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▸ To cite this version:

Janice Hau, Andrei Gorea. The influence of task difficulty, success and confidence on perceived brief durations. 2011. hal-00628660

HAL Id: hal-00628660

https://hal.science/hal-00628660

Submitted on 4 Oct 2011

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Université Paris Descartes

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Technical report

The influence of task difficulty, success and confidence on preceived brief durations

Janice Hau, Andrei Gorea

May 31, 2011

Abstract – Time is constant but it has been repeatedly shown that our perception of time is impacted by many factors. This is evidenced by the growing literature on temporal distortions. The interference effect, the finding that we tend to underestimate temporal durations when temporal processing is disrupted by a secondary (non-temporal) task, has been widely observed in the time literature. However, within the sub-second range the influence of a secondary task on temporal processing has been less-studied and the subject of much debate. In this study we looked at the effect of task difficulty on perceived duration under a dual-task paradigm. Additionally, we investigated two potential factors that may play a role in perceived duration: success and confidence. While no significant effects were found for our three main factors, we propose that our main contribution is our original dual-task visual search paradigm. Our negative results are discussed further with regard to the distinct timing hypothesis, which proposes distinct mechanisms for sub-second and supra-second timing.

Keywords – perception of duration, millisecond timing, task difficulty, attention, success, confidence, psychophysics

1 Introduction

Our perception of time is variable from one situation to another. The expressions "a watched pot never boils" and "time flies when you're having fun" are illustrations of the common variability of our duration perception. The first to write about a time sense was Czermak (1857) in the 19th century, the idea that time is a perceived quality processed internally. In addition to physical duration itself time perception is actually influenced by many factors such as emotional context (Langer et al., 1961), personality traits (Orme, 1969), age (Wallach & Green, 1961), drugs use (Frankenhaeuser, 1959), saccadic eye movements (Morrone et al., 2005), visual motion (Kanai & Verstraten, 2005), and visual space (Casasanto & Boroditsky, 2008). The implications for studying perceived time, particularly of brief durations holds significant importance for motor, sensory, and cognitive processes. Timing in the milliseconds is required for immediate perception (i.e., seeing, hearing) and also for the actions we produce in relation to these events (i.e., motor coordination is just one example). Without our ability to process time (relatively) precisely, our understanding of speech and music would be impaired, we would have difficulty catching a ball, driving a car, and doing simple tasks such as crossing the street – judging the moment when a car would pass by. In short, our daily functioning would suffer extensively.

The interference effect is a classical phenomenon involved in time perception that has been consistently demonstrated in the literature (Brown, 1997). The interference effect is the tendency to underestimate temporal durations when time processing is disrupted by a concurrent task. It also translates into less accurate (i.e., more variable) duration judgements (Brown & West, 1990; West, 1992), see review by (Brown, 2008). It is usually assessed by means of a dual-task paradigm, where a primary (duration estimation) task and an arbitrary (non-temporal) secondary task are performed simultaneously. These duration estimates are then compared to estimates obtained in a single (timing-only) task condition. Gradual effects when changing the difficulty of the secondary (non-temporal) task can also be observed. The more difficult the non-temporal task, the shorter the judged duration. This has held for a variety of secondary tasks involving perceptual (Brown, 1985; Coull et al., 2004; Field & Groeger, 2004; Zakay, 1993), verbal (Fortin & Massé, 1999; Fortin & Couture, 2002; Rammsayer & Ulrich, 2005; Miller et al., 1978), and memory (Fraisse & Leith, 1963; Brown, 1984; Zakay et al., 1983) processes. The lower duration estimation performance in the presence of a secondary task is usually accounted for in terms of a limited attentional capacity (Kahneman, 1973) that is taxed by the secondary task in proportion to its cognitive load (Hicks et al., 1976; Thomas & Weaver, 1975). When a secondary task is highly-demanding, less attention can be allocated to "keeping track" of time hence entailing degraded performance (Brown, 1985). Inasmuch as less attention entails a lesser number of processed events by the count of which perceived duration is putatively calibrated (Thomas & Weaver, 1975), less attention will also entail a duration underestimation (Treisman, 1963).

The study of time perception is complicated by the putative existence of different time scales. Mauk & Buonomano (2004) have categorized the limitless span of time into four time ranges: microseconds, milliseconds, seconds and circadian rhythms. It is remarkable that the central nervous system processes temporal information across all of these ranges throughout life. The way circadian rhythms function in the body is relatively well understood (Perreau-Lenz et al., 2004), however surprisingly little is known about how we process time in the intervals spanning milliseconds, seconds, and minutes. From the beginning of psychological time research scientists have raised the question of whether we process time differently in the brain within each of these time scales (Münsterberg, 1889; Wundt, 1903). More recently, researchers have suggested distinct mechanisms specifically for sub-second and supra-second timing (Lewis & Miall, 2003a; Ivry & Schlerf, 2008; Buonomano & Karmarkar, 2002; Buhusi & Meck, 2009; Michon, 1985). Gibbon et al. (1997) identified time ranges that showed distinct psychophysical characteristics. He noted differences in the coefficients of variation (standard deviation of interval estimates divided by the estimated mean) in the time ranges below 1-2 s and the ones above, and proposed the existence of different neurobiological mechanisms[1]. But recent evidence from Lewis & Miall (2009) revealed no such discrete differences, instead showing a continuous logarithmic decrease for durations ranging from 68 ms to 17.7 min. Pharmacological (Rammsayer, 1993, 1999; Rammsayer & Vogel, 1992; Mitrani et al., 1977), lesion (Breukelaar & Dalrymple-Alford, 1999; Clarke et al., 1996) and neuroimaging (Lewis & Miall, 2003a) studies also provide support for separate mechanisms.

[1]Equally interesting is the fact that similar Weber fraction values apply across a variety of tasks and species, which may indicate that the mechanisms that process time may be more similar than different, an observation that may favour a unified "clock". Matell & Meck (2000) approach this issue from an evolutionary perspective, favouring coincidence-detectors as a fundamental singular timing mechanism. For timing across different species, see (Lejeune & Wearden, 2006; Penney et al., 2008).

This so-called distinct timing hypothesis proposes that temporal discrimination of intervals in the range of seconds is cognitively mediated, whereas brief intervals in the sub-second range are processed automatically and therefore beyond cognitive control (Lewis & Miall, 2003b; Michon, 1985; Johnston et al., 2006; Ivry & Spencer, 2004)[2]. According to the distinct timing hypothesis then, temporal processing in the range of milliseconds should be unaffected by cognitive tasks and attention. But, whereas perceptual factors have been shown to influence duration judgments in this interval range (Rammsayer & Lima, 1991; Tse et al., 2004; Rammsayer & Ulrich, 2005; Kanai et al., 2006), the role of higher cognitive processing in this range is less clear. Only a few studies have looked into this issue. Of particular interest are the studies that involved dual-tasks, which we will consider in more detail.

Mattes & Ulrich (1998) manipulated attention by using a valid vs. invalid pre-cue to indicate the modality (Exp. 1-3) or spatial location (Exp. 4-6) of a stimulus whose duration was to be estimated. In the valid pre-cue trials subjects were correctly oriented to the stimulus (more attention) and in the invalid pre-cue trials subjects were misdirected away from the stimulus (less attention). They showed that directed attention (via the pre-cue) to a stimulus prolongs its perceived duration, a finding that contradicts the distinct timing hypothesis, given that milliseconds timing was mediated by attention. In dual-task studies, if the distinct timing hypothesis held, then differential impairment should be observed between temporal judgements for sub-second intervals and supra-second intervals, indicating different underlying mechanisms. Under a dual-task paradigm, Rammsayer & Ulrich (2005) found no differential interference between subjects' duration discrimination centred around 100 ms and 1000 ms. Both intervals were systematically influenced in the same way by a secondary mental arithmetic task and unaffected by secondary memory search and visuo-spatial memory tasks. In contrast, Rammsayer & Lima (1991) (see Exp.'s 2-3) showed differential impairment in duration discrimination in dual-task conditions for intervals in the sub-second and supra-second ranges. The secondary task was a word learning task and involved subjects having to learn a visually presented word on each trial and recall the words at the end of the experiment. Performance on the timing task in the milliseconds (centred around 50 ms) showed no difference in the presence of a secondary task versus in the single task (timing-only) condition. But for the intervals centred around

[2] It is important to note that this boundary is not clear cut, 250 ms: Spencer et al. (2009); 500 ms: Michon (1985).

