Processing temporal events simultaneously in healthy human adults and in hemi-neglect patients

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ABSTRACT

Many theories have been advanced to explain how the brain incorporates time into its computations, in particular for the purpose of estimating the duration of an event. In the present study we examine with a new paradigm the ability to compare the duration of two visual stimuli in the parafoveal visual field, presented either sequentially or overlapping in time. We found that judging the duration of a pair of objects is more difficult when they overlap in time. Furthermore, all healthy participants presented a bias to over-estimate the duration of the second event (a negative time-order-error). We then presented the same task to eight left neglect patients with extinction (N-patients). Relative to the healthy participants, the patients displayed similar loss of sensitivity and increased bias in the time overlap condition. However, N-patients were particularly impaired when the first object was presented in their right visual field and the second one appeared on their left before the first one vanished. Rather than a simple engage/disengage disorder, these results highlight a specific problem with shifting attention to the impaired visual field. We discuss these findings in the light of contemporary models of time estimation.

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1. Introduction

Time estimation is critical for a wide range of functions, from the millisecond delays for auditory perception to the seasonal changes for circadian rhythm adjustments. Many theories have been proposed to explain how the brain incorporates time into its computations, in particular when two events are separated in space and time, but many questions remain unresolved. The most common framework involves a central neuronal mechanism for all timing operations, some sort of internal clock, that is used as a reference for a wide range of sensory and motor tasks (e.g. Church & Gibbon, 1982; Meck, 2006). Unfortunately, clock-like accumulators have found little support in physiology. A second class of models instead proposes that intervals can be encoded in the evolving activity patterns of neural networks (e.g. Ivry & Schlerf, 2008; Karmarkar & Buonomano, 2007). These latter models suggest that timing might be distributed among different neural structures.

Visual spatial adaptation experiments provided some evidence against the assumption of a single clock. Johnston, Arnold, and Nishida (2006) showed that local visual adaptation to gratings induced a shortening of perceived duration only for the adapted position, thereby suggesting a spatial selectivity of the timing mechanisms. Using a similar paradigm, Burr, Tozzi, and Morrone (2007) found evidence in favor of multiple clocks, and further proposed that the neural structures involved represent space in the real world rather than viewer-centered space. Other studies highlight the role for a centralized supramodal clock. Morgan, Giora, and Solomon (2008) explored the formal analogy between space and time using a visual search paradigm where the target to be found differed from multiple distracters either in size or duration. The critical difference between estimates of temporal length and estimates of spatial length seems to be that the former can only be made at the end of the display, while the latter can be made at any time during the display. They found that search for size can have the same severe capacity limit as the search for duration, provided that stimuli are presented sufficiently briefly to prevent serial inspection. They suggest that there is a single "stopwatch" for durations and a single "ruler" for sizes.

The debate to determine whether temporal processing is governed by a central mechanism or by multiple mechanisms working in concert is still open and is related to the role of attentional mechanisms: could attentional resources be distributed across multiple locations during a task of simultaneous time estimations? Although the mechanisms underlying the timing estimation of events are currently a matter of debate, attention seems to play a critical role and the variability of estimates is sometimes

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argued to depend on attention (e.g. Block & Zakay, 1997; Brown, 1985, 1997; Griffin, Miniussi, & Nobre, 2001). The less we attend to the temporal properties of a stimulus, the more likely we are to misperceive its duration. In their study, Macar, Grondin, and Casini (1994) varied attentional allocation to time explicitly through the use of informative pre-cues that directed attention in varying proportions of a primary (time estimation) or secondary (semantic judgments) task. They found that when observers must process non-temporal information about stimuli during prospective tasks, or when they must perform a concurrent task, perceived time duration generally decreases as a function of the amount of information processed. This result was interpreted within the framework of a pacemaker–accumulator model of timing. Fewer attentional resources being allocated to timing resulted in a greater number of temporal pulses being lost from the temporal record, thus producing underestimates in duration (see also Brown, 1997; Tse, Intriligator, Rivest, & Cavanagh, 2004). More recently, Cicchini and Morrone (2009) investigated how perceived time is altered when attention is allocated to perform a concurrent visual task. They found that temporal intervals in proximity of the onset of the primary task stimuli are perceived as strongly compressed. This compression effect occurs only when the temporal interval is marked by two bars presented in separate spatial locations. When the interval is marked by two bars flashed in the same spatial position, no temporal distortion was found. These results indicate that attention can alter perceived duration when the central nervous system has to compare the passage of time at two different spatial positions, corroborating earlier findings that mechanisms of time perception may monitor separately the various spatial locations possibly at a high level of analysis.

Another group of researchers showed that if more attentional resources are allocated to one moment in time (e.g. a target delay or duration), behavioral reactivity at that particular moment is enhanced. This represents the process of temporal attentional *orienting* (e.g. Coull, Frith, Büchel, & Nobre, 2000). In addition, if more attention is allocated to time rather than another stimulus feature (such as color), estimation of duration is more accurate, and this represents a process of temporal *selective* attention (Coull, Vidal, Nazarian, & Macar, 2004). Overall, increased attentional allocation to either a particular moment in time or to the time dimension generally enhances behavioral performance in time estimation.

Attentional resources will be more recruited when there is not one but several time intervals to estimate, similarly to ecological situations. Humans perceive and can reproduce short intervals of time relatively accurately, and are capable of timing multiple overlapping intervals if these intervals are presented in different modalities (e.g. tones and light flashes; Rousseau & Rousseau, 1996). A related question is: can humans accurately estimate multiple overlapping time intervals expressed in the same modality (vision–vision or auditory–auditory)? In a series of experiments where participants have to *produce* two overlapping time intervals, van Rijn and Taatgen (2008) provide support for a single clock combined with a nonlinear underlying timescale. They show that when two equal but partly overlapping time intervals had to be estimated, the second estimate was positively correlated with the stimulus onset asynchrony between the two intervals. These results were accounted for by a model based on a single clock whose pacemaker generated pulses at a decreasing rate (see Taatgen, van Rijn, & Anderson, 2007).

