$), and $Choice_3^i(t)$ ($df = 13$, $t = 0.82$, $p > .1$). Instead, as expected, this difference was significant for $Choice_2^1(t)$ ($df = 13$, $t = 8.37$, $p < .001$), $Choice_3^1(t)$ ($df = 13$, $t = 25.75$, $p < .001$), and $Choice_3^2(t)$ ($df = 13$, $t = 3.41$, $p < .001$). This fits together all results of the previous experiments in a coherent picture. A letter is visible when presented within the fixation, within certain boundary limits described by *Konset* and *Koffset* (Experiments 1 and 2). However, confidence varies reaching a peak close to the end of the fixation (Experiment 1). Consistently when participants are asked to report only one letter they report it close to the peak of confidence (comparison between Experiments 1 and 3) but are able to report more letters in the entire extension of the fixation (comparison between Experiments 1 and 4).

General Discussion

The lack of visibility during saccades (observed in the four experiments) is consistent with a vast literature supporting the view that vision is actively suppressed during eye movements to avoid the perception of motion or a blurred image (i.e., saccadic suppression). Previous studies aimed at explaining this effect provided evidence that the mechanism underlying the lack of perception of motion is a selective suppression of the magnocellular visual pathway during saccades (Burr et al., 1994), which correlates with the silencing of motion-specific cells in the medial temporal lobe (Thiele, Henning, Kubischik, & Hoffmann, 2002). Our results show that visibility extends almost entirely and homogeneously to the fixation interval, starting only after 54 ± 4 ms (*Konset*). These times are similar to the latency at which the primary visual cortex enters into a phase where image elements that belong to figures start to evoke stronger neuronal responses than elements that are part of the background (Roelfsema, Tolboom, & Khayat, 2007; Supér, Spekreijse, & Lamme, 2003), and the first steps in hierarchical feed-forward models of attention (Itti & Koch, 2001; Khayat, Spekreijse, & Roelfsema, 2006). The boost in the activation of neural assemblies at this timing—also shown to be associated to

