Shifts in spatial attention affect the perceived duration of events

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We investigated the relationship between attention and perceived duration of visual events with a double-task paradigm. The primary task was to discriminate the size change of a 2° circle presented 10° left, right, above, or below fixation; the secondary task was to judge the temporal separation (from 133 ms to 633 ms) of two equiluminant horizontal bars (10 deg × 2 deg) briefly flashed 12° above or below fixation. The stimulus onset asynchrony (SOA) between primary and secondary task ranged from −1300 ms to +1000 ms. Temporal intervals in proximity of the onset of the primary task stimuli were perceived strongly compressed by up to 40%. The effect was proportional to the size of the interval with a maximum effect at 100 ms SOA. Control experiments show that neither primary-task difficulty, nor the type of primary task discrimination (form or motion, or equiluminant or luminance contrast) nor spatial congruence between primary and secondary task alter the effect. Interestingly, the compression occurred only when the intervals are marked by bars presented in separated spatial locations: when the interval is marked by two bars flashed in the same spatial position no temporal distortion was found. These data indicate that attention can alter perceived duration when the brain 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 high level of analysis.

Introduction

Little is known about the neuronal mechanisms that mediate time perception of visual events. However, it is well established that several factors, such as alertness (Penton-Voak, Edwards, Percival, & Wearden, 1996; Treisman, Faulkner, Naish, & Brogan, 1990; Wearden & Penton-Voak, 1995), attention (Rose & Summers, 1995; Tse, Intriligator, Rivest, & Cavanagh, 2004) or predictability (Pariyadath & Eagleman, 2007) and the intention to perform an action (Haggard, Clark, & Kalogeras, 2002; Morrone, Ross, & Burr, 2005; Park, Schlag-Rey, & Schlag, 2003) can modulate and alter our perception of time (for review see Eagleman, 2008; Eagleman et al., 2005; Hogendoorn, Carlson, & Verstraten, 2007; Matell & Meck, 2004; Mauk & Buonomano, 2004; Nobre & O'Reilly, 2004). Attention in particular has been shown to affect the temporal processing of the visual input, speeding up the attended stimuli (Carrasco & McElree, 2001; Shore, Spence, & Klein, 2001; Stelmach & Herdman, 1991; Titchener, 1908, but see Schneider & Bavelier, 2003). The net effect is a reduction of the processing time of the attended stimulus, that in some particular conditions can be strong enough to induce an alteration of the perceived order of the events (Reeves & Sperling, 1986).

Perceived duration of short events is also under attentional modulation. Many studies (Rose & Summers, 1995; Tse et al., 2004) found that the most surprising stimulus within a train is perceived longer, probably because it engages more transient attention or because the event is less predictable (Pariyadath & Eagleman, 2007). The overestimation occurs for stimuli longer than 200 ms and can be as large as 25% of the physical duration (Tse et al., 2004). On the other hand, dividing attentional resources (Macar, Grondin, & Casini, 1994, exp 2) between different properties of the same stimulus (like for example the color of the stimulus and the duration of the presentation), induces an underestimation of about 15% of the perceived duration, indicating the existence of a common and limited attentional resource between time and other forms of visual processing.

The classical model of time perception considers a single centralized clock that ticks at a constant rate. Attention could modulate the tick rate and hence the duration of the events (Zakay, 1989). However, much experimental evidence seems to question this model (Gibbon, 1992; Killeen, 1999; Matell & Meck, 2004; Staddon & Higa, 1999; Treisman, 1963). Recently, selective spatial adaptation experiments provided evidence against the assumption of a single clock. Johnston, Arnold, and Nishida (2006) showed that local visual

adaptation to gratings induces a shortening of perceived duration only for the adapted position, demonstrating directly a spatial selectivity of the timing mechanisms. A subsequent study from our group (Burr, Tozzi, & Morrone, 2007) indicated that the alteration is not related to an adaptation of the early analysis of the visual system but occurs only when the adapter and the event to be timed occupy the same position in space, not on the retina. Interestingly, the effect is selective for the temporal frequency of the adapting grating, being stronger at high temporal frequencies (Johnston et al., 2006). Taken together these results show that neuronal time mechanism are selective for the characteristics of the visual stimulus and also suggest that time analysis takes place quite late in the visual processing, when objects are already coded in allocentric coordinates. In any case they suggest that the brain either uses several parallel clocks to time duration of external events or uses a master clock that collects in parallel spatial information that can be individually addressed.

The intention to perform a motor act can also modulate the perceived duration of visual and other events. Haggard et al. (2002) have shown that performing an action induces a delay in the perceived time of a movement and also an anticipation of the sensory changes produced by the action. The temporal separation between the two events appears compressed, probably indicating a binding action. Morrone et al. (2005) have found a compression of an interval between two peripheral visual stimuli presented at the time of visually driven saccades. The underestimation can be up to 65%, with an interval of 100 ms reduced to 35 ms. Interestingly, the apparent compression of time is also associated with an increase in discrimination performance, with psychometric functions that are steeper during saccades than in fixation, implying greater precision. Morrone et al. (2005) also studied the time course of the effect and found it analogous to peri-saccadic compression of space, suggesting the existence of a common mechanism producing both effects. The other surprising result observed peri-saccadically was an apparent alteration of the temporal order of the events. Consistently stimuli separated by about 40 ms appear in the reverse order. The effect is similar to the inversion observed by Reeves and Sperling (1986), but it seems not to be associated with allocation of attention. All these phenomena have been interpreted as linked to the fast neural changes implemented by the brain to realign the external spatial coordinate system with the retinal one. The shift in the coordinate system would produce both a compression of spatial and temporal separation (Morrone, Ross, & Burr, 2008).