The literature briefly reviewed above on time perception leaves open several issues on our ability to process time for two events that are partially overlapping in time. This ability is critical for both perception and action in the dynamic environment in which we live, where new events continuously occur before old ones finish, and a deficit of this ability could have dramatic consequences on everyday life.

The performance cost to process two events simultaneously is reminiscent of the phenomenon of visual extinction in brain-damaged patients. Lesions of right posterior parietal or temporal cortex often lead to the disorder of unilateral neglect and visual extinction, namely the difficulty to detect two stimuli presented at the same time in separate hemifields. Neglect patients' lesions typically involve the right parietal lobe (Mort et al., 2003) and its connections with the prefrontal cortex (Bartolomeo, Thiebaut de Schotten, & Doricchi, 2007). Furthermore, activity of such fronto-parietal networks has been implicated in orienting attention (Nobre, 2001).

Visual extinction is relatively common in patients shortly after sustaining unilateral brain damage (Becker & Karnath, 2007). It is related to, but distinct from, the hemineglect syndrome (Heilman, Watson, & Valenstein, 1993), namely the defective ability of patients to explore the side of space contralateral to their lesion. A patient with visual extinction will correctly detect a single stimulus presented in either hemifield, but will report only the ipsilesional stimulus when two stimuli are presented bilaterally.

Over the last decade, numerous studies have attempted to investigate the temporal and spatial components of extinction (for a recent review see de Haan & Karnath, 2011). Several theories predict that maximal extinction should occur when stimuli are objectively simultaneous. Some of them suggest that the inability to generate a contralesional percept occurs precisely because all information is present at the same time (Baylis, Driver, & Rafal, 1993; Baylis, Gore, Rodriguez, & Shisler, 2001). These models suggest that extinction is similar to "repetition blindness" seen in neurologically healthy individuals. Such a view predicts that any asynchrony with a lead of either the contralesional or the ipsilesional item should decrease the deficit.

The first study to directly investigate whether extinction is maximal with simultaneous stimulation was a single case study by di Pellegrino, Basso, and Frassinetti (1997). They found that extinction was maximal when stimuli were presented perfectly simultaneously. The same year, Rorden, Mattingley, Karnath, and Driver (1997) presented patients with visual stimuli in both hemifields and asked them to make a temporal order judgment. Patients consistently reported the ipsilesional item as appearing first unless the contralesional item had a substantial lead (200 ms or more). This suggests that stimuli in the contralesional field are subjectively delayed to the patient. A recent study by Baylis, Simon, Baylis, and Rorden (2002) provides evidence for the importance of objective simultaneity. In one part of their study, patients made temporal order judgments to determine whether they experienced subjective slowing on the contralesional side. In agreement with Rorden et al. (1997), patients required the contralesional item to have a significant lead in order to be judged as occurring first. All patients demonstrated maximal extinction when stimuli were presented at objective simultaneity. In sharp contrast, Cate and Behrmann (2002) found maximal extinction when the ipsilesional item precedes the contralesional item. In their study, extinction patients were tested for within hemifield and between hemifield visual extinction, at various temporal asynchronies. Nonetheless their results should be interpreted with caution since the stimuli they used were biased both temporally (more ipsilesional first trials) and spatially (more items presented in the ispsilesional field).

In a more recent study, Rorden, Jelsone, Simon-Dack, Baylis, and Baylis (2009) examined the performance of nine patients with extinction, and found that maximal extinction was not influenced by temporal biases, but was modulated by the spatial location of the stimuli. On the one hand, when stimuli were presented exclusively in the ipsilesional visual field, patients showed maximal extinction when the ipsilesional item appeared slightly before the contralesional item (replicating the finding of Cate & Behrmann, 2002); on the other hand, when the two stimuli are on either side of

Patients 1, 2, 3, 4
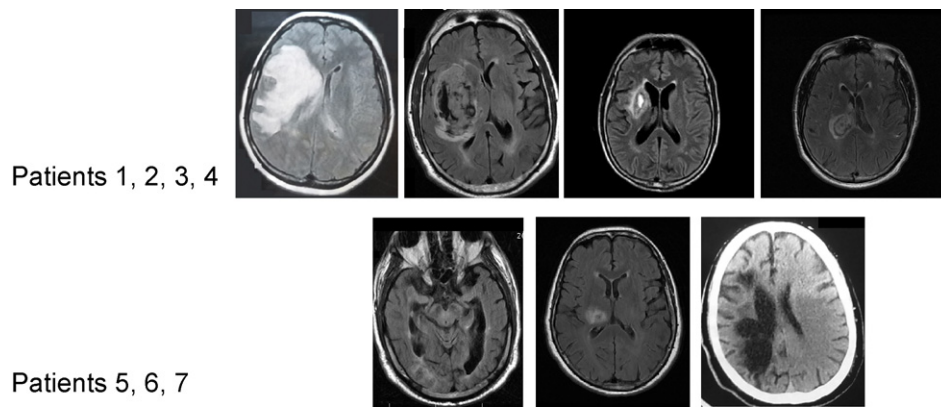
Patients 5, 6, 7

Fig. 1. Patients' lesion sites (FLAIR coronal brain MR images). The right hemisphere is shown on the left. One scan (patient 8) was not available. Five patients had a first single unilateral stroke (ischemic *n* = 3, hemorrhagic *n* = 2) in the right cerebral hemisphere and three other patients had a right hematoma.

the fixation, they observed that simultaneous presentation elicited maximal extinction (replicating the findings of di Pellegrino et al., 1997, and Baylis et al., 2002).

In the present study, we are interested in the difficulty of processing two events simultaneously rather than sequentially. These events are displayed in the parafoveal visual field, presented either sequentially or overlapping in time. We propose a new paradigm to measure our ability to *perceive* and to compare the duration of two visual stimuli (rather than to *produce* timing intervals; see van Rijn and Taatgen, 2008) and discuss the results in the light of contemporary models of time estimation. In addition, we are interested in the performance of left-neglect patients with visual extinction (N-patients) in this time estimation task.