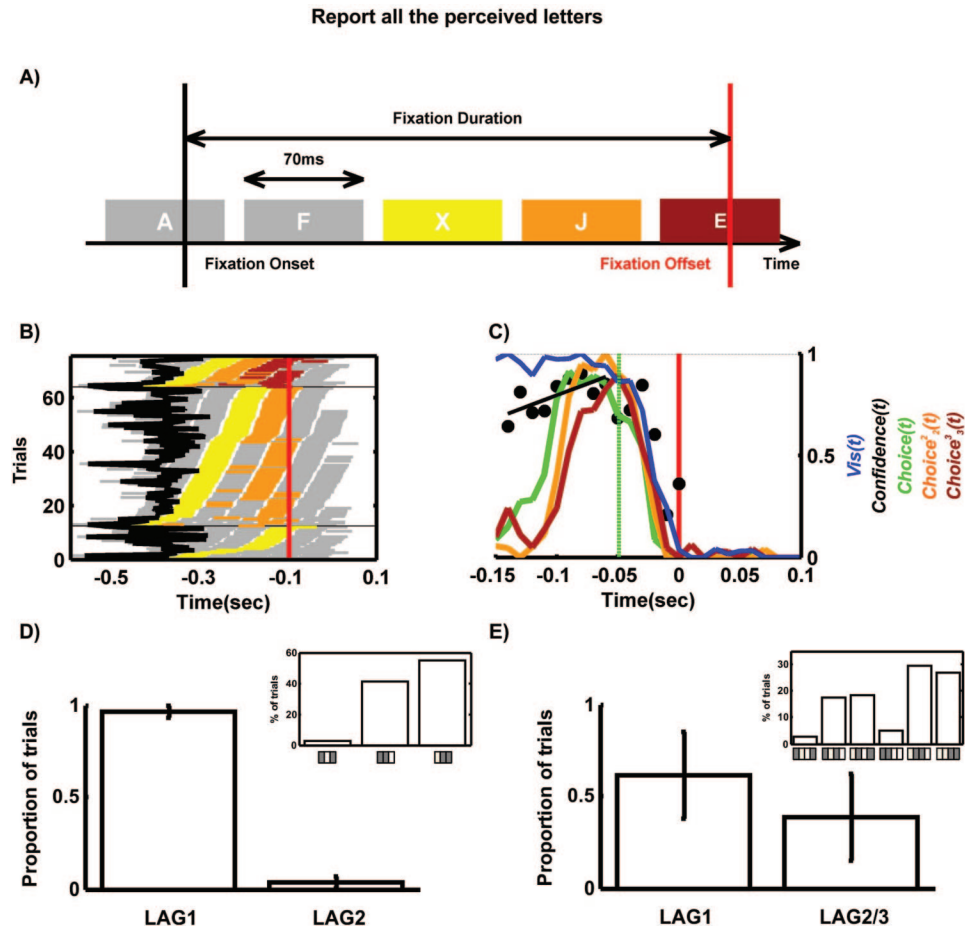


Figure 6. Dynamics of selection of multiple items. In Experiment 4, participants were instructed to report all the perceived items from the presented sequence. A) For each trial we computed the time of presentation of all letters (yellow for the first selected letter, orange for the second selected letter, burgundy for the third selected letter and light gray for all not selected letters), the time of onset of the central fixation (black), and the time of offset of the central fixation (red). B) These times relative to fixation offset for all considered trials of a typical participant. Trials are separated by the number of selected letters (one, two, or three) and then sorted by the time of presentation of the first selected letter. C) Probability to report the target (blue line, Experiment 1), confidence (black dots, Experiment 1), probability to select an item (green line, Experiment 3), probability to select the second of two items (orange line, Experiment 3), and probability to select the third of three items (burgundy line, Experiment 3) as a function of time relative to fixation offset. Data are superposed to a linear regression of the temporal dynamics of confidence (black solid line, Experiment 1) before *Koffset* (dotted line, Experiment 1). D) Trials in which three letters were presented during the fixation, and participants reported two items. Proportion of trials in which the participants reported a pair of letters with lag 1, and a pair of letters with higher lag. Inset: Proportion of trials for each possible combination of selecting two letters from three. E) The same as D but for the trials in which four letters were presented during the fixation and participants reported two items.

object-based attention (Roelfsema, Lamme, & Spekreijse, 1998)—might trigger the recognition of the target through a feed-forward mechanism. This notion is also supported by the fact that *Konset* was independent of the pattern of visual stimulation (Experiment 2).

Over the past years, an increasing number of studies have mapped different thalamic pathways contributing to the generation of a stable perception (Wurtz, McAlonan, Cavanaugh, & Berman, 2011). In particular, recent evidence has shown that neurons in the inferior pulvinar nucleus (PI) exhibit perisaccadic

suppression that is projected to occipito-parietal areas, including the middle temporal area (MT), region known to be involved in the perception of motion (Berman & Wurtz, 2011). Notably, this suppression can be observed before the eye movement, showing its stimuli-independence (Bremmer, Kubischik, Hoffmann, & Krekelberg, 2009). The timing of postsaccadic reactivation of these cells was reported to be approximately 80 ms after saccadic onset (i.e., ~50 ms after fixation onset), which is highly consistent with the recovery of visibility observed in Experiment 1. Moreover, this recovery was indepen-

dent on the stimulus properties such as temporal duration and update frequency (Experiment 2), similarly to the activity elicited by neurons in PI.

Several studies have previously supported the view that conscious updating is a rhythmic process that rely on oscillatory activity at the neural level (Busch, Dubois, & VanRullen, 2009; VanRullen & Koch, 2003b), and it was recently shown that these same oscillations modulate saccadic RTs (Drewes & VanRullen, 2011). In line, another study reported a reset in the phase of spontaneous EEG oscillations tens of milliseconds after the onset of a fixation (Ossandón, Helo, Montefusco-Siegmund, & Maldonado, 2010). Together, these results suggest that, because of the resetting of neural oscillations, conscious updating should be locked to the fixation onset. Here, we showed that conscious access is sharply locked to the onset of fixations, suggesting that phase resetting might play a role in the timing of visibility within a fixation. This hypothesis—different but not exclusive to the boost of activity in early visual areas—needs to be tested with electrophysiological experiments before drawing firm conclusions (see Future Work).