1-second, performance on the timing task was affected by the secondary task. Rammsayer & Ulrich (2011) showed the same pattern of differential impairment on temporal judgements between sub-second and supra-second intervals using the same word learning task, referred to as *elaborative rehearsal*, essentially replicating the results of Rammsayer & Lima (1991) but also showing that it was not the case for a different word learning task referred to as *maintenance rehearsal*. In maintenance rehearsal subjects only needed to recall the last word beginning with a designated letter such as the letter "B". According to these authors, the elaborative rehearsal task required continuous updating of information and transfer to long-term memory, producing interference in sub-second temporal processing. Instead, maintenance rehearsal presumably only requires passive information storage in working memory and therefore should not affect timing processes. This result is consistent other studies showing no interference effects for passive storing of information in working memory (Brown & Merchant, 2007; Fortin & Breton, 1995). In short, factors such as the type of the secondary task and the experimental design need to be considered further for a better appraisal of the interference effect in duration estimation (for discussion, see (Bangert et al., 2010)).

Here we address the issue of the impact of the difficulty of a secondary, perceptual task on sub-second duration estimations. In accord with a wide literature (Carrasco, 2011) we posit that attention intervenes at all processing levels and at all psychological time scales and therefore hypothesize that a more difficult visual task requires greater attention, hence less resources devoted to keeping track of time, and therefore a lower time units count leading to a duration underestimation.

In addition to manipulating the task difficulty, the present study tackles two duration estimation issues never addressed before, namely subject's success (vs. failure) and level of confidence in accomplishing the visual task. Intuitively, there is reason to believe the duration of a successfully accomplished task should be overestimated by comparison with the same duration of an unsuccessfully accomplished task. Retrospectively, success might entail the impression that sufficient time had been available to accomplish the task and if so failure should have the opposite consequence. Alternatively, it can be argued that the difficulty of the task may lie in the trial by trial strength of the evoked brain response (conditional on internal noise) and not on the overall task difficulty as assessed by a global performance/sensitivity index such as d′. Accordingly, successful secondary task trials should be associated with shorter and more accurate duration estimates than unsuccessful trials. Inasmuch as correct responses generally correlate with the level of confidence, (e.g., Henmon (1911); Harvey (1997); Barthelmé & Mamassian (2009)) the same should be true for duration estimates associated with 'confident' and 'not-confident' secondary task trials, respectively. As the probability of succeeding is inversely proportional with task difficulty, our experimental design should disentangle these factors. To our best knowledge, the dependence of duration perception on the correctness of the responses in a secondary task and on the confidence subjects have in these responses has never been studied.

1.1 The present study

The large majority of studies involving the effects of task difficulty in time perception have focussed on durations in the supra-second range (2 s to several minutes). Several neuroimaging studies (fMRI) have manipulated duration discrimination difficulty itself in the milliseconds range either by means of varying the difference between the two durations to be discriminated (Tregellas et al., 2006) or the time interval between two events whose temporal order was to be discriminated (Lewandowska et al., 2010). Task difficulty manipulations have also been used to study sensitivity in timing (Ferrara et al., 1997), and the perception of one's own response times (Petrusic & Baranski, 2009).

There are a number of methodological issues that are associated with a task difficulty manipulation. One is to design a task whose difficulty is equally maintained for the entire duration to be estimated and which does not differ with time. Petrusic & Baranski (2009) investigated the effects of task difficulty on the perceived duration of subjects' own response times which, of course, correlated with task difficulty. Hence, not only was the duration to be estimated varying from trial to trial but subjects' estimates could simply be based on their estimate of the task difficulty, on their response time or on both. In our paradigm task difficulty is manipulated within a fixed physical duration given to subjects to accomplish their perceptual (secondary) task with no speeded response. Hence duration estimation can be achieved based on time processing only. Fortin et al. (1993) used a visual search task in which subjects were asked to produce a fixed

3 s temporal interval while simultaneously finding a target in a visual search array. Regardless of the task difficulty, the time interval needed to accomplish the search task was significantly shorter (by at least 1 s) than the interval to be produced. Hence the secondary task only partly overlapped with the required time processing that remained partly undisturbed.

In our study, we use a visual search task within a modified version of the Rapid Serial Visual Presentation (RSVP) (Forster, 1970), of a constant total duration and tailored so that subjects needed to sustain their attention until the very end of the given interval. Another difference between our study and previous studies concerns the fact that duration estimation and difficulty were related to disjoint, independent events. As such the secondary task added a cognitive load difficulty to this task's difficulty per se. In the present experiment, subjects were asked to estimate the duration of the very same time interval that they were given to perform the visual search task knowing that this time interval is kept constant for all difficulty levels. Also in contrast with other studies that have manipulated difficulty within a poorly defined dimension space, i.e., using different qualitative tasks (Axel, 1924; Gulliksen, 1927), the present study varies task difficulty along a single dimension, i.e. orientation.

The modified RSVP task consisted in visual stimuli (vertical Gabors) briefly displayed at non-overlapping (hence lateral-masking free) iso-eccentric locations with a deviant orientation target presented at the end of the sequence. Such presentation was meant to entail a high and constant attentional level throughout a given RSVP sequence while dissociating the difficulty of the task (the difference between target and distracters) from the duration of the RSVP sequence to be estimated. A standard visual search task and Multiple Object Tracking (MOT) task were also considered and rejected as they entail such confounds and were not feasible for sub-second durations.

In sum, our study contributes in several ways: it measures difficulty effects on sub-second duration estimation with an original visual search task that circumvents confounds identified in the literature, and addresses two unstudied putatively interfering factors in duration estimation namely success and confidence.

2 Method

2.1 Participants

Six subjects took part in the study (5 female). Five subjects had ages that ranged from 22 to 26 years (mean = 23.6 yrs) and one subject was 59 years of age. All subjects had normal or corrected-to-normal vision and gave their informed consent to participate. All subjects were compensated 30 euros for their participation in the study.

2.2 Apparatus and stimuli

The stimuli were displayed on a $19''$ $E96f + SB$ ViewSonic screen (1024×768 pixels, 100 Hz refresh rate) 60 cm away from observers' eyes. Lighting conditions in the room were dim. The presentation of stimuli and response recording were controlled using the Psychophysics toolbox (Brainard, 1997; Pelli, 1997) in Matlab. The target and distracter stimuli were Gabor patches with a sigma of 0.5 deg, a spatial frequency of 4 cpd, and a 99% contrast. They were presented on a 35 cd/m^2 grey background. The stimuli were presented in two successive modified rapid serial visual presentation (RSVP) sequences. These displays differed from the standard RSVP mode in that the stimuli appeared at pseudo-random locations on a 6.5 deg radius virtual circle around fixation (see Figure 1). The pseudo-randomization was such that the locations of items $i+1$ to $i+n$ in the RSVP sequence were at least 45 deg of visual angle away from the location of item i within a sliding temporal window of 100 ms. This presentation scheme was meant to prevent lateral interactions between items. Each item i was displayed for 20 ms with inter-stimulus intervals randomized in-between 10, 20 and 30 ms so that the number of items within the "non-interaction" window varied from trial to trial. The randomization of the inter-stimulus interval was meant to prevent subjects from potentially basing their duration judgments on the number of displayed items[3]. The number of distracters (vertical Gabors) displayed before the target was varied so as to yield one of three total RSVP durations (300, 400 and 500 ms), the 'standards'. The target (a tilted Gabor) was always followed by one distracter that terminated a given RSVP sequence. Fixating the rank order of the target one item before the end of a random (one out of three) RSVP durations insured that observers had to sustain their attention until the end of that duration. A target

[3] An unlikely event given the fast presentation pace.

item concluding the RSVP sequence would have allowed observers to passively wait until the end of the sequence and base their orientation discrimination on this last item/target orientation stored in iconic memory. The target item was always presented in the second RSVP sequence, the standard. The duration of the first RSVP sequence (the 'probe' duration) was randomly chosen out of 5 durations centred logarithmically on the duration of one of the three standards. Target orientation was randomly rotated clockwise or counter-clockwise by a predefined amount to yield two orientation discrimination difficulty levels (67 and 96 percent correct as assessed in a two-alternative forced-choice (2AFC) preliminary experiment; see Procedure).