2. Methods

2.1. Healthy participants

Twenty participants (mean age = 45.95 years, SD = 14.64, range = 27–80 years) with no history or evidence or neurological damage participated to the experiment. Sixteen of them were right-handed. All had normal or corrected-to-normal vision.

2.2. Neglect patients

A total of eight patients with left neglect and visual extinction (N-patients) (mean age = 53.6 years, SD = 11.2, range = 36–70 years) participated in the experiment. All patients suffered unilateral lesions to the right hemisphere (Fig. 1) and all of them were impaired within the three months before the test except one who was impaired about a year before the experiment but still present signs of neglect (patient 8, scan not available). All patients had normal or corrected-to-normal visual

acuity. All of them were right-handed and had no history of psychiatric disorders or dementia. The neuropsychological evaluation of each patient revealed no language disorders and no signs of apraxia or agnosia. We used a program using Matlab to test hemianopia in patients (de Montalembert, Auclair, & Mamassian, 2010). They were asked to detect whether a vertical or a horizontal line was present on a computer screen. Targets were presented in the left, right or both hemifields. None of them presented hemianopia or any other visual field deficit. Neglect and visual extinction were assessed by using a standardized battery of paper-and-pencil tests (Azouvi, Samuel, Louis-Dreyfus, Bernati, & Bartolomeo, 2002; Rousseaux, Beis, & Pradat-Diehl, 2001). This battery included two visuo-motor exploratory tasks (line bisection and letter cancellation), a reading task, and a drawing copy task. In all tasks, the center of the display was located on the mid-sagittal plane of the patients' trunk: they were free to move their head and eyes. The presence of extinction was tested clinically by wiggling fingers for two seconds in one or both visual fields. Six trials were given, in a fixed pseudo-random sequence including four unilateral trials (two on each side), and two simultaneous bilateral trials. Fingers were presented diametrically opposed at different spatial positions and the distance to the patient's head was about 30 cm (the distance was always the same across all trials). Extinction was considered present when a patient failed at least once to report a contralesional stimulus during bilateral simultaneous presentation, while accurately detecting unilateral stimuli. Seven patients had both left neglect and extinction while one had only neglect (patient 8). The patients' demographic and neurological features are summarized in Table 1. The healthy participants serves as a control group and there was no difference in terms of age between the group of healthy participants and the group of patients (*t*(26) = 2.01, *p* = 0.35).

All participants gave informed consent prior to the study, but were naïve concerning the specific aims of the experiment and the experimental protocol used is in accordance with the Helsinki declaration in 2004.

2.3. Apparatus

All experiments were conducted on a 13-in. MacBook computer. The monitor was set at a resolution of 1024 × 768 pixels and ran at a refresh rate of 60 Hz. The

Table 1

Demographic and neurological data on the eight neglect patients. All patients presented a right brain lesion. The letter "T" stands for Temporal, "P" for Parietal, and "O" for Occipital. For line bisection, positive deviations are rightward. Percentages correspond to: ((left distance – half of stimulus line length)/(half of stimulus line length)) × 100. A star (*) corresponds to a deviation greater than 11.1% and is considered pathological (0). For cancellation tests, left/right correct responses are reported. The landscape drawing, consisting of a central house with two trees on each side, was scored by assigning two points to the house and one point to each tree that was completely copied (2). The extinction was tested with the BEN task (Azouvi et al., 2002; Rousseaux et al., 2001); a "+" means the presence of the extinction symptom.

Patient	Gender/age	Days from lesion onset	Etiology	Locus of lesion	Line bisection (% deviation)	Letter cancellation (max. 30 left/30 right)	Landscape drawing (max. 6)	Visual extinction
N1	F/48	22	Ischemic	Right. T, P, subcortical	+15.2*	21/28	3	+
N2	F/50	41	Hemorrhagic	Right. T, P	+2.3	27/30	5	+
N3	M/36	28	Hematoma	Right. T, P	+8.9	16/27	3	+
N4	M/57	90	Hematoma	Right. T, P	−1.2	22/30	6	+
N5	M/68	43	Hemorrhagic	Right. P, O	+2.1	23/30	5	+
N6	F/48	35	Hematoma	Right. Internal capsule and thalamic	+3.7	28/30	6	+
N7	M/52	84	Ischemic	Right. T, P	+18.8*	18/29	6	+
N8	M/70	300	Ischemic	Right. T, P	+20.9*	15/20	4	−
Controls (N = 20)	46 ± 14.64				2.1 ± 7.4	30/30	6	
Neglect (N = 8)	53.6 ± 11.2	80.4 ± 91			8.8 ± 8.5	21.2 ± 4.8/28 ± 3.4	4.8 ± 1.3	
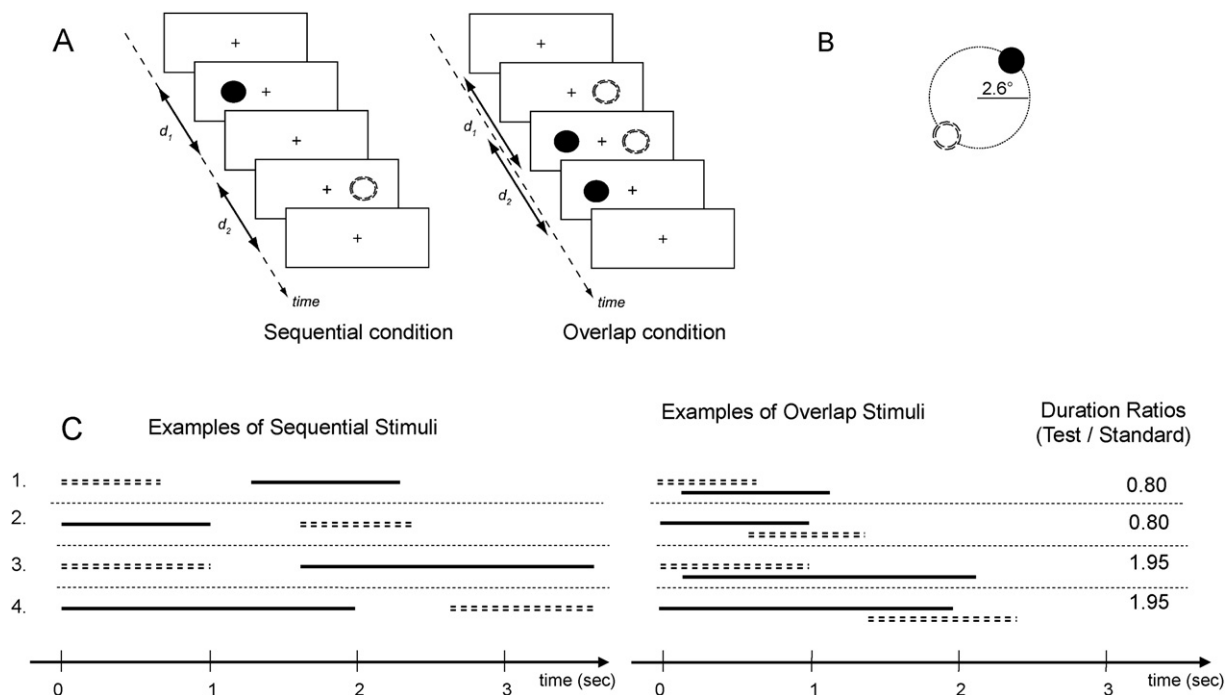
Fig. 2. Experimental temporal conditions. (A) Represents the two conditions, on the left when stimuli are presented sequentially, and on the right when they overlap. In each condition the two discs (represented here either by a filled disc or an open disc) were shown diametrically opposed (here left and right, although any other position was possible). (B) Represents an example of the different positions of the two discs; the first disc could appear anywhere on a virtual circle centered on the central fixation (radius = 2.6° of visual angle), but the second disc was always diametrically opposed (here the first disc is randomly placed at 1 o'clock, thus imposing the second disc appears at 7 o'clock). (C) Represents some examples for both temporal conditions, on the left when stimuli are presented in a sequential manner, on the right when they overlap in time. One disc was always presented for one second (the standard) and the other (the test) was presented for a variable duration such that the duration ratio varied between 0.3 and 3.0. The continuous line represents the duration of the one disc and the two dashed lines represent the duration of the other disc. In the sequential condition, the second disc follows the first one after half a second. In the examples (2) and (3), the standard is presented before the test. In the examples (1) and (2) the duration ratio is 0.80 and in the examples (3) and (4) the duration ratio is 1.95.