Together with the compression of temporal interval, that may implicate a functional binding or fusion of peri-saccadic visual events, the absolute timing of peri-saccadic events is also altered. Yarrow, Haggard, Heal, Brown, and Rothwell (2001) have found that the duration of a stimulus proximal to the saccadic target is increased by a constant 100 ms (Yarrow, Haggard, & Rothwell, 2004), as if the stimulus were referred earlier. The effect has been named "*Chronostasis*" (corresponding to a perceived temporal expansion) and interpreted as a momentary interruption of timing mechanisms, like a compensation for the visual time lost during saccades. Unfortunately, the effect is not specific to saccades, but has been observed also for pointing and non-visual multimodal stimuli (Hodinott-Hill, Thilo, Cowey, & Walsh, 2002; Park et al., 2003). This casts some doubts on the time compensation interpretation, pointing to an attentional modulation. Replicating Yarrow et al.'s paradigm, Georg and Lappe (2007) found that the *Chronostasis* effect depends on the position of the visual target: when the event was located far from the saccadic target, where spatial attention is allocated, *Chronostasis* was no longer observed.

The goal of the present research is to study duration judgements in conditions of divided visual attention (Sperling & Melchner, 1978). This paradigm separates the location of spatial attention and the location of the visual event to be measured. Varying the spatial and temporal proximity between the visual primary task (used to decrease attentional resources) and the secondary stimulus (the duration judgement) allows the characterization of the time course and the spatial selectivity of the attentional modulation of time mechanisms. To test whether a fast shift of attention could reproduce some of the duration compression observed for the peri-saccadic stimuli, we used test stimuli similar to those used by Morrone et al. (2005) (a time interval delimited by two brief bars flashed in the periphery).

We report here three different experiments: the first experiment measures the temporal distortion as a function of the temporal overlap between the primary and secondary tasks; the second experiment measures the effect as a function of the duration of the interval; the third experiment as a function of the spatial position and other characteristics of the primary and secondary task stimuli. The results show that a deprivation of attentional resources induces a compression of time and that the effect is spatially selective: time perception is not altered when only one spatial position is monitored to perform the secondary task.

Methods

Apparatus

Stimuli were presented on a Sony Triniton 21-in. CRT monitor at a refresh rate of 120 Hz, with an 800×600 resolution and subtending $39° \times 19°$ of visual field. The viewing distance was 57 cm. The experiment was controlled by a Matlab 6 program using the PsychToolbox

routines release 2.54 (Brainard, 1997; Pelli, 1997). The experiment was run in a dimly lit room.

Stimuli and procedure

Primary task stimuli

Each trial sequence began with the presentation of a fixation point (0.1 deg in diameter) at the center of a uniform gray screen (x = 0.31, y = 0.31 luminance 9 cd/m^2) and two bright green circles (diameter 2°, border 0.15°, luminance 39 cd/m^2 CIE x = 0.29, y = 0.60) to the right and left of fixation. The eccentricity of both circles varied from trial to trial over a range of 6° and 10°. After a variable delay (1500–2000 ms) from the start of the trial, one of the two circles changed size following two possible temporal patterns. In one case the circle first expanded (to 2.2°) for 2 frames (16.7 ms), shrunk (to 1.8°) for other 2 frames and then expanded again to baseline size (2°). In the another case the circle first shrunk then expanded and finally returned to the baseline size. The subject's primary task was to discriminate between the two possible sequences.

If not explicitly stated, the two circles were presented on the horizontal meridian left and right of fixation (see upper panel of Figure 1, locations A and B). We also

tested the Vertical Condition in which the two circles were presented symmetrically above and below of the fixation point (Figure 1 upper panel, locations C and D) and a Central Condition where one only circle, centered on the fixation point, was presented (location E).

We used different types of primary task stimuli. The primary task for the condition named "Object Recognition—Horizontal (ORH)" entailed the discrimination of a briefly (33 ms) flashed stimulus either left or right of fixation (10°). In this condition the starting display contained only the fixation point and the stimulus comprised a red disk (2° diameter, equiluminant with the background) and a small green equiluminant sector (45° of angle) in one of four possible positions. The subject's task was to report the sector positions (25% chance level).

Secondary task stimuli

At a variable asynchrony (SOA) from the primary task, a pair of horizontal red bars equiluminant to the background (3 × 30°: average CIE x = 0.62, y = 0.35 across subjects) were briefly presented (17 ms, two video frames) at 12° vertical eccentricity (top or bottom of the screen). The equiluminance setting of the red bars was assessed independently for each subject by standard flicker photometry.
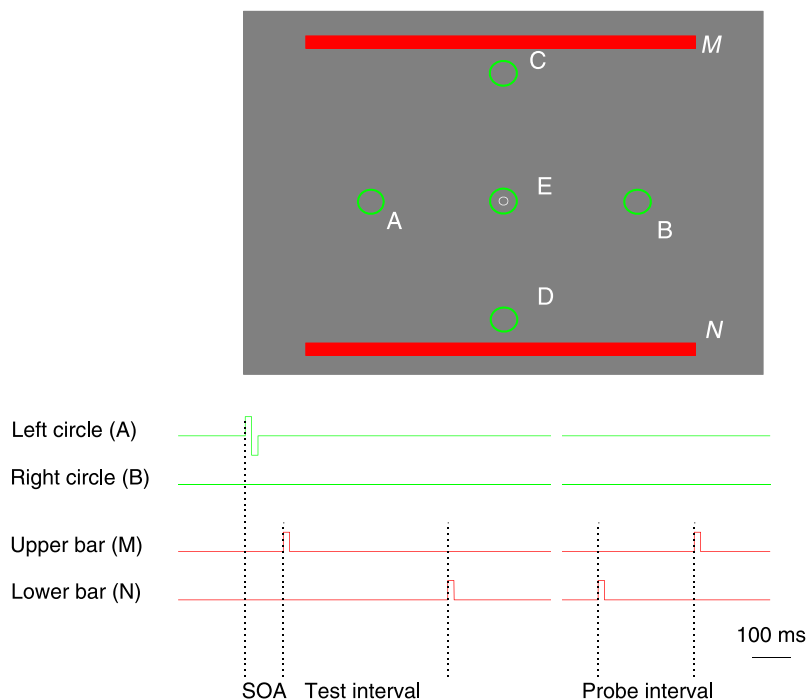