2.3 Procedure

Preliminary experiment. It was meant to assess the orientation discrimination psychometric function of each observer with the RSVP presentation mode described above. The same dual-task

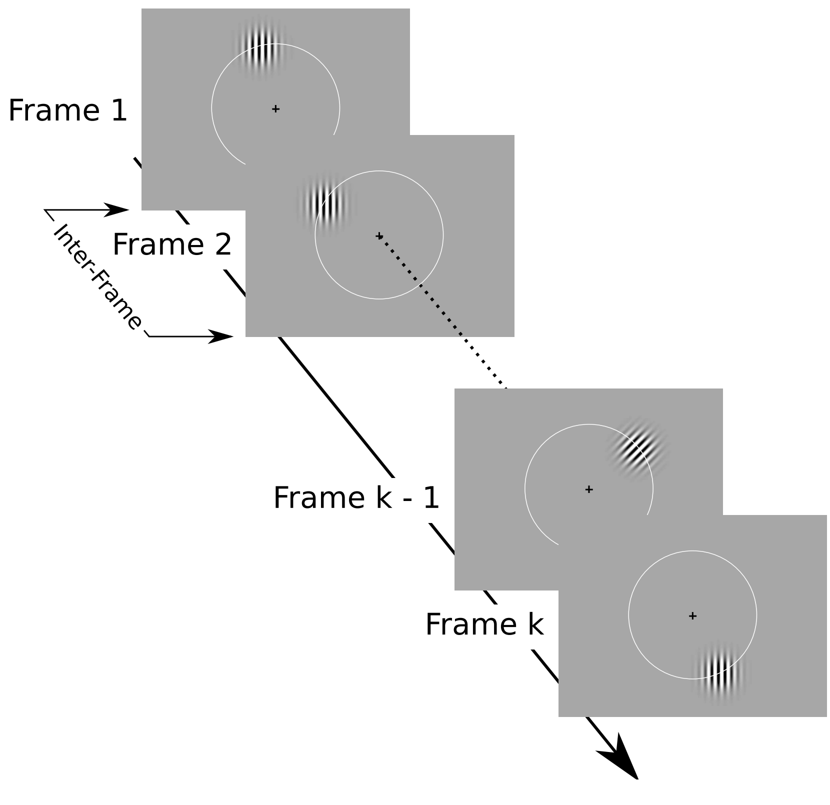


Figure 1: Spatio-temporal sequence of stimuli presented in the RSVP visual search task. The target (an oblique Gabor) is always presented in the first to last frame (k-1). Location constraints are placed on the target/distracters so that items never overlap within a 100 ms sliding window. The illustration is for the 'standard' RSVP sequence that could be of 300, 400 or 500 ms. The 'probe' sequence, always presented first, included no target. Its duration was randomly chosen out of 5 durations centred logarithmically on the duration of the standard.

procedure used in the Main experiment was applied here. Observers were required to specify the clockwise/counter-clockwise orientation of the target (2AFC method with constant stimuli) by pressing one of four keys on a standard keypad. The four keys were aligned horizontally with the two extreme keys designating a high level of confidence that the target was tilted counter- or clockwise and with the middle keys designating a low level of confidence. On each trial observers were also required to perform the duration discrimination task (see Main experiment). The duration of the standard for these trials was fixed and set at 450 ms. Four target orientations (+/- 2, 4, 8 and 15 deg away from the vertical) were presented 50 times each in a randomized order once the first $24-48$ (training) trials were discarded for each observer. A cumulative Gaussian was used to fit the four performance levels and the target orientations yielding theoretical correct responses of 67% (d′ = $.62$) and 96% (d′ = 2.48) were used in the main experiment. The preliminary experiment together with the training trials was run in 15 to 25 min.

Main experiment. The main task focused on observers' estimation of the duration of the RSVP sequences while also performing the target orientation discrimination task described above. The probe sequence appeared first and was followed 300 ms later by the onset of the standard sequence. At its end observers first provided a 2AFC duration judgment (standard duration longer or shorter than the probe) and then the 2AFC orientation discrimination response. Probe durations varied in proportion to the standard durations; specifically, they were either equal to the standard or 17 and 34% shorter or longer than the standard). These values were chosen based on preliminary trials meant to bracket the duration discrimination psychometric function. As noted above, subjects also qualified their target orientation choice on a scale of 1 to 2 by means of pressing one of four keys. The following trial started 500 ms after the orientation response. The two levels of difficulty (as determined for each subject in the preliminary experiment) were run in separate blocks. Each block consisted of 150 trials, i.e., 10 trials per each of the 3 standards and per each of the 5 probe durations associated with each standard. Within each block both standard and probe durations were drawn randomly across trials. Each block was repeated 5 times in a random order for each observer to yield a total 250 trials per orientation discrimination difficulty level and per standard duration (i.e., 50 trials per each probe duration). The estimated Points of Subjective Equality of each standard duration and for each orientation discrimination difficulty level were taken to be the probe durations entailing 50% "shorter standard" responses as derived from the fit cumulative Gaussians to observers' percentages of "shorter standard" responses. The accuracy of the duration judgments was the fit standard deviation of these cumulative Gaussians. Trials were classified into two confidence levels depending on subjects' responses for the orientation discrimination task (whether they pressed the extreme or middle keys). The 1500 trials total per observer (750 trials per difficulty level x 2 difficulty levels) were run in about 2h30 not including short brakes after no more than 150 trials. Participants were instructed to concentrate on both duration and orientation tasks equally, without giving priority to one or the other. The experiment was run in three hour-long sessions.

3 Results

3.1 Preliminary experiment

Figure 2.a shows the psychometric function of a typical subject's orientation discrimination data fitted with a rescaled Weibull function of the form $P(x) = \gamma + (1-\gamma)p(x)$, where $P(x)$ is the probability of a correct response in the 2AFC paradigm as a function of the orientation x of the target, γ is the guess factor (0.5 in 2AFC) and $p(x)$ is the Weibull function $W(\mu, \sigma^2)$ where μ and