experimental stimuli were created with Matlab V.730 (Mathworks, Sherborn, MA, USA) and displayed with the PsychToolbox (V1.05; Brainard, 1997; Pelli, 1997).

2.4. Stimuli and procedure

All stimuli consisted of two discs, a blue and a red one (represented respectively by a filled disc and by an open disc in Fig. 2), displayed on a uniform white background (luminance set to 40 cd/m²). Each disc had a diameter of 1.0° of visual angle. The first disc could appear anywhere on a virtual circle centered on the central fixation (radius = 2.6° of visual angle), but the second disc was always diametrically opposed. For instance, the first disc could be randomly placed at 4 o'clock on the virtual circle, thus imposing that the second disc appears at 10 o'clock. We presented the stimuli as centrally as possible (parafoveal presentation) in order to avoid peripheral stimulation of the visual hemifields. One of the discs, called the standard, always lasted one second, while the other, called the test, was presented with a different duration every trial. The method of constant stimuli was used to manipulate the duration ratio between standard and test. Six duration ratios were chosen equally spaced on a log-scale, between 0.3 and 3.0 (the ratio of 1.0 was avoided because it is physically ambiguous). Two temporal conditions were contrasted: in the *sequential condition*, one stimulus was presented after the other one, whereas in the *overlap condition*, the two stimuli overlapped in time. In the sequential condition, the gap between the first and second discs was 500 ms. In the overlap condition, the first disc disappeared halfway through the duration of the second disc (Fig. 2).

The experiment took place in the experimenter's office. It lasted for about half an hour. The display was viewed from approximately 57 cm, although participants were free to move their head. A trial began with the presentation of a small fixation cross in the center of the display area for 500 ms. The stimulus (the two discs) was then presented binocularly (the fixation cross was always present), followed by a blank screen until the participant responded by pressing a key. The next trial followed immediately. Participants were asked to compare the duration of the two discs by answering the question: "is the red disc presented for longer than the blue one?" They had to press the space bar to answer YES and not press it to answer NO (go/no-go task). A training set was presented before the session and no feedback was provided. For each participant, we collected the proportion of times the red disc was reported to have lasted longer than the blue one, and then converted this into the proportion of times the first disc was reported to have lasted longer than the second one.