Figure 1. Stimuli (upper panel) and time course of a sample presentation (lower panel). Each trial comprised the presentation of the stimuli for the primary task (green circles) and a fixation spot. In the horizontal condition the circles were positioned in A and B, in the vertical condition, in C and D, in the central condition, only the circle in E was presented. The primary task was to discriminate the temporal sequence of expansion and contraction applied to one of the circle. At a specific Stimulus Onset Asynchrony (SOA) from the size change of one of the circles, two bars equiluminant to the background were flashed. The temporal separation between the two bars the (test interval) is measured as the difference between the onset of the two bars. The bars could either appear in Two Locations (e.g. first M then N) or in the Same Location (both in M or both in N). After a few seconds a variable probe interval was presented.

The values obtained with this technique were very close to the physical equiluminance setting. The eccentricity, wide separation and color of the bar were selected to minimize the sensation of motion. The majority of data was collected with test intervals of 433 ms. For SOA 100 ms and in 2 subjects we tested a wide range of test intervals (133, 233, 333, 433, or 633 ms) varying at random within each session.

The first and the second bar of the pair could appear at the two different positions (at the top and the bottom of the screen) ("Two Locations"), or at the same position ("Same Location"). The position of the first bar of the pair was chosen at random between the top and the bottom position of the screen both for the test interval and the probe interval.

Data acquisition

Two to three seconds after both the primary and the secondary task stimuli had been presented a second pair of bars was flashed. The temporal separation between the bars of the second pair (probe) was determined according to a double staircase algorithm which started at the beginning of the experimental session approximately at 30% and 170% of the test interval. The subject had to choose which of the two intervals was longer. Observers were instructed to keep central fixation throughout the whole trial.

SOA values between the two tasks are defined as the time between the first motion frame of the primary task stimulus and the first frame of the first bar of the temporal interval. SOA values are considered positive when the first bar was presented after the primary-task disk changed size; SOA values are considered negative when first bar is presented before it. If the SOA is negative but smaller than the test duration, the first bar is presented before the primary stimulus whereas the second bar is presented after the primary stimulus.

Responses to the two tasks were made at the end of each trial by pressing two separate pairs of computer keys. The subject entered first the response to the primary task then to the duration judgement. Response order was compulsory: the keys for the secondary task response were active only after one of the keys for the primary task response had been pressed. Feedback was given to the subject only on the correctness of the response to the primary task. Accuracy values of the first task were stored for subsequent analysis. Duration judgements were analyzed by an offline program that binned the responses according to their SOA. The point of subjective equality (PSE) of the test and probe duration was estimated by best fitting the psychometric function with a cumulative Gaussian distribution and by taking the median of the Gaussian probability density function. The precision in the duration task was calculated as the difference between the 3rd and 1st Quartiles divided by two. *SEM* were

calculated via a bootstrap procedure which re-sampled with replacement for 500 times the set of responses (Efron & Tibshirani, 1993).

Results

Temporal compression

Figure 2 shows how perceived duration of an interval delimited by two peripheral bars flashed in two different spatial locations varied with the asynchrony from the primary task (SOA) for two subjects. The data refer to judgments of an interval of 433 ms, while the subject was performing a concurrent motion discrimination of the expanding and contracting sequence of one of the disks positioned on the horizontal midline (for details see Methods). The subjects perform veridically when the interval is presented very early (SOA = −1500 ms) or very late (SOA = 1000 ms) with respect to the primary task stimulus. However, when the primary stimulus is close to or overlaps with the interval between the two bars to be discriminated, the perceived duration is strongly biased and compressed. The underestimation is maximal at an SOA of 100 ms where, on average intervals, of 433 ms are perceived lasting about 272 ms. The effect holds over a large range of SOAs (from about −700 ms to 200 ms) and in this range the underestimation is on average 65.8% of the physical duration. Figures 2C and 2D show the precision of the secondary task (JND) as a function of SOA. Precision is not modulated by task asynchrony: the subject performed equally at SOAs where a compression of the temporal duration occurred as well as at SOAs when their temporal precepts were unbiased.

To assess whether the compression effect is related to the primary task difficulty, we measured the accuracy of the primary task (Figures 2E and 2F). There is no trade off between performance of the primary task and perceived temporal compression but a slight decrease of accuracy for SOA where the compression is stronger. The lack of a trade off between performance of the primary and secondary task was observed for all reported data, conditions and subjects. For this reason it will not be illustrated further.