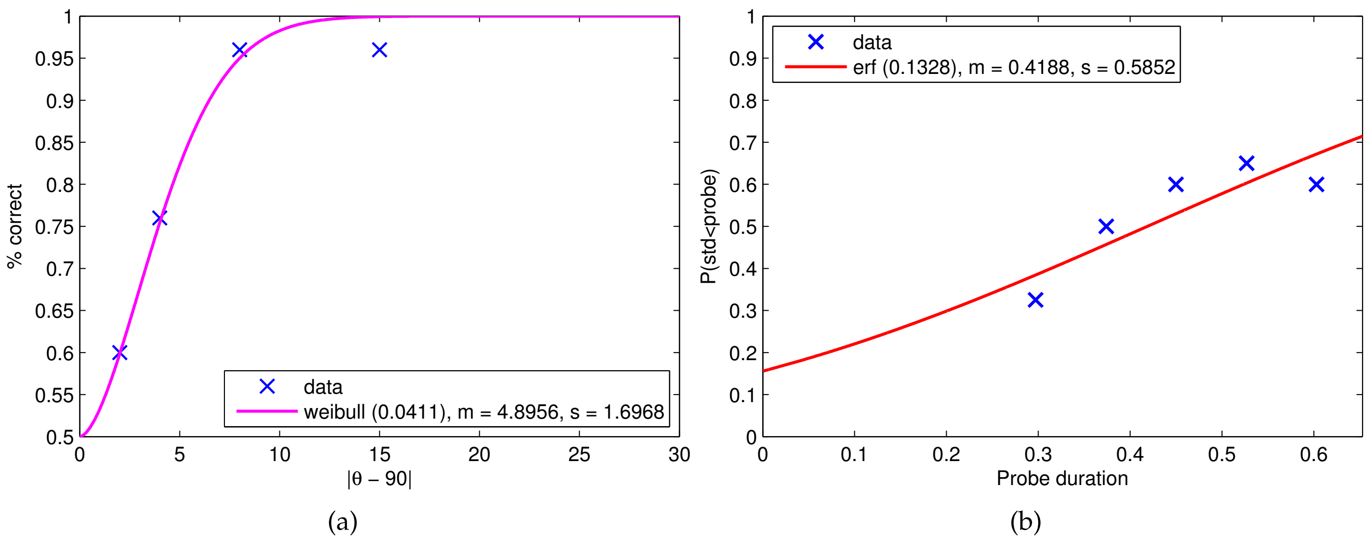


Figure 2: Fitted Weibull and cumulative Gaussian of a typical subject's orientation discrimination data (a) and duration discrimination data (b) in the preliminary experiment. (a) shows the percentage of correct orientation responses for orientation differences from the vertical of ± 2, 4, 8, and $15°$, for a fixed 450 ms standard; (b) shows the percentage the standard was judged shorter than the probe. In the insets, the error of the fits are given between parentheses and the parameters μ and σ of the respective fits are given by 'm' and 's', respectively.

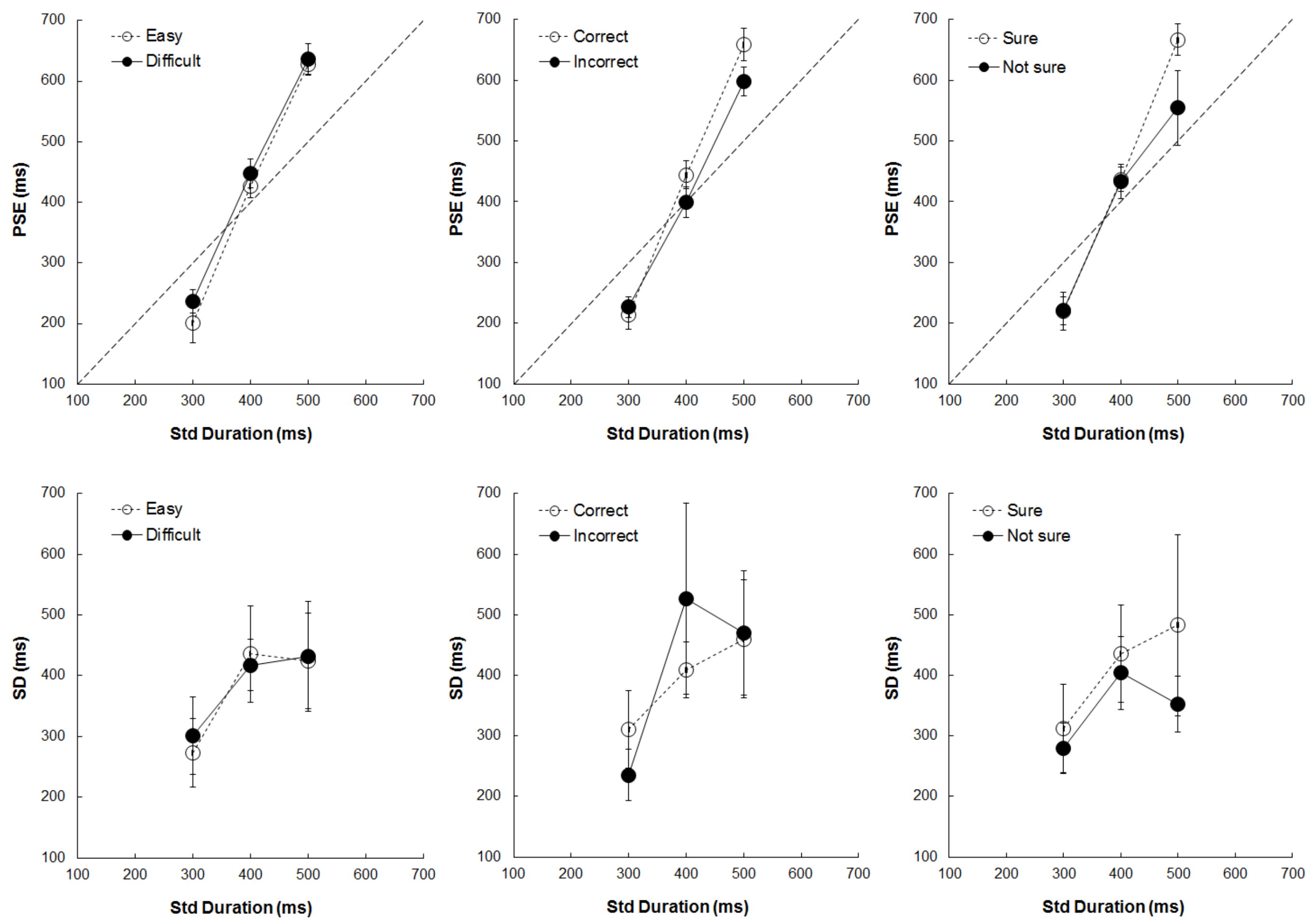
Table 1: Points of Subjective Equality (μ) and sensitivity indices (σ) derived from the duration estimates of a 450 ms standard by the 5 participants for each of the 4 orientation discrimination difficulty levels (i.e. angles relative to the vertical) in the preliminary experiment.

	Orientation angle difference							
	"+/- 2°"		"+/- 4°"		"+/- 8°"		"+/- 15°"	
	µ	σ	µ	σ	µ	σ	µ	σ
jh	367	156,5	449,6	458,8	433,9	358,4	451,4	342,3
ag	477,5	323,5	499,1	1039,4	509,7	215,6	564,5	523,8
cad	385,9	2593,9	377,6	341,1	431,1	1038,6	404,7	470,2
sc	340,9	377,6	495,9	209,9	480,6	372,8	433,3	393,9
md	457,9	-591,6	411,4	468,2	381	536,2	481,2	366,6
Mean	405,84	571,98	446,72	503,48	447,26	504,32	467,02	419,36
SE	26,43	534,52	23,66	141,95	22,18	142,9	27,36	33,81

σ are free parameters corresponding to its mean (the detection threshold) and standard deviation (an index of sensitivity)[4]. Subjects' thresholds (μ) ranged from 4.42 to 7.08 deg with a mean of 5.36 deg. Their fit standard deviations (σ) ranged from 0.89 to 2.83 deg with a mean of 1.68 deg. The orientations yielding performance levels of 67% and 96% (corresponding to d' values of $.62$ and 2.48) for the six participants were $\pm 2.6°$, $\pm 2.6°$, $\pm 2.9°$, $\pm 4.8°$, $\pm 2.5°$, $\pm 5.4°$ (67% performance) and $\pm 8.4°$, $\pm 8.4°$, $\pm 8.5°$, $\pm 9.1°$, $\pm 8.1°$, $\pm 25.6°$ (96% performance). These values were used in the main experiment and specified the "easy" and "difficult" detection conditions run concurrently with the duration estimation task. Figure 2.b shows percentages of the standard 450 ms duration being judged "shorter" than the probe (abscissa) for the same observer together with a rescaled cumulative Gaussian function of the form $P(x) = \gamma + (1 - \gamma)p(x)$ where $p(x)$ is the cumulative Gaussian function $\Phi(\mu, \sigma^2)$ where μ is this time the observer's Point of Subjective Equality (PSE) and σ is the sensitivity index[5]. Table 1 shows these fit values for each of the five observers and for each of the four orientations (difficulty levels) of the target stimulus. Observer NP could not do the task and her fit values are not included in the overall averages. The PSE of the remaining 4 observers bracket more or less the duration of the standard (450 ms) with a grand mean (over the 4 orientations and 5 observers) of 442 ms. Notice however the very large standard deviations (σ) of the fits (grand mean of 499 ms, $\sigma/\mu > 100\%$) that indicate that the task was particularly difficult. This is partly due to observers not being trained enough at this stage of the experiment.