A session was composed of 48 stimuli presented in a random order (two colors (blue and red) × two order conditions (the standard before the test or the reverse) × two temporal conditions (sequential or overlap) × six duration ratios). Participants ran seven sessions, thereby judging 336 pairs of stimuli altogether. After each session, they could take a resting break as long as they wished. Throughout the data collection, the experimenter sat on the opposite side of the computer monitor, at a location where she could monitor the participant's gaze direction. Before initiating each block, the experimenter ensured that the participant's gaze was directed close to the center of the screen.
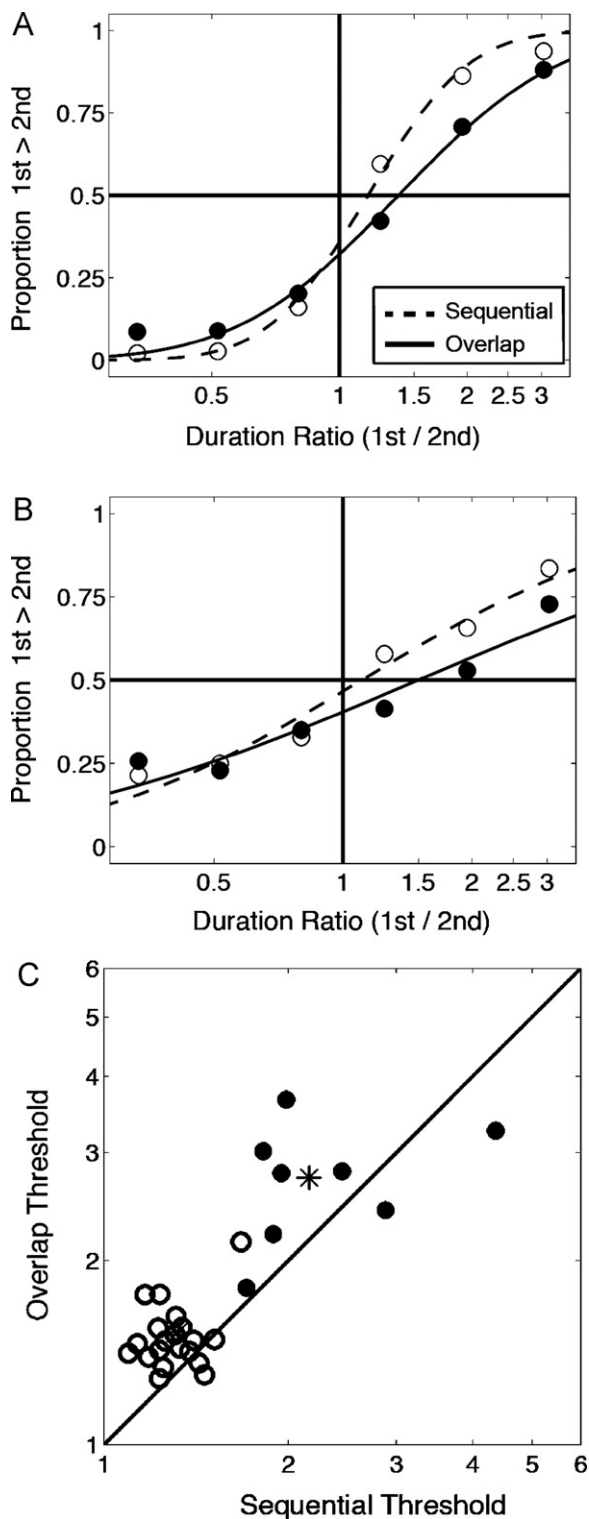
3. Results

3.1. Healthy participants

For each observer and each temporal condition, we computed the proportion of times the first disc was perceived to be longer than the second as a function of the duration ratio between the two discs. These proportions were fitted by a psychometric function (cumulative Gaussian) after taking the logarithm of the duration ratios. The fits provided two parameters, the bias (corresponding to the duration ratio that lead to chance performance) and the slope (the rate at which proportions increased with duration ratios). Fig. 3A represents the psychometric functions for the two temporal conditions.

The bias of each psychometric function corresponds to the point of subjective equality (PSE). The PSE represents the duration ratio for which a test disc is perceptually equal in duration to the standard disc duration (always one second in duration). Standard and test discs were presented in random order in each trial. In the literature, a bias to perceive the first or second object longer in time is referred as a "time-order-error" (TOE; e.g. Hellström, 1985). The TOE is "positive" when it corresponds to an overestimation of the first stimulus relative to the second, and negative otherwise. In

Fig. 3. Results for healthy participants (A) and left neglect patients (B). (A and B) The proportion of times the first disc was perceived to last longer than the second disc is shown against the duration ratio (first disc duration divided by second). On the psychometric functions, the continuous line represents the overlap condition and the dashed line represents the sequential condition. Data were pooled across all healthy participants ($N = 20$) and across all N-patients ($N = 8$). (C) Comparison between sequential and overlap sensitivities. Thresholds for the overlap condition are plotted against those for the sequential condition. Each circle represents one participant, healthy participants as open circles ($N = 20$) and left neglect patients as filled circles ($N = 8$). The gray cross represents the threshold mean for the overlap/sequential conditions for healthy participants, and the black cross for the left neglect patients. The overlap condition was more difficult (higher thresholds) for the majority of participants.

our experiment, the TOE is negative if the bias is larger than 1; for instance, a bias of 1.3 means that the second stimulus is over-estimated in duration by 30%.

All healthy participants systematically over-estimate the duration of the second event in all temporal conditions, and therefore display a negative TOE. The over-estimation bias reaches 1.14 ± 0.16 in the sequential condition and 1.29 ± 0.25 in the overlap condition; these biases are both significantly different from 1.0 ($F(1, 18) = 3.55$, $p < 0.01$). Furthermore, the TOEs for the two temporal conditions were significantly different from each other, the overlap condition presenting a larger bias ($t(38) = 4.18$, $p = 0.03 < 0.05$).

The slope of each psychometric function corresponds to the sensitivity of the participant to discriminate the durations of each stimulus, the steeper the slope, the better the discrimination. Equivalently and maybe more intuitively, sensitivity can also be characterized by the threshold measure that represents how different the two stimuli have to be in order to discriminate them better than chance. The smaller the duration ratio threshold, the better the sensitivity to discriminate two durations. Here, we report thresholds to reach 75% discrimination performance, and compute this entity from the psychometric fit as the difference in duration ratio between the points at 75% and 50% (in order to eliminate the effect of the TOE bias).

When we compare sequential and overlap conditions for each participant, we observe that thresholds are systematically larger in the overlap than in the sequential condition (see Fig. 3C, each participant is represented by an open circle). In other words, the majority of participants were worse at discriminating the duration of two stimuli when these stimuli overlapped in time (the effect was non-significant for the remaining participants). The duration ratio threshold in the sequential condition was on average 1.32 and in contrast in the overlap condition, this threshold rose to 1.53.

In summary, we found that judging the duration of a pair of objects is more difficult when they overlap in time. In addition, healthy observers present a bias to over-estimate the duration of the second event (a negative time-order-error), and this bias is larger when objects overlap in time.