Koffset was 49 ± 5 ms before the fixation offset. The absence of visibility just before fixation offset could be associated to an impoverished perception due to the remapping of the receptive fields before saccade execution (Burr & Morrone, 2011). In fact, realistic models of saccade generation in reading tasks contemplate a preprocessing stage independent from the programming of the saccades (Engbert, Nuthmann, Richter, & Kliegl, 2005). In agreement with this view, we showed that the individual onset and offset times of visibility are not correlated with each other, indicating that these are unrelated processes. Moreover, whereas the time of disengagement from the sequence of letters was dependent on the frequency in which the array was updated, the time of the preprocessing stage was robust to manipulations to the physical properties of the visual stimulation (Experiment 2).

The abrupt onsets and offsets of visibility observed within the central fixation may cohesively form an episode (Bowman & Wyble, 2007; Wyble et al., 2009; Wyble, Potter, Bowman, & Nieuwenstein, 2011), such as the one we previously proposed as a mechanism underlying the lack of attentional blink within and across fixations (Kamienkowski et al., 2012). Moreover, the fact that the visibility is impaired close to saccadic boundaries would explain why the no-blink effect was more effective far from the saccadic boundaries. Here, we provide evidence that these episodic boundaries would be explained a) by the allocation of the gaze in a fixated point and the retina-brain lag, and b) by planning a saccade. However, we also showed that these stages are both embedded in the fixation, but driven by different mechanisms.

The Dynamics of Confidence Determines the Timing of Visibility and Saccade Planning

Within a temporal window included in the fixation, visibility was largely constant and close to perfect. In contrast, confidence showed a slow monotonic ramping, reaching its maximum just before *Koffset*. A traditional view in the decision making literature is that confidence provides an analog measure of the decision signal (Kiani & Shadlen, 2009; Pleskac & Busemeyer, 2010; Vickers, 2001; Vickers & Smith, 1985). These findings have been challenged with several demonstrations that show that the confi-

dence system does not access all elements of the decision variable, resulting in systematic departures between Type I (objective) and type II (accuracy of the confidence system) performance (Graziano & Sigman, 2009; Kotowicz et al., 2010). In particular, Kotowicz et al. (2010) used a visual search task to demonstrate that short (~ 10 ms) fixations to the target are sufficient to report its location, whereas longer fixations increase confidence but not performance. In line with these findings, here we showed that the kernel of confidence throughout a fixation is not homogeneous. The main difference and novelty of our results is that the variable parameter in our experimental setup is not the duration of stimulus presentation, which is constant unless the saccade is made during target presentation. Instead, confidence varies for stimuli which remain in the retina for the exact same time, when the stimulus occurs during the late segment of the fixation. This demonstrates an endogenous regulation of confidence for fixed presentations times. Conscious access has been shown to relate from the interaction between bottom-up and top-down signals (Dehaene et al., 2003; Lamme, 2000; Mumford, 1992) and to depend on the specific timing between internal rhythms and external stimuli (Fries, Reynolds, Rorie, & Desimone, 2001; VanRullen & Koch, 2003b). Our results show that the temporal synchrony between saccades and stimulus occurrence, instead of the accumulation of stimulus intensity, provides a better marker of perceived confidence.

Decision-Making Among Multiple Items Presented Within a Fixation

We investigated whether the steady increase of confidence could bias the decision-making among multiple items presented within a fixation. The last item within the kernel of conscious access was selected with a probability significantly larger than chance (Experiment 3).

Within each fixation participants reported up to 3 items. Previously, VanRullen and Koch have shown that humans can reliably report up to 4 objects presented within a single “glance” to a natural scene (250 ms; VanRullen & Koch, 2003a). These data were interpreted as evidence favoring the hypothesis that perception is not continuous but relies on discrete processing epochs periodically updated (VanRullen & Koch, 2003b). This view is also consistent with the episodic origin of the attentional blink (Bowman & Wyble, 2007; Wyble et al., 2009; Wyble et al., 2011). Consequently, here we showed that variations in visibility produced by eye-movements cohesively form episodes modulating the discrete sequencing of attention and perception (Kamienkowski et al., 2012).