[4] Percentages correct were also fit with cumulative Gaussian $[p(x) = (1 + erf(-(x - \mu)/\sigma)/2]$ and logistic $[p(x) = 1/(1 + e(-(x - \mu)/\sigma))]$ functions that yielded comparable error functions.

[5] Percentages shorter were also fit with Weibull $[p(x) = 1 - e(-(x/\mu)\sigma]$ and logistic $[p(x) = 1/(1 + e(-(x - \mu)/\sigma))]$ functions that yielded comparable error functions.



(a) (b) (c)

Figure 3: PSEs (top row) and standard deviations (bottom row) of the fit cumulative Gaussians in the duration estimation task (averaged over all subjects) as a function of the standard duration for easy and difficult conditions (a), correct and incorrect orientation discrimination (b), and high ("sure") and low ("not sure") confidence levels (c). Vertical bars are ± 1 SE. The dotted line represents accurate perception of physical duration (slope = 1).

As shown below, all observers improved their duration discrimination in the main experiment.

3.2 Main experiment

Performance on the orientation discrimination task was between $81 - 98\%$ (mean = 92.8%) for the easy condition and $67 - 83\%$ (mean = 74.6%) for the difficult condition across observers. The large standard deviations observed for the duration task in the preliminary.

Duration discrimination performances and their cumulative Gaussian fits in this experiment

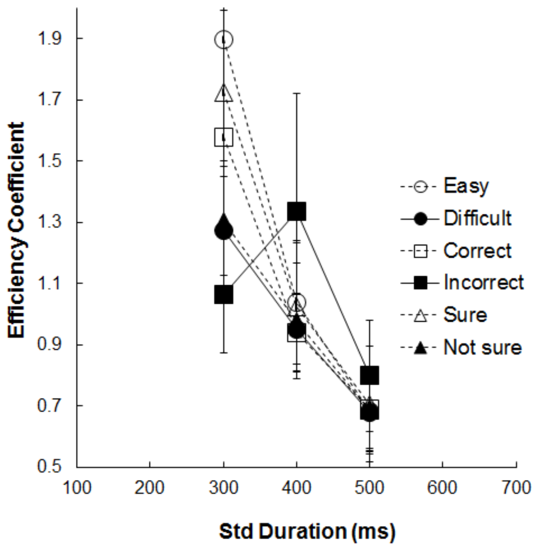


Figure 4: Coefficients of variation for easy and difficult conditions (circles), correct and incorrect orientation discrimination (squares), and high and low confidence levels (triangles).

were classified in three categories specified by (i) the difficulty of the orientation discrimination task ("easy" vs. "difficult"; Figure 3.a), (ii) the success of the orientation discrimination responses (correct vs. incorrect; Figure 3.b) and (iii) observers' level of confidence in their orientation responses (low vs. high; Figure 3.c). Table 2 presents the fit parameters for each observer and for each of the three data partitions. One subject (np) was not included in the analysis due to deviant performance on the duration discrimination task and the low number of high confidence responses reported (see Supplementary information in Appendix C).

As a preliminary observation, note that the precision of observers' duration estimate (i.e., σ) improved with respect to the preliminary experiment (grand mean of 327 ms, $\sigma/\mu = 78\%$) but remained rather high. Also note that the coefficients of variation (σ/μ) were not constant over the three standard durations tested which is evidence against Weber's law (or scalar property; see Figure 4). With one exception (incorrect responses; Figure 4.) out of 6 cases they decreased with the standard duration which is to say that σ increased less than required by the scalar property within this $400 - 600$ ms range (see Figure 3). Departures from Weber's law within this duration range have been frequently reported (Allan, 1979; Gorea et al., 2010; Kristofferson, 1980, 1984; Mauk & Buonomano, 2004; Wearden, 2004; Wright et al., 1997).

This being said, inspection of Figure 3 already tells us that none of the three factors of interest (difficulty of the concurrent orientation discrimination task, success and confidence) appears to play a systematic role in observers' duration estimation. This is the case both for observers' PSEs (μ; Figure 3 top row) and for their accuracies (σ; Figure 3 botton row).

In order to add statistical validity to these observations, six 2-way ANOVAs with repeated measures were run separately for the fit PSEs and σ-s and for each partition (difficulty, success, and confidence). As expected, for PSEs (μ) the standard duration factor (3 modalities, 300, 400 and 500 ms) was always significant ($p < 10^{-9}$). The three main factors (difficulty, success, and confidence) failed to reach significance ($0.10 < p < 0.30$). For the standard deviations (σ) the difficulty and success factors were close to but did not reach significance (difficulty: $p = 0.09$, success: $p = 0.08$, confidence: $p = 0.27$).

The only clear and consistent result is the slope of the PSE function of the standard duration which is always larger than 1. This may be explained by an effect of regression to the mean within the duration discrimination task (see Discussion).

4 Discussion

The aim of this study was to better understand the influence of task difficulty on perceived duration in the sub-second range. Additionally, two factors that have never before been considered in the time perception literature - the effects of success and of confidence, were investigated. We predicted that given a more difficult secondary task, more attention will be allocated to accomplishing the secondary task and less attention for the primary task, leading to fewer time units processed and time shrink (Thomas & Weaver, 1975). This has been widely found in the literature (Brown, 1985; Zakay et al., 1983; **?**; Hicks et al., 1976). In addition, as a result of less attention the accuracy of estimates would also vary with difficulty (the more difficult task being less accurate) (Brown & West, 1990; West, 1992). For success, we predicted an overestimation of time in the "correct" trials as a result of subjects retrospectively assessing the time duration. They would perceive that they had adequate time for successful trials and hence overestimate the duration relative to failed trials. However, without feedback in this

Table 2: Points of Subjective Equality (μ) and sensitivity indices (σ) of duration estimates by the 5 participants grouped according to the difficulty, correct/incorrect responses and confidence levels in the concurrent orientation discrimination task.