3.2. Left neglect patients

In the light of the results in healthy participants, we were particularly interested in the performance of right brain damaged patients to process two visual events overlapping in time. We presented the same experimental paradigm to a group of eight left neglect patients with visual extinction (seven patients showed visual extinction and one of them, patient 8, showed only a neglect syndrome).

Even though we tried to make the procedure as simple as possible, some patients (nine) did not understand the procedure and the experiment was interrupted before its end; the results of these patients are not presented in the present paper. As a comparison, all healthy participants understood the procedure.

We performed the same analysis as for the healthy participants: for each patient and each temporal condition, we computed the proportion of times the first disc was perceived to be longer than the second as a function of the duration ratio between the two discs (Fig. 3B). For N-patients the bias to over-estimate the duration of the second event (i.e. the negative TOE) reaches 1.02 ± 0.93 in the sequential condition, and 1.42 ± 1.02 in the overlap condition. When stimuli are presented sequentially, N-patients did not present a significant TOE ($F(1, 3) < 1$, ns) in contrast to when stimuli overlap in which case they present a negative TOE just like healthy participants (p values for each patient < 0.01).

Fig. 3C compares sequential thresholds with overlap thresholds for healthy participants (open circles) and N-patients (filled circles). N-patients display the same pattern of thresholds across the temporal conditions: thresholds were systematically larger in the overlap condition than in the sequential condition. The duration ratio threshold in the sequential condition was on average 2.20, and in contrast in the overlap condition, this threshold rose to 2.73.

In a further analysis, we used the "Single Bayes" procedure (modified t-score; Crawford, Garthwaite, & Porter, 2010) to draw inferences concerning the difference between each patient's scores and the control group's. The Single Bayes procedure uses Bayesian Monte Carlo methods to test whether a patient's score is sufficiently below the scores of controls that the null hypothesis, that it is an observation from the population of healthy participants, can be rejected. The Bayesian method for standardized differences has the advantage that (1) it can directly evaluate the probability that a healthy participant will obtain a more extreme difference score, (2) it appropriately incorporates errors in estimating the standard deviations of the tasks from which the patient's difference score is derived, and (3) it provides a credible interval for the abnormality of the difference between an individual's standardized scores. For all patients, we used this procedure to investigate whether their sequential and overlap thresholds were significantly different from the ones found for healthy participants. Patients' scores were compared to controls' using the modified t-score for single case studies developed by Crawford and Garthwaite (2007). Differences between each patient and the group of healthy participants were considered significant when the one-tailed probability was equal to or below 0.05. With this analysis, we show that all patients have significantly lower performances than healthy participants for both temporal conditions (sequential and overlap), when they are asked to compare the duration of two discs. For the eight patients all Bayesian p values were at most equal to 0.01, for both temporal conditions (sequential and overlap).

In a final analysis, we checked whether the spatial configuration of the display induced any effect. We were particularly interested in a potential deficit in patients when stimuli were presented on their contralesional side and predict a deficit for left neglect patients with visual extinction to disengage their attention from their ipsilesional side to process a stimulus on their contralesional side (Posner, Walker, Friedrich, & Rafal, 1984). In our experiment, the two discs were always on opposite sides of the central fixation, but across trials, the disc locations were completely randomized on a virtual circle centered on the fixation (fixed eccentricity). Therefore, we analyzed left-right asymmetries by pooling all trials where the first disc appeared in one hemifield and the second disc in the other. A trial was labeled with a "left-right direction" if the first disc appeared in the left hemifield and the second disc in the right hemifield.

Fig. 4 shows the thresholds for the two temporal conditions as a function of the direction, for healthy participants (left plot) and neglect patients (right plot). The main difference between the two groups of participants was that, relative to healthy participants, patients were particularly impaired when the first disc was presented in their right visual field and the second one appeared on their left before the first one vanished.

In healthy participants, there was a significant effect of the temporal factor ($F(1, 18) = 2.87$, $p < 0.05$) with the overlap condition being worse than the sequential one. There were no effect of the direction ($F(1, 18) < 1$, ns) and no interaction between the temporal and the direction factors ($F(4, 48) = 3.18$, $p = 0.09$). For N-patients, we again found a significant effect of the temporal factor ($F(1, 6) = 3.26$, $p < 0.01$) similar to the healthy participants (overlap condition worse than sequential). In addition, there was also a significant effect of the direction factor ($F(1, 6) = 5.37$, $p < 0.01$), N-patients being more impaired when the first disc appeared in
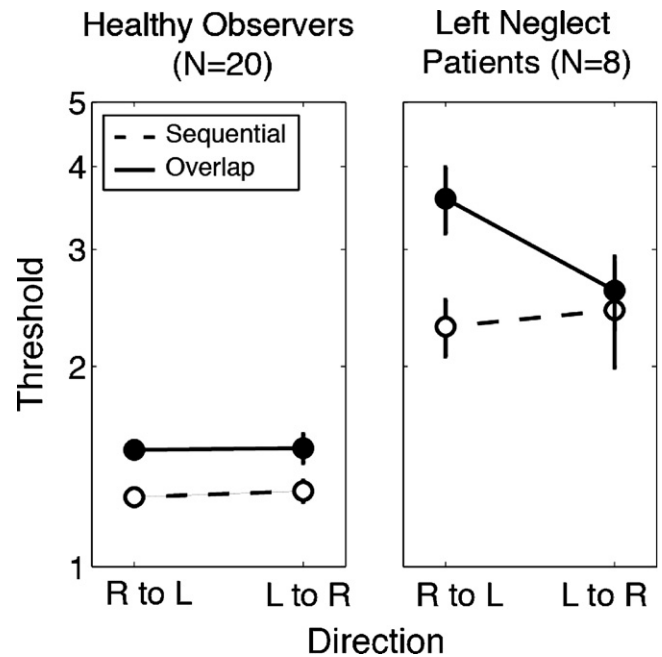

Fig. 4. Effect of presenting the stimuli left-to-right or right-to-left. Data were pooled across all stimulus locations where the first disc was presented in the left hemifield and the second one on the right (L to R direction), and where the first disc was presented on the right and the second on the left (R to L). Mean thresholds across participants are shown against the direction of the stimulus presentation and separately for the two temporal conditions. The left plot shows mean performance for healthy participants ($N = 20$) and the right plot represents all neglect patients ($N = 8$). There is a large drop of performance (high threshold) for neglect patients in the overlap condition when the first stimulus was presented on the right. Error bars are standard errors across participants.

the right hemifield and the second disc in the left hemifield. The two factors (temporal and direction) also interacted ($F(4, 48) = 8.94$, $p < 0.01$). To test further this interaction, we ran a Tukey post hoc analysis for the N-patients and found an effect of direction only in the overlap condition ($t = 5.27$, $p < 0.01$).