Experiment 4 was designed to study the number of items that can be reported with a single fixation to an RSVP. Because of the short duration of the visual stimuli, and the fact that all items are potential targets, we cannot rule out that backward masking plays a significant role in the dynamics of free choice across eye movements (Experiments 3 and 4). Experiments 1 and 2, however, were based on a single target and all remaining letters were distractors. Therefore, in those paradigms, participants are in principle subject to backward and forward masking (Enns & Di Lollo, 2000). Given the fact that Experiment 2 changed the number of distractors in the vicinity of the target and their duration, we believe that the increment in confidence observed in Experiments 1 and 2 is not simply explained by a masking effect. Conversely, we propose that this reflects an endoge-

nous integration process by which later stimuli in a fixation are assigned greater confidence.

Future Work

A possible follow up of this study might be to set up an electrophysiological experiment in the same line, linking spontaneous oscillatory activity, eye movements, and perception, and combining our results with previous studies showing that both perception and saccades are highly determined—or locked—to spontaneous oscillations in alpha and low beta bands (Drewes & VanRullen, 2011; Ossandón et al., 2010). This experiment could also be an effort in bringing *confidence* into this scheme, to understand how it arises from the internal timing of attentional episodes and not merely as the evidence collected along with fixation time (Vickers, 2001; Vickers & Smith, 1985).

Summary and Conclusion

Visibility during eye movements is restricted to a temporal window embedded in the fixations. However, although objective measures of visibility are close to perfect during that window, subjective confidence increases with a slower rate, reaching its maximum just before the offset of the kernel, even when stimulus duration does not change. This asymmetry in the kernel of visibility is decisive when participants may opt among several alternatives, responding to stimuli which are presented at the time in which a single target elicits maximal confidence. This inhomogeneity is not likely to be explained by a masking mechanism, and the increment of confidence can be regarded as an internal representation of the stimulus. These results argue against models by which confidence reflects the integral (accumulation) of stimulus intensity (Vickers, 2001; Vickers & Smith, 1985), or at least constrain them by showing that the strength of accumulation is not constant throughout the time-course of a fixation.