The effect of perceived compression is not limited to intervals of medium duration but holds also for intervals as short as 100 ms. Figure 3 illustrates an example of the data obtained for 133 ms interval duration for two subjects. The time course of the effect is very similar to those obtained with a 433 ms interval. Also for this duration the effect is stronger for intervals that overlap in time with the primary task stimuli (motion sequences). The range of SOAs which yield strong temporal compression is
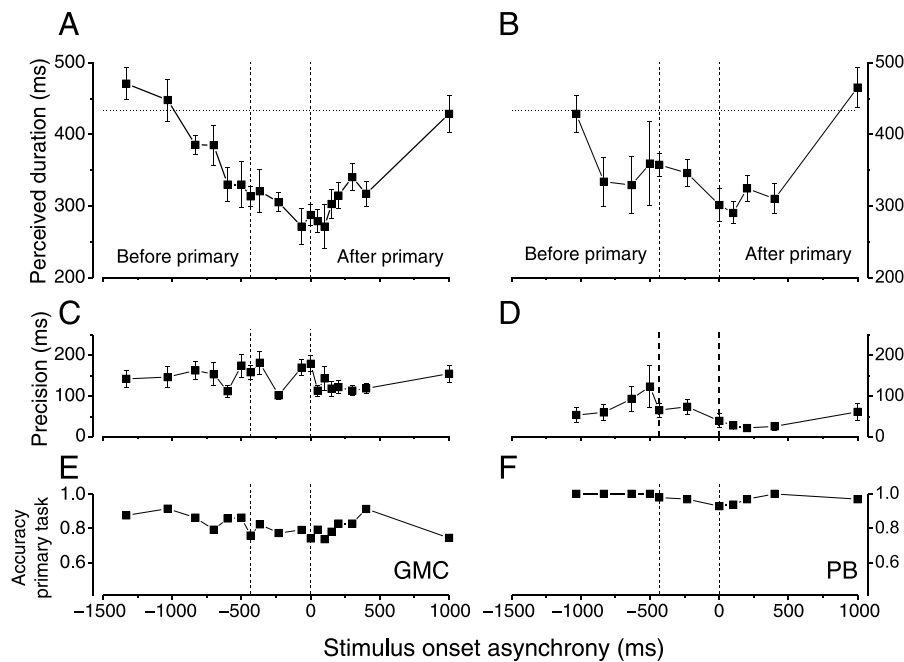
Figure 2. Data for two representative subjects for primary task stimuli displayed along the horizontal meridian. Top row (panels A and B): perceived duration of a 433 ms interval as function of the Stimulus Onset Asynchrony between the primary task and secondary task stimuli. The horizontal line indicates the physical target duration of 433 ms. Positive SOA values indicate intervals starting after the appearance of the primary task stimuli. Negative values indicate intervals where the first bar is flashed before the appearance of the primary task stimuli. The two vertical bars, placed at −433 ms and 0 ms indicate respectively, intervals which terminate with the presentation of the primary task stimulus and intervals which start with primary task stimulus. Error bars are *SEM* calculated via bootstrap procedure (see Methods). Middle row (panels C and D): precision of the duration judgement, measured as difference between the 50th percentile and the 75th percentile of the psychometric function. Error bars are *SEM*. Bottom row (panels E and F): accuracy of the primary task as function of Stimulus Onset Asynchrony between the primary task and secondary task stimuli. Chance level is 50%.

narrower consistent with the fact that the temporal overlap between the two tasks is smaller.

The maximum effect both for the 133 ms and the 433 ms durations occurred at an asynchrony (SOA) of about 100 ms, while at SOAs of about 1000 ms both judgements were veridical. For SOA of about 100 ms, both intervals (Figures 2 and 3) appear underestimated by about 40%. To generalize this finding to other intervals,

we measured the apparent duration of a range of interval at an SOA of 100 ms, thus under conditions of reduced attentional resources (Figure 4).

Perceived duration at SOA of 100 ms varies linearly with physical duration. The linear regressions of the scatter plots show that the intercepts are very little altered, while the slope is about halved (see Table 1). These results indicate that the compression is proportional to the
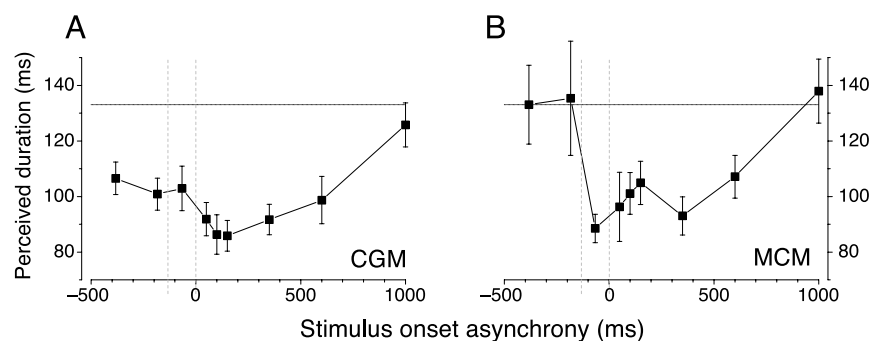

Figure 3. Perceived duration of a 133 ms interval as function of the Stimulus Onset Asynchrony between the primary task and secondary task for two subjects. The horizontal line indicates the physical duration of 133 ms. The two vertical bars, placed at −133 ms and 0 ms indicate, respectively, intervals which terminate and intervals which start with the presentation of the primary task stimulus. Error bars are *SEM*.
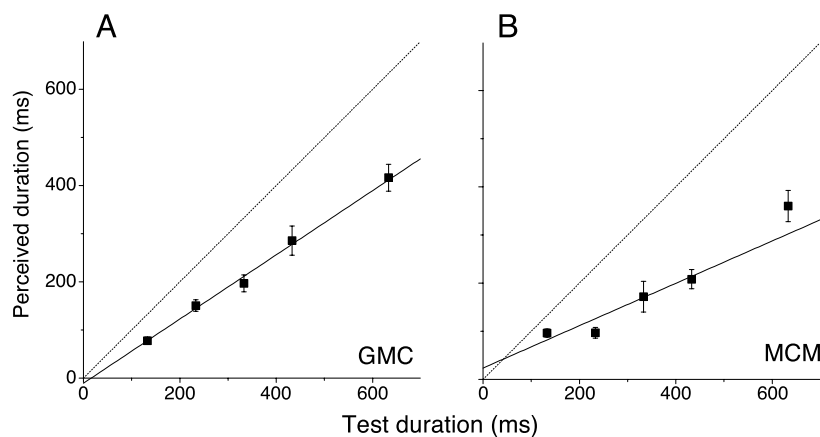
Figure 4. Perceived duration as function of interval duration for two subjects. Perceived duration for intervals starting 100 ms after the presentation of the primary task stimulus as function of the duration of the interval. The diagonal dashed line indicates veridical judgements. The continuous line is the best fitting line of the data. Error bars are *SEM*.

physical interval (multiplicative) and cannot be ascribed to a constant time loss associated with the execution of the primary task.