		Duration of Standard (ms)					
		300		**400**		**500**	
Orientation task	**Observers**						
Easy	jh	231,90	191,90	398,90	347,40	597,70	376,00
	ag	203,10	175,60	400,00	326,70	614,20	269,10
	cad	77,10	404,10	425,00	563,50	663,90	578,00
	sc	272,40	176,90	502,80	261,20	669,70	258,60
	md	218,40	417,10	408,20	679,80	590,20	640,10
	Mean	**200,58**	**273,12**	**426,98**	**435,72**	**627,14**	**424,36**
	SE	*32,95*	*56,24*	*19,52*	*79,39*	*16,68*	*78,76*
Difficult	jh	234,60	185,70	402,60	404,30	606,80	350,50
	ag	172,40	195,80	459,30	518,20	676,90	342,20
	cad	222,40	358,70	431,80	464,20	663,60	783,30
	sc	289,40	243,00	533,90	266,00	684,70	272,50
	md	263,30	522,30	409,50	433,90	550,50	410,70
	Mean	**236,42**	**301,10**	**447,42**	**417,32**	**636,50**	**431,84**
	SE	*19,78*	*63,26*	*23,78*	*42,26*	*25,46*	*90,56*
Correct	jh	237,30	207,30	404,90	354,50	639,80	410,20
	ag	183,10	199,60	424,50	377,20	648,90	312,40
	cad	140,70	401,40	440,00	477,60	751,00	799,10
	sc	278,20	224,20	531,80	289,00	670,60	247,90
	md	228,70	519,30	420,10	548,60	585,30	529,20
	Mean	**213,60**	**310,36**	**444,26**	**409,38**	**659,12**	**459,76**
	SE	*23,67*	*64,13*	*22,59*	*46,14*	*26,93*	*97,22*
Incorrect	jh	201,70	217,60	358,70	552,70	579,00	333,30
	ag	188,30	181,90	414,80	1064,60	615,60	285,60
	cad	223,80	275,00	387,80	594,00	607,10	826,60
	sc	284,40	126,20	488,20	196,20	669,00	330,80
	md	233,80	376,50	344,60	221,90	519,70	573,10
	Mean	**226,40**	**235,44**	**398,82**	**525,88**	**598,08**	**469,88**
	SE	*16,56*	*42,77*	*25,41*	*157,59*	*24,42*	*102,44*
Sure	jh	230,50	191,40	393,40	366,00	629,70	398,10
	ag	201,70	184,40	442,80	369,70	665,80	272,40
	cad	116,40	485,10	407,70	669,60	758,40	1050,70
	sc	309,80	203,70	509,30	214,20	676,70	213,00
	md	241,10	495,70	431,30	560,40	603,10	478,60
	Mean	**219,90**	**312,06**	**436,90**	**435,98**	**666,74**	**482,56**
	SE	*31,37*	*72,89*	*20,07*	*80,17*	*26,39*	*149,46*
Not sure	jh	237,30	278,50	408,70	492,20	330,10	330,10
	ag	140,80	234,00	390,80	522,20	608,40	365,80
	cad	202,30	241,50	470,70	219,50	650,00	256,70
	sc	269,00	206,10	523,80	301,20	667,00	289,90
	md	252,90	437,00	371,30	485,60	516,00	519,00
	Mean	**220,46**	**279,42**	**433,06**	**404,14**	**554,30**	**352,30**
	SE	*22,77*	*41,05*	*28,15*	*60,42*	*61,85*	*45,55*

experiment subjects had no indication of success or failure meaning that any hypothetical effect would have arisen only from a highly cognitive nature below one's awareness (Kunimoto et al., 2001). We predicted the same for confidence, that their estimates would be based on retrospective assessment and therefore perceive trials in which they responded "less confident" as shorter in duration compared with high confidence trials. We proposed a second hypothesis: that success/failed trials and confidence responses would be an indication of the strength of the evoked signal in the brain and therefore reflect the influence of the difficulty of the orientation discrimination task (easy condition = stronger signal). Confidence has been linked to success and show sensitivities to variations in the difficulty of a task (Petrusic & Baranski, 2009). Under this hypothesis, successful and high confidence trials should be associated with shorter and more accurate duration estimates.

Lack of rigorous methods in past and current task difficulty manipulations have led to some weaknesses in the results obtained thus far. These include: 1) perceived duration-difficulty confounds (i.e., if the estimated durations were based on subjects' own response times, then response time would covary with difficulty (Petrusic & Baranski, 2009), 2) variable attention over the duration to be estimated (i.e., if the overlap in time between the primary and secondary tasks was variable from trial to trial, for example if the secondary task was finished before the primary timing task so that the subject is left to wait passively until the end of the duration, then the attention paid to the duration would be variable depending on when they finished the secondary task (Fortin et al., 1993; Rammsayer & Ulrich, 2005), 3) the secondary (non-temporal) task and the primary task being disjoint events (such that the subject must be simultaneously aware of two separate sets of stimuli for a single duration (i.e., two different modalities), and their onsets may occur at different times within the trial,) may pose too high demands on subjects (Fortin et al., 1993; Rammsayer & Ulrich, 2005; Rammsayer & Lima, 1991; Rammsayer & Ulrich, 2011), and 4) poorly defined difficulty modulation involving discrete levels and/or levels differing on not one but multiple dimensions (Axel, 1924; Gulliksen, 1927; Brown, 1985). Based on the weaknesses identified here, we implemented an original method for systematic and controlled study of task difficulty in the sub-second duration range. Our method has several key features: 1) it has controlled fixed standard durations (from which we are able to fit psychometric functions to approximate PSEs), 2) it requires a high constant attentional level (the targets appear at the end of sequences of variable durations), 3) the secondary (non-temporal) task is embedded in the actual duration event to be estimated (therefore both tasks are presented in a single coherent stimulus, from which duration is to be judged; hence biases in the duration estimates must be linked to the characteristics of the secondary task), and 4) task difficulty varies along a single continuous dimension (allowing for the systematic study of task difficulty and avoiding potential confounds, such as a third variable). In previous studies, it could be argued that subjects' attentional level may have weaned for the start of each duration, knowing that the target always appeared at the end of a sequence, and waited till the end of the sequence. However, given the brief durations studied here (the lowest being 300 ms) and the unpredictability of the duration to be estimated on each trial, it is unlikely that subjects could have selectively attended to the end of the sequence only. Concerning the manipulation of the difficulty of the secondary task (orientation discrimination), it became apparent during the course of the experiment that it was drowned out by the overall difficulty of simultaneously monitoring the two concurrent (primary and secondary) tasks. While this drawback is probably shared by all dual task paradigms involving duration estimations (as primary tasks; see Brown (2008), it definitely hampered in the present experimental design the successful manipulation of the orientation discrimination difficulty effects on duration estimation (discussed below).

As expected, the results show a significant main effect of the physical standard duration on its perceived duration (Points of Subjective Equality, PSEs). Instead, statistical analyses revealed no significant PSE effects of any of the three main factors, namely task difficulty, success, and confidence. No such effects were obtained either for the standard deviations of the estimated durations.

Difficulty in our experiment referred to the orientation discriminability (d′) measured in the secondary (non-temporal) task. Unfortunately, both subjects' reports and the large standard deviations of the perceived duration judgments (the primary task in both the preliminary and the main experiments), indicated that the manipulation of the orientation discrimination difficulty was negligible in comparison with the overall difficulty of simultaneously monitoring these two tasks. Hence, the absence of a difficulty effect is most likely due to this ”drowning out” effect. While one might hope that rendering the duration estimation/discrimination task easier would render the difficulty manipulation of the secondary task more effective, such means would also hamper the assessment of the duration estimation psychometric function. A better alternative would be to replace the duration discrimination method with a duration reproduction one.

Nevertheless, several other studies have also failed to obtain significant effects on task difficulty in the sub-second range (Rammsayer & Lima, 1991; Rammsayer & Ulrich, 2011). Moreover, some researchers have suggested that temporal processing mechanisms in the milliseconds range are automatic and therefore unimpaired by additional cognitive processing. Our study fits into this distinct timing hypothesis. Interestingly, there has been no account of why Rammsayer & Ulrich (2005) produced interference in the temporal judgments of supra-second intervals but Rammsayer & Lima (1991) study did not. One critical difference between the two studies is that the secondary task was not done simultaneously for the latter study, rather they induced cognitive load (so that rehearsal occurred during the temporal discrimination task but the word to be learned was shown before the onset of this task). It is also important to note that the three dual-task studies discussed above all used an adaptive time comparison method and in our study we used the classic time comparison method. These contradictory results and the lack of a theoretical account indicate that very little is known about how and when a concurrent task influences temporal judgements (more specifically, which types of tasks cause interference on temporal judgements).