References

- Berman, R. A., & Wurtz, R. H. (2011). Signals conveyed in the pulvinar pathway from superior colliculus to cortical area MT. *The Journal of Neuroscience*, *31*, 373–384. doi:10.1523/JNEUROSCI.4738-10.2011
- Bowman, H., & Wyble, B. (2007). The simultaneous type, serial token model of temporal attention and working memory. *Psychological Review*, *114*, 38–70. doi:10.1037/0033-295X.114.1.38
- Brainard, D. H. (1997). The psychophysics toolbox. *Spatial Vision*, *10*, 433–436. doi:10.1163/156856897X00357
- Bremmer, F., Kubischik, M., Hoffmann, K., & Krekelberg, B. (2009). Neural dynamics of saccadic suppression. *The Journal of Neuroscience*, *29*, 12374–12383. doi:10.1523/JNEUROSCI.2908-09.2009
- Burr, D. (2004). Eye movements: Keeping vision stable. *Current Biology*, *14*, R195–R197. doi:10.1016/j.cub.2004.02.020
- Burr, D. C., & Morrone, M. C. (2011). Spatiotopic coding and remapping in humans. *Philosophical Transactions of the Royal Society B-Biological Sciences*, *366*, 504–515. doi:10.1098/rstb.2010.0244
- Burr, D. C., Morrone, M. C., & Ross, J. (1994). Selective suppression of the magnocellular visual pathway during saccadic eye-movements. *Nature*, *371*, 511–513. doi:10.1038/371511a0
- Burr, D. C., Ross, J., Binda, P., & Morrone, M. C. (2010). Saccades compress space, time and number. *Trends in Cognitive Sciences*, *14*, 528–533. doi:10.1016/j.tics.2010.09.005
- Busch, N. A., Dubois, J., & VanRullen, R. (2009). The phase of ongoing EEG oscillations predicts visual perception. *The Journal of Neuroscience*, *29*, 7869–7876. doi:10.1523/JNEUROSCI.0113-09.2009
- Cornelissen, F. W., Peters, E. M., & Palmer, J. (2002). The eyelink toolbox: Eye tracking with MATLAB and the psychophysics toolbox. *Behavior Research Methods Instruments & Computers*, *34*, 613–617. doi:10.3758/BF03195489
- Crouzet, S. M., Kirchner, H., & Thorpe, S. J. (2010). Fast saccades toward faces: Face detection in just 100 ms. *Journal of Vision*, *10*, 4. doi:10.1167/10.4.16
- Dehaene, S., Sergent, C., & Changeux, J. P. (2003). A neuronal network model linking subjective reports and objective physiological data during conscious perception. *Proceedings of the National Academy of Sciences of the United States of America*, *100*, 8520–8525. doi:10.1073/pnas.1332574100
- De Pisapia, N., Kaunitz, L., & Melcher, D. (2010). Backward masking and unmasking across saccadic eye movements. *Current Biology*, *20*, 613–617. doi:10.1016/j.cub.2010.01.056
- Drewes, J., & VanRullen, R. (2011). This is the rhythm of your eyes: The phase of ongoing electroencephalogram oscillations modulates saccadic reaction time. *The Journal of Neuroscience*, *31*, 4698–4708. doi:10.1523/JNEUROSCI.4795-10.2011
- Duhamel, J. R., Colby, C. L., & Goldberg, M. E. (1992). The updating of the representation of visual space in parietal cortex by intended eye-movements. *Science*, *255*, 90–92. doi:10.1126/science.1553535
- Engbert, R., Nuthmann, A., Richter, E. M., & Kliegl, R. (2005). SWIFT: A dynamical model of saccade generation during reading. *Psychological Review*, *112*, 777–813. doi:10.1037/0033-295X.112.4.777
- Enns, J. T., & Di Lollo, V. (2000). What's new in visual masking? *Trends in Cognitive Sciences*, *4*, 345–352. doi:10.1016/S1364-6613(00)01520-5
- Fries, P., Reynolds, J. H., Rorie, A. E., & Desimone, R. (2001). Modulation of oscillatory neuronal synchronization by selective visual attention. *Science*, *291*, 1560–1563. doi:10.1126/science.1055465
- Graziano, M., & Sigman, M. (2009). The spatial and temporal construction of confidence in the visual scene. *Plos One*, *4*, e4909. doi:10.1371/journal.pone.0004909
- Henderson, J. M. (2003). Human gaze control during real-world scene perception. *Trends in Cognitive Sciences*, *7*, 498–504. doi:10.1016/j.tics.2003.09.006
- Hunt, A. R., & Cavanagh, P. (2011). Remapped visual masking. *Journal of Vision*, *11*, 13. doi:10.1167/11.1.13
- Hurlburt, R., & Heavey, C. L. (2001). Telling what we know: Describing inner experience. *Trends in Cognitive Sciences*, *5*, 400–403. doi:10.1016/S1364-6613(00)01724-1
- Insabato, A., Pannunzi, M., Rolls, E. T., & Deco, G. (2010). Confidence-related decision making. *Journal of Neurophysiology*, *104*, 539–547. doi:10.1152/jn.01068.2009
- Itti, L., & Koch, C. (2001). Computational modelling of visual attention. *Nature Reviews Neuroscience*, *2*, 194–203. doi:10.1038/35058500
- Kamienkowski, J. E., Navajas, J., & Sigman, M. (2012). Eye movements blink the attentional blink. *Journal of Experimental Psychology: Human Perception and Performance*, *38*, 555–560. doi:10.1037/a0027729
- Kawahara, J., Di Lollo, V., & Enns, J. T. (2001). Attentional requirements in visual detection and identification: Evidence from the attentional blink. *Journal of Experimental Psychology: Human Perception and Performance*, *27*, 969–984. doi:10.1037/0096-1523.27.4.969
- Khayat, P. S., Spekrijse, H., & Roelfsema, P. R. (2006). Attention lights up new object representations before the old ones fade away. *The Journal of Neuroscience*, *26*, 138–142. doi:10.1523/JNEUROSCI.2784-05.2006
- Kiani, R., & Shadlen, M. N. (2009). Representation of confidence associated with a decision by neurons in the parietal cortex. *Science*, *324*, 759–764. doi:10.1126/science.1169405
- Kirchner, H., & Thorpe, S. J. (2006). Ultra-rapid object detection with saccadic eye movements: Visual processing speed revisited. *Vision Research*, *46*, 1762–1776. doi:10.1016/j.visres.2005.10.002
- Kliegl, R., Nuthmann, A., & Engbert, R. (2006). Tracking the mind during reading: The influence of past, present, and future words on fixation