Spatial selectivity of the temporal discrimination

The results of Figures 2 and 3 show that during reduced attentive resource the duration of a temporal interval can be grossly misjudged appearing compressed. The duration task entails that two different spatial positions are monitored simultaneously. After the appearance of the first stimulus, all subjects reported that they shifted their attention to the position of the second stimulus to evaluate the temporal separation between the two bars. To test whether the simultaneous monitoring of two spatial positions and the unpredictability of the stimulus location could modulate or cause the temporal compression, we modified the duration judgement using an interval marked by two bars presented in the same location. Figure 5 reports the results for a representative subject and Figure 6 for all subjects for two representative SOAs. The top panels of Figure 5 show the psychometric curve for duration discrimination of 433 ms interval at SOA of 100 ms (Figure 5A) and 1000 ms (Figure 5B). The red

symbols and curves show data collected when the bars delimiting the interval are presented in the same location, the black symbols and curves when the bars are presented in different locations, similarly to the data of Figures 2, 3, and 4. At long SOAs (1000 ms) both intervals are perceived correctly and the two psychometric functions are practically identical, with no bias and similar width. At short SOAs the two psychometric functions are shifted, determining two different points of subjective equality. Intervals between bars in two locations (black lines) undergo temporal compression: 433 ms is equated to a 286 ms interval. Intervals between bars in the same location (red lines) on the other hand are estimated close to the veridical value of 433 ms. Note also the two psychometric functions have the same slope, and how the bias in perceived duration is not accompanied by a consistent change of precision.

The absence of temporal compression in the "same location" condition is not specific to the 100 ms SOA. The performance of this subject (Figure 5C) was always veridical for all SOAs for the intervals marked in the *Same location,* while she perceived as strongly compressed the interval between the bars flashed at two separate locations, in agreement with the data of Figures 2, 3, and 4.

The lack of temporal compression for stimuli in the *Same location* might be due to flicker sensitive mechanism that mediates the discrimination, without necessarily engaging timing mechanisms. Equiluminant stimuli responses can be integrated up to 200 ms or longer time (Burr & Morrone, 1993; Swanson, Ueno, Smith, & Pokorny, 1987), although temporal order judgment of equiluminant co-localized stimuli are performed correctly for separations longer than 90 ms. To control for this possible artifact we further increased the separation between the two bars to 633 ms, a value about 10 times larger than the flicker fusion threshold for these stimuli (equal to about 57 ms). The same pattern of results occurred for all subjects both for intervals of 633 ms and

	GMC	MCM
Slope	0.67 ± 0.03	0.44 ± 0.10
Intercept	10.7 ± 6 ms	23.6 ± 26 ms

Table 1. Linear Regression Parameters for perceived duration as function of physical interval duration. Regression is performed on two subjects (the same as of Figure 4) and refer to temporal judgements performed under conditions of attentional deprivation (SOA 100 ms).
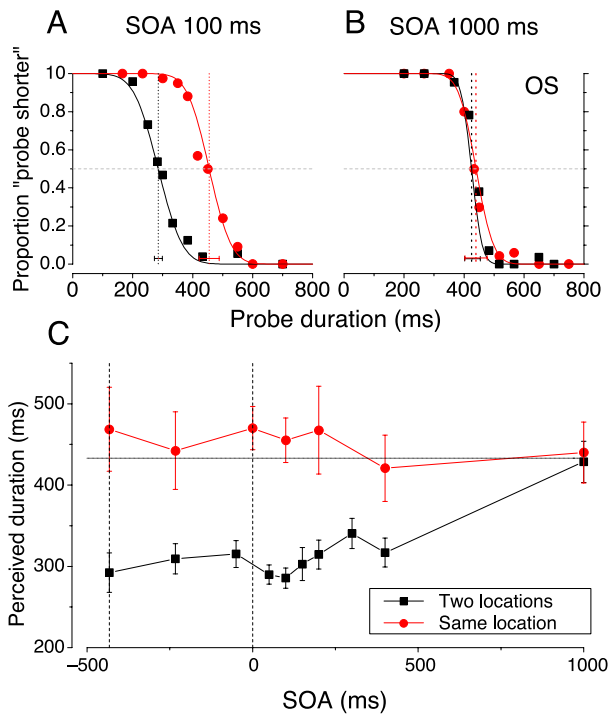
Figure 5. Comparison of duration judgement for stimuli marked by bars in the same or different spatial positions. Top panels (A and B): psychometric functions for intervals of 433 ms at 100 ms (A) and 1000 ms (B) asynchrony from the primary task stimulus (SOA). The red points refer to when the two bars delimiting the interval were flashed in the same spatial location; the black points when the bars were flashed in two different positions. Data-points are binned responses whereas continuous lines are best fitting cumulative Gaussians. Vertical lines are the PSEs for both judgements. Bottom (panel C): perceived duration (PSE) of a 433 ms interval as function of stimulus onset asynchrony (SOA) for both judgements. Intervals marked by bars presented in two separated locations are in black, intervals marked by bars in the same position are in red. The horizontal line indicates the target value of 433 ms. The two vertical bars, placed at −433 ms and 0 ms indicate respectively, intervals which terminate or intervals which start with the presentation of the primary task stimulus. Error bars are *SEM* calculated via bootstrap procedure (see Methods).

of 433 ms. Figure 6 shows a summary of this data for all subjects, plotting perceived duration for 100 ms SOA against the perceived duration of intervals at 1000 ms SOA. Black symbols plot results for the intervals between bars in two spatial locations; red symbols for the intervals between bars in the same location. For different locations bars, the data lie below the diagonal indicating that at an SOA of 100 ms these intervals are grossly underestimated. For the same location bars, the data lie on the diagonal indicating that perceived duration is independent of the asynchrony between the two tasks (SOA), confirming that these duration judgements are not affected by a concurrent task.

In all previous experiments the two bars could be flashed unpredictably at the top or the bottom of the display. We also reduced the uncertainty of the localization by flashing the bars always at the same known position both for the same and the two position conditions. However we obtained the same pattern of result: no compression for the same position and a strong compression for the two separate positions.