At first sight the observation that subjects underestimated the shortest standard duration (300 ms) and overestimated the longest one (500 ms; figure 3 is contrary to Vierordt's law (Vierordt, 1868) (regression to the mean) observed in many duration reproduction studies (e.g., Kanai et al. (2006); Tse et al. (2004); Brown (1985); Schiffman & Bobko (1974); Jazayeri & Shadlen (2010)). However, when taking into account that the duration judgments consisted in a comparison between two durations (probe and standard), these findings can be taken as essentially Vierordt's law. Perceiving the probe duration as longer for short physical durations and shorter for long durations (Vierordt's law) implies that the standard was judged respectively shorter and longer than the physical duration. However, this interpretation raises the question of why the regression to the mean applies only (or possibly more) to the probe stimuli (than to the standards). An interesting observation is that the standards appear five times more frequently than the probe durations. The conditions for regression to the mean and its relative effects require further investigation.

The coefficients of variation revealed that Weber's law did not hold in this experiment. According to the Scalar Expectancy Theory (SET) (Gibbon, 1977; Gibbon et al., 1984), standard deviations should be proportional to the estimated duration (Weber's law). Figure 4 shows the coefficients of variation for the three factors studied (task difficulty, success, and confidence) and clearly shows non-monotonic increases/decreases with the standard duration. Deviations from Weber's law have been frequently observed, particularly in the sub-second range (Allan, 1979; Kristofferson, 1980; Mauk & Buonomano, 2004; Wearden, 2003; Wright et al., 1997). It is possible that failure to reveal a constant Weber fraction is due to the restricted duration range used here, which happens to be within Kristofferson's (1980) slow rise range.

5 Conclusion

In this study we investigated the effects of task difficulty, success and confidence on perceived temporal durations. We found no significant effects for any of the three factors and discussed that while it may be evidence to support the distinct timing hypothesis, the absence of any effect could also have been a result of potential ceiling effects due to the difficulty of simultaneously performing both tasks. This was indicated by the large standard deviations observed in both the preliminary and main experiments. Our main contribution here is our proposed (dual-task) RSVP visual search paradigm to study the effect of task difficulty, and our exploration of two potential factors (success and confidence) that may play a role in perceived time.

References

Allan, L. (1979). The perception of time. *Perception & Psychophysics*.

Axel, R. (1924). *Estimation of time* (Vol. 12). New York.

Bangert, A., Reuter-Lorenz, P., & Seidler, R. (2010). Dissecting the clock: Understanding the mechanisms of timing across tasks and temporal intervals. *Acta psychologica*.

Barthelmé, S., & Mamassian, P. (2009). Evaluation of objective uncertainty in the visual system. *PLoS computational biology*, *5*(9), e1000504.

Brainard, D. (1997). The psychophysics toolbox. *Spatial vision*, *10*(4), 433–436.

Breukelaar, J., & Dalrymple-Alford, J. (1999). Effects of lesions to the cerebellar vermis and hemispheres on timing and counting in rats. *Behavioral neuroscience*, *113*(1), 78.

Brown, S. (1984). Cognitive effort and temporal information processing.

Brown, S. (1985). Time perception and attention: The effects of prospective versus retrospective paradigms and task demands on perceived duration. *Perception & Psychophysics*, *38*(2), 115–124.

Brown, S. (1997). Attentional resources in timing: Interference effects in concurrent temporal and nontemporal working memory tasks. *Attention, Perception, & Psychophysics*, *59*(7), 1118–1140.

Brown, S. (2008). Time and attention: Review of the literature. *Psychology of time*, 111–138.

Brown, S., & Merchant, S. (2007). Processing resources in timing and sequencing tasks. *Perception & psychophysics*, *69*(3), 439.

Brown, S., & West, A. (1990). Multiple timing and the allocation of attention. *Acta psychologica*, *75*(2), 103.

Buhusi, C., & Meck, W. (2009). Relativity theory and time perception: Single or multiple clocks. *PloS one*, *4*(7), e6268.

Buonomano, D., & Karmarkar, U. (2002). How do we tell time. In *Neuroscientist.*

Carrasco, M. (2011). Visual attention. *Vision Research.*

Casasanto, D., & Boroditsky, L. (2008). Time in the mind: Using space to think about time. *Cognition*, *106*(2), 579–593.

Clarke, S., Ivry, R., Grinband, J., Roberts, S., & Shimizu, N. (1996). Exploring the domain of the cerebellar timing system. *Advances in Psychology*, *115*, 257–280.

Coull, J., Vidal, F., Nazarian, B., & Macar, F. (2004). Functional anatomy of the attentional modulation of time estimation. *Science*, *303*(5663), 1506.

Czermak, J. (1857). Ueber den schallerzeugenden apparat von crotalus. *Zeitschr. wiss. Zool*, *8*, 294–302.

Ferrara, A., Lejeune, H., & Wearden, J. (1997). Changing sensitivity to duration in human scalar timing: An experiment, a review, and some possible explanations. *The Quarterly Journal of Experimental Psychology Section B*, *50*(3), 217–237.

Field, D., & Groeger, J. (2004). Temporal interval production and short-term memory. *Attention, Perception, & Psychophysics*, *66*(5), 808–819.

Forster, K. (1970). Visual perception of rapidly presented word sequences of varying complexity. *Attention, Perception, & Psychophysics*, *8*(4), 215–221.

Fortin, C., & Breton, R. (1995). Temporal interval production and processing in working memory. *Attention, Perception, & Psychophysics*, *57*(2), 203–215.

Fortin, C., & Couture, E. (2002). Short-term memory and time estimation: Beyond the 2-second" critical" value. *Canadian Journal of Experimental Psychology/Revue canadienne de psychologie expérimentale*, *56*(2), 120.

Fortin, C., & Massé, N. (1999). Order information in short-term memory and time estimation. *Memory & cognition*, *27*(1), 54–62.

Fortin, C., Rousseau, R., Bourque, P., & Kirouac, E. (1993). Time estimation and concurrent nontemporal processing: Specific interference from short-term-memory demands. *Perception & Psychophysics*, *53*(5), 536–548.

Fraisse, P., & Leith, J. (1963). *The psychology of time*. Harper & Row New York.

Frankenhaeuser, M. (1959). Estimation of time: An experimental study.

Gibbon, J. (1977). Scalar expectancy theory and Weber's law in animal timing. *Psychological Review*, *84*(3), 279–325.

Gibbon, J., Church, R., & Meck, W. (1984). Scalar timing in memory. *Annals of the New York Academy of Sciences*, *423*(Timing and Time Perception), 52–77.

Gibbon, J., Malapani, C., Dale, C., & Gallistel, C. (1997). Toward a neurobiology of temporal cognition: advances and challenges. *Current opinion in neurobiology*, *7*(2), 170–184.

Gorea, A., Mamassian, P., & Cardoso-Leite, P. (2010). Introspective duration estimation of reactive and proactive motor responses. *Acta psychologica*, *134*(2), 142–153.

Gulliksen, H. (1927). The influence of occupation upon the perception of time. *Journal of Experimental Psychology*, *10*(1), 52.

Harvey, N. (1997). Confidence in judgment. *Trends in Cognitive Sciences*, *1*(2), 78–82.

Henmon, V. (1911). The relation of the time of a judgment to its accuracy. *Psychological Review*, *18*(3), 186.

Hicks, R., Miller, G., & Kinsbourne, M. (1976). Prospective and retrospective judgments of time as a function of amount of information processed. *The American Journal of Psychology*, *89*(4), 719–730.

Ivry, R., & Schlerf, J. (2008). Dedicated and intrinsic models of time perception. *Trends in Cognitive Sciences*, *12*(7), 273–280.

Ivry, R., & Spencer, R. (2004). The neural representation of time. *Current Opinion in Neurobiology*, *14*(2), 225–232.

Jazayeri, M., & Shadlen, M. (2010). Temporal context calibrates interval timing. *Nature neuroscience*, *13*(8), 1020–1026.