- durations. *Journal of Experimental Psychology: General*, 135, 12–35. doi:10.1037/0096-3445.135.1.12
- Kliegl, R., Risse, S., & Laubrock, J. (2007). Preview benefit and parafoveal-on-foveal effects from word $n+2$. *Journal of Experimental Psychology: Human Perception and Performance*, 33, 1250–1255. doi:10.1037/0096-1523.33.5.1250
- Kotowicz, A., Rutishauser, U., & Koch, C. (2010). Time course of target recognition in visual search. *Frontiers in Human Neuroscience*, 4, 31. doi:10.3389/fnhum.2010.00031
- Lamme, V. A. F. (2000). Neural mechanisms of visual awareness: A linking proposition. *Brain & Mind*, 1, 385–406. doi:10.1023/A:1011569019782
- Marti, S., Sackur, J., Sigman, M., & Dehaene, S. (2010). Mapping introspection's blind spot: Reconstruction of dual-task phenomenology using quantified introspection. *Cognition*, 115, 303–313. doi:10.1016/j.cognition.2010.01.003
- Milosavljevic, M., Madsen, E., Koch, C., & Rangel, A. (2011). Fast saccades toward numbers: Simple number comparisons can be made in as little as 230 ms. *Journal of Vision*, 11, 4. doi:10.1167/11.4.4
- Morrone, M. C., Ross, J., & Burr, D. (2005). Saccadic eye movements cause compression of time as well as space. *Nature Neuroscience*, 8, 950–954. doi:10.1038/nn1488
- Mumford, D. (1992). On the computational architecture of the neocortex. 2. The role of corticocortical loops. *Biological Cybernetics*, 66, 241–251. doi:10.1007/BF00198477
- Naccache, L., Blandin, E., & Dehaene, S. (2002). Unconscious masked priming depends on temporal attention. *Psychological Science*, 13, 416–424. doi:10.1111/1467-9280.00474
- Ossandón, J. P., Helo, A. V., Montefusco-Siegmund, R., & Maldonado, P. E. (2010). Superposition model predicts EEG occipital activity during free viewing of natural scenes. *The Journal of Neuroscience*, 30, 4787–4795. doi:10.1523/JNEUROSCI.5769-09.2010
- Otero-Millan, J., Troncoso, X. G., Macknik, S. L., Serrano-Pedraza, I., & Martinez-Conde, S. (2008). Saccades and microsaccades during visual fixation, exploration, and search: Foundations for a common saccadic generator. *Journal of Vision*, 8, 21. doi:10.1167/8.14.21
- Pleskac, T. J., & Busemeyer, J. R. (2010). Two-stage dynamic signal detection: A theory of choice, decision time, and confidence. *Psychological Review*, 117, 864–901. doi:10.1037/a0019737
- Posner, M. I. (1980). Orienting of attention. *The Quarterly Journal of Experimental Psychology*, 32, 3–25. doi:10.1080/00335558008248231
- Ratcliff, R., & McKoon, G. (2008). The diffusion decision model: Theory and data for two-choice decision tasks. *Neural Computation*, 20, 873–922. doi:10.1162/neco.2008.12.06.420
- Raymond, J. E., Shapiro, K. L., & Arnell, K. M. (1992). Temporary suppression of visual processing in an RSVP task - an attentional blink. *Journal of Experimental Psychology: Human Perception and Performance*, 18, 849–860. doi:10.1037/0096-1523.18.3.849
- Rayner, K. (1998). Eye movements in reading and information processing: 20 years of research. *Psychological Bulletin*, 124, 372–422. doi:10.1037/0033-2909.124.3.372
- Reichle, E. D., & Reingold, E. M. (2013). Neurophysiological constraints on the eye-mind link. *Frontiers in Human Neuroscience*, 7, 361. doi:10.3389/fnhum.2013.00361
- Roberts, S. W. (2000). Control chart tests based on geometric moving averages. *Technometrics*, 42, 97–101. doi:10.1080/00401706.2000.10485986