Spatial selectivity of the primary task stimuli

The results of the previous experiment (Figures 5 and 6) indicate that the spatial location of stimuli may be a crucial factor in duration judgements. It is possible that the location of the spatial attention required for the primary task may influence the perceived duration. To test this we repeated the "Two location" duration judgement, changing the location of the primary task stimulus. Attention was allocated to positions closer to the position of one of the bars of the secondary task. Two conditions were tested: primary task stimuli positioned along the vertical meridian and a single stimulus (instead of two) always at fixation.

In the vertical condition arrangement, the side of primary stimulus is no longer neutral with respect to the presentation of the bars, although still a positional uncertainty is present and still the subject had to keep
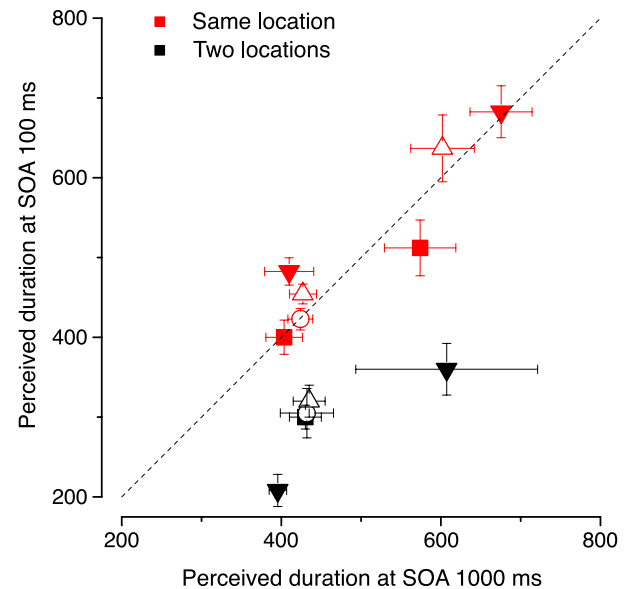

Figure 6. Temporal compression for intervals marked either by bars in the same or in two separate locations. Perceived duration for intervals presented at an SOA of 100 ms plotted against perceived duration at an SOA of 1000 ms. The black symbols plot perceived duration for intervals marked by bars in two locations, red symbols for intervals marked by bars in the same location. Horizontal and Vertical error bars indicate *SEM*. Test duration could be of either 433 ms or 633 ms. Different symbols refer to different subjects.

open a large attentional window to select the primary task stimulus. Trials for this condition have been subdivided into those where the primary stimulus pre-cues the first bar and those cueing the opposite hemifield. When the primary stimulus and the first bar are close, the subject is required to perform an attentional shift from fixation to the primary stimulus and from the first bar to the second bar position. When they are in opposite hemifields the subject needs to add an additional attentional shift from the primary task stimulus to the first bar position. A comparison between congruent and incongruent trials allows assessing if the number and direction of the attentional shifts might play a role in the temporal judgement. To simplify the data collection we ran the experiment with only two representative SOAs of 100 ms and 1000 ms.

In the central condition only one circle is presented around the fixation point, eliminating positional uncertainty and decreasing the spatial extent of the attentional shift.

Psychometric functions of the duration judgements of 100 (continuous curve) and 1000 ms (dashed curve) SOAs at the four possible locations for the primary task stimulus are shown in Figure 7 for a representative subject. The average data for four subjects are shown in Figure 8. The temporal compression is present both for the central position of the primary task stimulus and the vertical position, all these conditions yielding a similar effect. This is surprising given the great variation in uncertainty, eccentricity, spatial congruence and accuracy in the primary task.
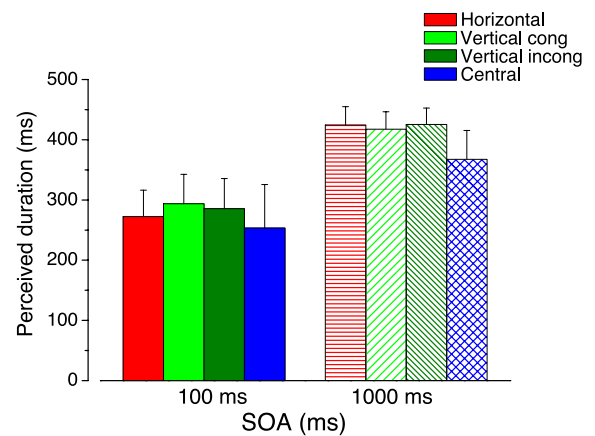

Figure 8. Effect of primary task stimuli position. Perceived duration of a 433 ms interval at two representative SOAs (100 and 1000 ms). The different color bars show data collected in different spatial positions of the primary task stimuli. Data are means of four subjects, error bars are *SE*.