As a control test, we also performed the same analysis for the "upper" and "lower" hemifields (rather than left and right) and did not find any effect of this factor, neither for the healthy participants nor for the N-patients.

We found that N-patients were particularly impaired in the overlap condition when the first disc appeared in the right hemifield and the second disc in the left. Let us now decompose the steps of such a right-left direction trial. (1) The first disc appears on the right and participants have to register the onset of this stimulus; (2) shortly after, a second disc appears on the left and participants have to disengage their attention from the first disc, shift their attention to the left in order to correctly register the onset of this second stimulus; (3) shortly after still, the first disc disappears and participants have to shift back their attention to the right in order to correctly register the offset of the first stimulus; finally, (4) the second disc disappears on the left. The first and last steps of the sequence are non-problematic since they involve only one stimulus in the display. The third step is potentially critical, but there is a vast literature suggesting that a visual target presented in the right hemifield is correctly detected, or even leads to "a magnetic gaze attraction" (Gainotti, D'Erme, & Bartolomeo, 1991). The only remaining step is the second one where participants have to disengage their attention from a stimulus presented on the right and engage their attention on a stimulus presented on the left. We believe that our N-patients were critically impaired in this temporal shift of attention from their ipsilesional to their contralesional side.
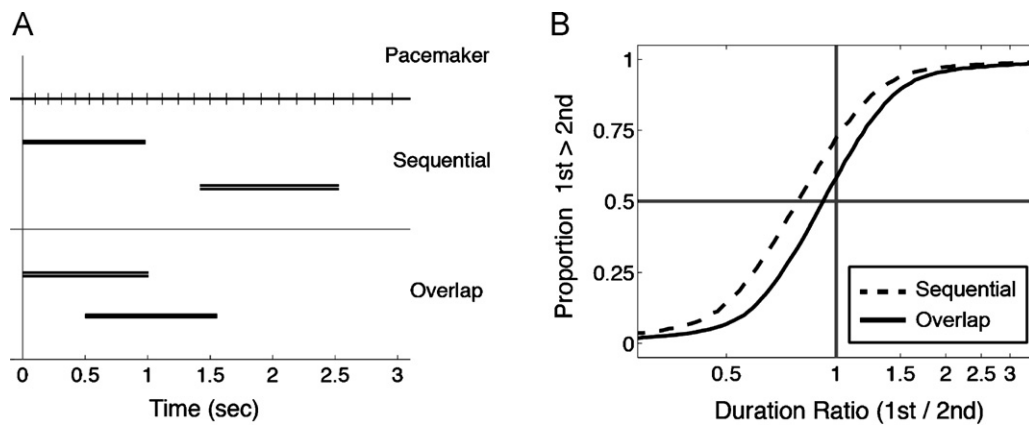
Fig. 5. Simulations for a model based on a single clock. (A) A single pacemaker generates pulses at intervals that become larger as time goes by. In the sequential condition, the second interval maps to fewer pulses than the first, thereby producing a bias for the second interval to appear briefer than the first. In the overlap condition, a similar bias is expected, but smaller given that the rate of impulses is more similar between the two intervals. (B) Simulations for the sequential and overlap conditions are presented in the same format as the results figures. The crossing of the psychometric functions to the left of the value 1.0 for the aspect ratio corresponds to a positive time order error (first interval perceived longer than the second). This bias is opposite from the one found in the experimental data.

4. Single clock model behavior

It is informative to reflect on the mechanism that can be responsible for the data obtained in the experiments. Our purpose here is not to derive a model that can fully account for the data, but rather to present the behavior of two simple models. One model is based on two independent clocks, one used to estimate the duration of each interval. Such a model would be consistent with some recent results indicating that multiple locations can be independently adapted (Johnston, Arnold, & Nishida, 2006). The other model is based on one single clock to estimate the duration of both intervals.

We can easily discard the first model because if the two clocks are independent, then the estimation of one interval does not depend on the estimation of the other, and thus this model predicts the same behavior in both sequential and overlap conditions. Given the large differences found between these two conditions, both in terms of sensitivity and response bias, a simple model where two clocks are independent is inappropriate to account for our data.

We now turn to a model based on a single clock to evaluate the duration of the two intervals. We use the implementation of the model proposed by van Rijn and Taatgen (2008) to account for their results on the production of two overlapping time intervals. Their model is based on a single accumulator that counts the number of pulses generated by a pacemaker (Fig. 5A). The initial rate of the pulses is one pulse every tenth of a second (time between two pulses: $t_0 = 0.1$ s). A non-linear timescale is then used for the pacemaker: individual pulses of the clock are gradually more distant from each other. This non-linear timescale is implemented by a pulse multiplier factor ($a = 1.02$) that represents the ratio of the time between pulses (n) and ($n+1$) and the time between pulses ($n-1$) and (n). The precise timing of the next pulse is also subjected to a small multiplicative Gaussian noise of standard deviation ($b = 0.015$ s). One modification we brought to the model is to add some uncertainty on the timing of the onset and offset of the intervals. We have modeled this uncertainty as Gaussian noise with standard deviation ($c = 0.2$ s). Without this uncertainty, the psychometric functions were too steep relative to our experimental data.