- Roelfsema, P. R., Lamme, V. A. F., & Spekreijse, H. (1998). Object-based attention in the primary visual cortex of the macaque monkey. *Nature*, 395, 376–381. doi:10.1038/26475
- Roelfsema, P. R., Tolboom, M., & Khayat, P. S. (2007). Different processing phases for features, figures, and selective attention in the primary visual cortex. *Neuron*, 56, 785–792. doi:10.1016/j.neuron.2007.10.006
- Ross, J., Morrone, M. C., & Burr, D. C. (1997). Compression of visual space before saccades. *Nature*, 386, 598–601. doi:10.1038/386598a0
- Sergent, C., Baillet, S., & Dehaene, S. (2005). Timing of the brain events underlying access to consciousness during the attentional blink. *Nature Neuroscience*, 8, 1391–1400. doi:10.1038/nn1549
- Shalom, D. E., de Sousa Serro, M. G., Giaconia, M., Martinez, L. M., Rieznik, A., & Sigman, M. (2013). Choosing in freedom or forced to choose? introspective blindness to psychological forcing in stage-magic. *Plos One*, 8, e58254. doi:10.1371/journal.pone.0058254
- Shapiro, K. L., Caldwell, J., & Sorensen, R. E. (1997). Personal names and the attentional blink: A visual “cocktail party” effect. *Journal of Experimental Psychology: Human Perception and Performance*, 23, 504–514. doi:10.1037/0096-1523.23.2.504
- Sperling, G. (1960). The information available in brief visual presentations. *Psychological Monographs: General and Applied*, 74, 1–29. doi:10.1037/h0093759
- Supér, H., Spekreijse, H., & Lamme, V. A. (2003). Figure-ground activity in primary visual cortex (V1) of the monkey matches the speed of behavioral response. *Neuroscience Letters*, 344, 75–78. doi:10.1016/S0304-3940(03)00360-4
- Thiele, A., Henning, P., Kubischik, M., & Hoffmann, K. P. (2002). Neural mechanisms of saccadic suppression. *Science*, 295, 2460–2462. doi:10.1126/science.1068788
- VanRullen, R., & Koch, C. (2003a). Competition and selection during visual processing of natural scenes and objects. *Journal of Vision*, 3, 8. doi:10.1167/3.1.8
- VanRullen, R., & Koch, C. (2003b). Is perception discrete or continuous? *Trends in Cognitive Sciences*, 7, 207–213. doi:10.1016/S1364-6613(03)00095-0
- Vickers, D. (2001). Where does the balance of evidence lie with respect to confidence? In E. Sommerfeld, R. Kompass & T. Lachmann (Eds.), *Proceedings of the seventeenth annual meeting of the international society for psychophysics* (pp. 148–153). Lengerich, Germany: Pabst.
- Vickers, D., & Smith, P. (1985). Accumulator and random-walk models of psychophysical discrimination - a counter-evaluation. *Perception*, 14, 471–490. doi:10.1068/pp.140471
- Wurtz, R. H., McAlonan, K., Cavanaugh, J., & Berman, R. A. (2011). Thalamic pathways for active vision. *Trends in Cognitive Sciences*, 15, 177–184. doi:10.1016/j.tics.2011.02.004
- Wyble, B., Nieuwenstein, M., & Bowman, H. (2009). The attentional blink provides episodic distinctiveness: Sparing at a cost. *Journal of Experimental Psychology: Human Perception and Performance*, 35, 787–807. doi:10.1037/a0013902
- Wyble, B., Potter, M. C., Bowman, H., & Nieuwenstein, M. (2011). Attentional episodes in visual perception. *Journal of Experimental Psychology: General*, 140, 488–505. doi:10.1037/a0023612
- Yarbus, A. L. (1967). *Eye movements and vision*. New York, NY: Plenum Press. doi:10.1007/978-1-4899-5379-7
- Zylberberg, A., Bartfeld, P., & Sigman, M. (2012). The construction of confidence in a perceptual decision. *Frontiers in Integrative Neuroscience*, 6, 79. doi:10.3389/fnint.2012.00079

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