Form discrimination of equiluminant stimuli for the primary task

In all the previous experiments, the primary task discrimination was motion direction discrimination. This task may share common circuitry to the timing mechanism (Gibson, 1975; Johnston et al., 2006; Poynter, 1989). In addition, for the shortest duration, discrimination of the secondary task might be mediated by motion mechanism. This opens the possibility that the measured interference
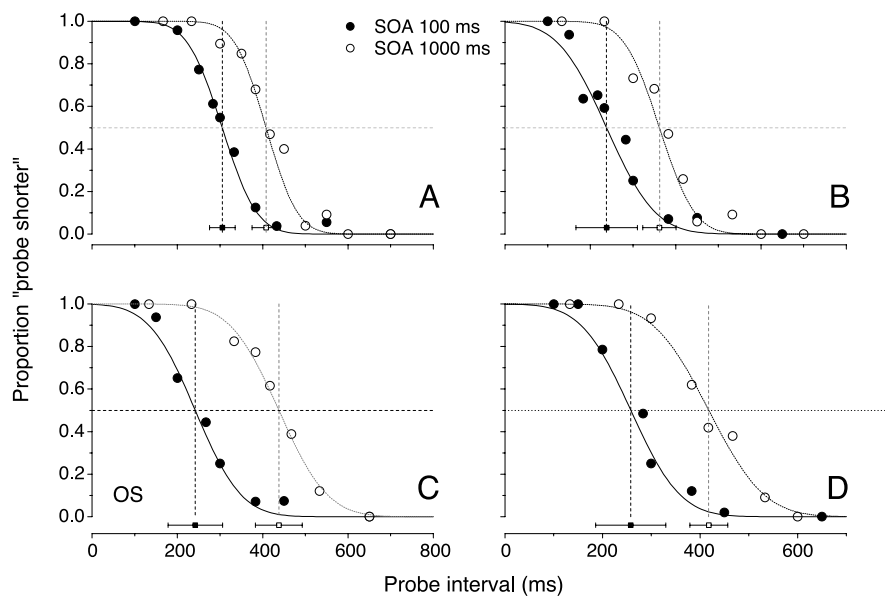

Figure 7. Effect of primary task position for a representative subject. Psychometric functions for discriminating a 433 ms interval at two SOAs: 100 ms (filled symbols) and 1000 ms (open symbols) for various positions of the primary task stimuli. The position of the primary task stimuli were Horizontal in A, Central in B, Vertical in C and D. C plots the data where the position of the primary stimulus is in the same hemifield of the first bar, D when it was in the opposite hemifield.
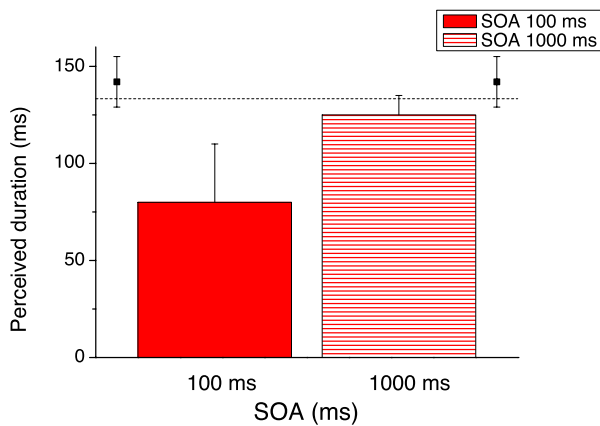
Figure 9. Perceived duration when performing a concurrent form discrimination primary task. Perceived duration of a 133 ms interval for Stimulus Onset Asynchronies of 100 ms (red bar) and 1000 ms (hatched bar) from the appearance of an equiluminant disk used for a form discrimination task. The horizontal line is the physical duration of 133 ms. The black data points indicate performance in a control condition where the primary task was not performed. Data are the average of four subjects, error bars are *SE*.

between primary and secondary tasks is specific to the motion system. To test this possibility we replicated some of the results using form discrimination as primary task. The task consisted of discriminating which sector of an otherwise red equiluminant disks was green. The disk appeared transiently (33 ms), either on the left or the right hemifield symmetrically respect to fixation along the horizontal meridian. Average performance data across four subjects are presented in Figure 9 for the 133 ms interval at two different SOAs. The compression of time is also present in this condition and the effect is similar to the one elicited by a motion discrimination task, indicating that the interference is not specific to particular features of the stimuli.

Discussion

In this series of experiments we investigated how perceived time is altered when attention is allocated to perform a concurrent visual task. The main results show that temporal intervals in proximity of the onset of the primary task stimuli are perceived as strongly compressed. The effect is proportional to the size of the interval and amounts to underestimate duration of about 35%. Interestingly, the compression occurs only when the intervals are marked by bars presented in separate spatial locations. When the interval is marked by two bars flashed in the same spatial position, no temporal distortion has been found.

Perception of intervals marked by events in the same location seems not to be modulated by attention, while a strong modulation is present when the subject needs to monitor two separate locations or needs to shift attention between the two locations. Particular care has been taken to ensure that when the stimuli occupied two locations, no motion cue were present. The two locations were very far apart and the stimuli were equiluminant. No motion perception was elicited even for the shortest interval used (133 ms), as reported qualitatively by all subjects, making it unlikely that the differential attentional modulation could be ascribed to a selective modulation of the motion mechanisms. For the one location experiment, we used long intervals to ensure that flicker cues could not be used to perform the task. Nevertheless, no attentional modulation was present even for very large separations. The integration time of briefly flashed equiluminant stimuli is of the order of 200 ms (Burr & Morrone, 1993; Eskew, Stromeyer, & Kronauer, 1994; Uchikawa & Ikeda, 1986), the separations employed in this study is more than 600 ms, nearly 3 times greater. Having dismissed the possibility of motion or flicker artifacts, the data indicate that attention can modulate time perception when the visual activity between two different spatial positions needs to be monitored, at least in our paradigm of divided attention. Interestingly, recent evidence demonstrates a selectivity of timing mechanisms on spatial position. Adapting to a local grating alters the perception of the duration of a test grating by about 25% (Johnston et al., 2006) when the gratings have the same spatial position. The selectivity is not for retinal location of the stimuli, but for the external space position (Burr et al., 2007). This later result excludes the possibility that the perceptual alteration can reflect a distortion of early visual analysis, like a change of the shape of the temporal response function or a change in the processing delay of the early visual mechanism. The existence of separate and parallel clocks, each monitoring independently various allocentric spatial positions, probably at high level of analysis, is in agreement with the present set of data. In conditions of limited attentional resources, the brain seems to have great difficulty in comparing the outputs of two separate clocks (or more generally timing mechanisms), while can still cope with monitoring a single clock.

It is also interesting to compare the amount of compression between adaptation and attentional modulation. The maximal attentional modulation is on average 45% of the physical duration, nearly double the adaptation effect. The difference of the amount could reflect the different types of visual stimuli employed (luminance and prolonged versus briefly flashed equiluminant) or possibly that adaptation and attention modulate timing mechanisms differently, as it has been demonstrated for modulation of contrast (Pestilli, Viera, & Carrasco, 2007).