Simulations of the modified model of van Rijn and Taatgen (2008) are shown in Fig. 5B. Because the second interval always maps to fewer pulses than the first, there is a bias for the second interval to appear briefer than the first. In the overlap condition, this bias is less pronounced than in the sequential condition because the two intervals are closer to each other in time, and therefore the

rate of impulses is more similar between the two intervals. This bias to perceive the first interval longer than the second (positive Time Order Error) is opposite to the one found experimentally. In addition, we note that the slopes of the psychometric functions for the sequential and overlap conditions are rather similar, another property of the model that is different from the experimental data. We should note however that these failures are not specific to the model of van Rijn and Taatgen (2008); in particular, using a linear rather than a non-linear scale worsens the fit of the model to the data.

It is plausible that the second interval appears longer than the first for attentional reasons. In addition, the uncertainty to detect the boundaries of the two intervals might be different between the two conditions. In the overlap condition, it is plausible that the uncertainty to detect the offset of the first interval and the onset of the second interval are a bit higher than in the other conditions because in these cases, the visual system is already engaged in accumulating information about another interval. This increased uncertainty in the overlap condition will translate to a more shallow psychometric function for the overlap as compared to the sequential condition. While it would be possible to modify the current model to account for the biases and sensitivities found in the experimental data, we believe that it is a rather futile exercise to carry out here given the large number of parameters required to account for such a small dataset.

5. General discussion

Many theories have been proposed to explain how the central nervous system processes time, in particular to estimate the duration of a single event. In the present study we examine with a new simple paradigm the ability to compare the duration of two visual events in the parafoveal visual field, presented either sequentially or overlapping in time. A first result consistently found is that all participants (both healthy observers and N-patients) tend to systematically over-estimate the duration of the second event in all temporal conditions. This phenomenon is called time-order-error (TOE; Hellström, 1985, 2003) and an overestimation of the second event is more specifically called negative TOE. Both positive and negative TOEs are encountered in the literature and the origin of these biases is still not clear (Eisler et al., 2008). In particular, the neural correlates of these biases have yet to be explored (for a review, see Hairston & Nagarajan, 2007). However, it is

plausible that the TOE we found has little to do with time estimation per se. Response biases are very often reported in two-alternative forced-choice discrimination tasks, where observers have to compare two stimuli presented sequentially (Allan, 1977). For instance, Klein (2001) noticed that "the second interval typically appears subjectively to be about 5% higher in contrast than it really is" (p. 1424). Therefore, it is possible that our negative TOE is simply the result of using a two-alternative forced-choice paradigm. Somewhat related to this explanation, some authors have suggested that all stimuli presented for discrimination are compared to a global standard that emerges during the experiment (e.g. Vos, Assen, & Franek, 1997). In this case, when a stimulus is presented first, it requires more resources to be matched to the internal representation, thus diminishing the ability to make an accurate decision when the second stimulus appears. Consistent with these explanations, let us recall that our simple model of duration estimation based on well-accepted concepts revealed just the opposite TOE (i.e. a tendency of overestimate the duration of the first object). Notwithstanding this bias in duration judgments, future studies should be dedicated to help constrain new models that can account for the cost resulting from judging two events that partially overlap in time.

A second result of the present study is that, relative to healthy participants, patients were particularly impaired when the first disc was presented in their right visual field and the second one appeared on their left before the first one vanished. This "directional result" is consistent with several past studies. For example, Husain, Shapiro, Martin, and Kennard (1997) have shown that once attention is committed to the analysis of a visual object, there is an impairment in the ability to direct it to another, even if both stimuli are presented at the same location. These authors suggested that neglect had two components: (1) a spatial bias to direct attention towards stimuli processed by the undamaged cerebral hemisphere, and (2) a deficit in temporal processing, regardless of where attention is directed. The first of these components could be the main cause of our directional result. In addition, let us also remark that this directional result is similar to a deficit we observed on the vertical–horizontal illusion in neglect patients (de Montalembert & Mamassian, 2010). In that study, we found that an horizontal-'T' figure oriented to the left (where the top of the 'T' is to the right) produced much less bias in length estimation than the same figure rotated by 180°. It was as if neglect patients had difficulty to disengage from the junction between the horizontal and vertical segments when this junction was presented ipsilaterally. In summary, the present study brings new evidence that neglect patients present a dramatic deficit to disengage their attention on their ipsilesional side for both spatial and temporal tasks.

Our results are fairly consistent with the idea of one single-clock model with a crucial role of attentional mechanisms. When two events partially overlap in time we must divide our attention to preserve the time estimation of the first stimulus and to estimate the duration of the second event. For neglect patients, this capacity to divide attention is impaired when it is first oriented to the ipsilateral side. Attentional mechanisms are divided to feed the clock, not the reverse; when events overlap in time, attention can be divided rather than shifting from one event to the other, it is clearly not a fixed or rigid mechanism. Others studies on neurological patients have shown that patients with schizophrenia are impaired in discriminating simultaneous from asynchronous stimuli (Giersch, Lalanne, & Corves, 2009). Work with brain damaged or psychiatric patients remains to be completed to better understand how their deficit can extend current theoretical models of time estimation.

To conclude, in the present study we examined with a new simple paradigm the ability to compare the duration of two visual events in the parafoveal visual field, presented either sequentially or overlapping in time. We found an accuracy cost in processing the duration of two events that overlap in time. Our results on both healthy participants and neglect patients highlight the importance of attentional mechanisms for timing judgments and about the potential neural substrates of these mechanisms. Convergent findings from brain imaging and neuropsychological studies have suggested a large-scale fronto-parietal network of brain regions that support spatial attention. When identifying areas specifically involved in focused spatial and temporal attentional orienting, there is a right hemispheric lateralization within this fronto-parietal system (e.g. Chica, Bartolomeo, & Valero-Cabré, 2011). There is also a preferential activation of the right posterior parietal cortex during spatial orienting (e.g. Carrasco, 2011). In contrast, temporal orienting is often associated with preferential activation of the left parietal and inferior premotor cortex (e.g. Coull & Nobre, 1998). In real life, segmenting events into relevant and irrelevant ones is of critical importance for survival, and the precise neural mechanisms that help us allocate resources to estimate the duration of relevant events have yet to be found.

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