Despite the quantitative differences in the amount, both adaptation and attention seem to modulate the perceived duration at late stages of processing. Several of the present

results indicate that the temporal compression by attention cannot be ascribed to sensory delay of the timing of the markers. It is important to note that if the processing time of the bar is increased in the unattentive condition, this would produce an opposite pattern of distortion depending if the effect affects the first or the second bar delimiting the interval. Contrary to this prediction, we never observed an expansion of perceived duration although we tested a large range of SOAs and durations. We always observed a temporal compression. In addition, and most surprisingly, the temporal compression is proportional to the size of the physical interval. This pattern of results cannot be predicted simply by a deterministic distortion in the timing of the markers. The temporal compression can induce a loss of about 250 ms of subjective time for larger intervals. In addition it is surprising that the effect is proportional to the physical duration, considering that attention endowing and shifting time are very short (Hogendoorn et al., 2007; Remington & Pierce, 1984; Sperling & Weichselgartner, 1995). A model of a mobile spotlight of attention shifting between the primary and secondary task stimuli would predict a constant loss of perceived time, not a proportional compression, if it were not the case, as recently suggested, that attention dwell-time changes with the stimulus temporal characteristics (Hogendoorn et al., 2007). It is also surprising that the effect is still measurable more than 500 ms after the primary task stimuli offset and for intervals extinguished before the primary task stimulus onset. The multiplicative and prolonged nature of the compression indicates that the attentional modulation takes place late in the visual analysis, probably at high representational level. It is indeed highly possible that the interference takes place in the working memory circuits that have to retain the two information simultaneously. In this light it is even more surprising that the attentional modulation on temporal duration is spatially specific, indicating that the problem may arise when the system has to compare the information flow of two different position and/or clocks.

The interference at a high cognitive level is also in agreement with the lack of dependence on the difficulty of the primary task and on the spatial location of the primary task stimuli. In the central condition, the location of the primary task stimulus is known in advance, so there is no uncertainty and the subject has to monitor simultaneously 3 and not 4 spatial positions. With the vertical condition and no positional uncertainty, the positions needed to be monitored simultaneously are reduced to two. Nevertheless the pattern of the results and the magnitude of the interference did not change with the spatial position of the primary task stimuli. The condition with the primary task stimuli on the vertical axis generates trials in which the location of the primary and secondary tasks can be congruent or not, inducing attentional shifts in the same or in the opposite direction. However, neither the direction of the attentional shifts nor the numbers of shifts modulated the interference. Even a different primary task

using equiluminant stimuli and relying on a form rather than motion discrimination, produced similar results, consistent again with the idea that the interference happens late, after that all the parallel visual analysis of the different features have been performed and the features are bound together in the percept of a single object. fMRI studies of time estimation during divided attention indeed show that the cortical–striatal circuit correlates with the attention dedicated to the task and in this circuits the pre-supplementary motor area could absolve an important role in duration estimation (Coull, Vidal, Nazarian, & Macar, 2004; Nobre & O'Reilly, 2004).

The present results agree with a large literature showing that attention allocation to the stimulus induces an increase of its apparent duration both in the sub-second and second range (Zakay, 1989). Abrupt stimuli that capture transient attention appear to last longer (Rose & Summers, 1995; Tse et al., 2004) and diverting attention to other features of the same stimulus reduces perceived duration (Coull et al., 2004; Macar et al., 1994). In particular Macar et al. (1994) found a small reduction (amounting to 15% of perceived duration) of perceived duration when sustained (not transient) attention was diverted to the color of the same stimuli. This may appear to contradict the lack of interference reported here, when the interval is marked by bars at the same position. However, Macar's experiment uses the same stimulus for the primary and the secondary task, studying the interference in the domain of feature attention (Blaser, Pylyshyn, & Holcombe, 2000). This difference reinforces the idea that the transient shifts of spatial attention between the two targets and between the primary and secondary stimuli may be the important variable that interferes with the timing mechanisms.

It is also interesting to compare our data to those obtained at the time of saccadic eye movements. In the unattentive condition of two bars at two spatial locations the compression appears similar to that observed perisaccadically. However, Morrone et al. (2005) reported a maximum compression greater than 65% for a separation of 100 ms, while here at maximum we obtained a compression of 50%. There are other two major differences between these compressive effects. During saccades the compression is accompanied by an increase in discrimination of the interval, not observed in the unattentive condition. This indicates that depriving attention induces an increase of the noise, but the noise is reduced during saccades. The second difference is that in the unattentive condition the compression is multiplicative, while performing a saccade seems to compress the interval by a constant amount of about 50–75 ms. These differences implicate that saccadic compression may not be related to the performance of dual task or to the allocation of attention at saccadic target. However, it is interesting that the two phenomena share some similarities. The saccadic compression has been linked to the transient shift of the neuronal coordinate frame at the time

of saccades. The analogy between transient shift of attention and shifts of reference systems of the two experiments is interesting, although no direct evidence is available to establish this further.

The other peri-saccadic effect is *Chronostasis*: the dilation of a peri-saccadic interval when the stimulus is located at saccadic target where attention is allocated. The effect is not observed in other spatial positions (Georg & Lappe, 2007). Interestingly this pattern of results is consistent with our data: perceived duration of unattended stimuli is veridical if the location of the object does not change.

In conclusion, our data indicate that attention can dramatically change our perception of event duration. The effect is multiplicative, and probably takes place at a late stage of visual or representational processing of the stimulus. Interestingly, attention distorts time estimation only for events presented in separate locations, indicating that the neuronal mechanisms that compare the passage of time at different spatial positions may be under attentional modulation. This result corroborates and extends previous findings on the existence of spatial selectivity of neuronal mechanisms of time.

Acknowledgments

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