Johnston, A., Arnold, D., & Nishida, S. (2006). Spatially localized distortions of event time. *Current Biology*, *16*(5), 472–479.

Kahneman, D. (1973). *Attention and effort*. Prentice Hall.

Kanai, R., Paffen, C., Hogendoorn, H., & Verstraten, F. (2006). Time dilation in dynamic visual display. *Journal of Vision*, *6*(12).

Kanai, R., & Verstraten, F. (2005). Visual motion dilates the time. *Ninth Annual Association for the Scientific Study of Consciousness, Pasadena, CA, June*.

Kristofferson, A. (1980). A quantal step function in duration discrimination. *Attention, Perception, & Psychophysics*, *27*(4), 300–306.

Kristofferson, A. (1984). Quantal and deterministic timing in human duration discrimination. *Annals of the New York Academy of Sciences*, *423*(1), 3–15.

Kunimoto, C., Miller, J., & Pashler, H. (2001). Confidence and accuracy of near-threshold discrimination responses. *Consciousness and Cognition*, *10*(3), 294–340.

Langer, J., Wapner, S., & Werner, H. (1961). The effect of danger upon the experience of time. *The American Journal of Psychology*, *74*(1), 94–97.

Lejeune, H., & Wearden, J. (2006). Scalar properties in animal timing: Conformity and violations. *The Quarterly journal of experimental psychology*, *59*(11), 1875–1908.

Lewandowska, M., et al. (2010). Changes in fmri bold response to increasing and decreasing task difficulty during auditory perception of temporal order. *Neurobiology of learning and memory*.

Lewis, P., & Miall, R. (2003a). Brain activation patterns during measurement of sub-and supra-second intervals. *Neuropsychologia*, *41*(12), 1583–1592.

Lewis, P., & Miall, R. (2003b). Distinct systems for automatic and cognitively controlled time measurement: evidence from neuroimaging. *Current Opinion in Neurobiology*, *13*(2), 250–255.

Lewis, P., & Miall, R. (2009). The precision of temporal judgement: milliseconds, many minutes, and beyond. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *364*(1525), 1897.

Matell, M., & Meck, W. (2000). Neuropsychological mechanisms of interval timing behavior. *BioEssays*, *22*(1), 94–103.

Mattes, S., & Ulrich, R. (1998). Directed attention prolongs the perceived duration of a brief stimulus. *Attention, Perception, & Psychophysics*, *60*(8), 1305–1317.

Mauk, M., & Buonomano, D. (2004). The neural basis of temporal processing. *Neuroscience*, *27*(1), 307.

Michon, J. (1985). The compleat time experiencer. *Time, mind, and behavior*, 20–52.

Miller, G., Hicks, R., & Willette, M. (1978). Effects of concurrent verbal rehearsal and temporal set upon judgements of temporal duration* 1. *Acta Psychologica*, *42*(3), 173–179.

Mitrani, L., Shekerdjiiski, S., Gourevitch, A., & Yanev, S. (1977). Identification of short time intervals under lsd25 and mescaline. *Activitas nervosa superior*, *19*(2), 103.

Morrone, M., Ross, J., & Burr, D. (2005). Saccadic eye movements cause compression of time as well as space. *Nature Neuroscience*, *8*(7), 950–954.

Münsterberg, H. (1889). *Beiträge zur experimentellen Psychologie*. JCB Mohr.

Orme, J. (1969). *Time, experience and behaviour*. Elsevier Science Ltd.

Pelli, D. (1997). The videotoolbox software for visual psychophysics: Transforming numbers into movies. *Spatial vision*, *10*(4), 437–442.

Penney, T., Gibbon, J., & Meck, W. (2008). Categorical scaling of duration bisection in pigeons (columba livia), mice (mus musculus), and humans (homo sapiens). *Psychological Science*, *19*(11), 1103.

Perreau-Lenz, S., Pévet, P., Buijs, R., & Kalsbeek, A. (2004). The biological clock: the bodyguard of temporal homeostasis. *Chronobiology international*, *21*(1), 1–25.

Petrusic, W., & Baranski, J. (2009). Probability assessment with response times and confidence in perception and knowledge. *Acta psychologica*, *130*(2), 103–114.

Rammsayer, T. (1993). On dopaminergic modulation of temporal information processing. *Biological psychology*, *36*(3), 209–222.

Rammsayer, T. (1999). Neuropharmacological evidence for different timing mechanisms in humans. *The Quarterly Journal of Experimental Psychology Section B*, *52*(3), 273–286.

Rammsayer, T., & Lima, S. (1991). Duration discrimination of filled and empty auditory intervals: Cognitive and perceptual factors. *Attention, Perception, & Psychophysics*, *50*(6), 565–574.

Rammsayer, T., & Ulrich, R. (2005). No evidence for qualitative differences in the processing of short and long temporal intervals. *Acta psychologica*, *120*(2), 141–171.

Rammsayer, T., & Ulrich, R. (2011). Elaborative rehearsal of nontemporal information interferes with temporal processing of durations in the range of seconds but not milliseconds. *Acta Psychologica*.

Rammsayer, T., & Vogel, W. (1992). Pharmacologic properties of the internal clock underlying time perception in humans. *Neuropsychobiology*, *26*(1-2), 71–80.

Schiffman, H., & Bobko, D. (1974). Effects of stimulus complexity on the perception of brief temporal intervals. *Journal of Experimental Psychology*, *103*(1), 156.

Spencer, R., Karmarkar, U., & Ivry, R. (2009). Evaluating dedicated and intrinsic models of temporal encoding by varying context. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *364*(1525), 1853.

Thomas, E., & Weaver, W. (1975). Cognitive processing and time perception. *Perception & Psychophysics*.

Tregellas, J., Davalos, D., & Rojas, D. (2006). Effect of task difficulty on the functional anatomy of temporal processing. *Neuroimage*, *32*(1), 307–315.

Treisman, M. (1963). Temporal discrimination and the indifference interval. Implications for a model of the" internal clock". *Psychological Monographs*, *77*(13), 1.

Tse, P., Intriligator, J., Rivest, J., & Cavanagh, P. (2004). Attention and the subjective expansion of time. *Perception & psychophysics*, *66*(7), 1171.

Vierordt, C. (1868). *Der Zeitsinn: Nach Versuchen von Karl Vierordt*. Laupp.

Wallach, M., & Green, L. (1961). On age and the subjective speed of time. *The Journal of Gerontology*, *16*(1), 71.

Wearden, J. (2003). Applying the scalar timing model to human time psychology: Progress and challenges. *Time and mind II: Information processing perspectives*, 21–39.

Wearden, J. (2004). Decision processes in models of timing. *Acta Neurobiologiae Experimentalis*, *64*(3), 303–318.

West, A. (1992). Attention, multiple timing, and psychophysical scaling of temporal judgments. *Time, action, and cognition: Towards bridging the gap*, 129.

Wright, B., Buonomano, D., Mahncke, H., & Merzenich, M. (1997). Learning and generalization of auditory temporal–interval discrimination in humans. *The Journal of neuroscience*, *17*(10), 3956.

Wundt, W. (1903). *Grundzilge derphysiologischen psychologic.* Leipzig: Wilhelm Engelmann.

Zakay, D. (1993). Relative and absolute duration judgements under prospective and retrospective paradigms. *Perception & psychophysics*, *54*(5), 656–664.

Zakay, D., Nitzan, D., & Glicksohn, J. (1983). The influence of task difficulty and external tempo on subjective time estimation. *Attention, Perception, & Psychophysics*, *34*(5), 451–456.

Appendices

A Locations of Gabor patches

Gabor patches are used as our stimuli in our experiment. Gabors are displayed on a virtual circle of radius R around the fixation point of coordinates (x_F, y_F) whose equation is given by:

$$(x - x_F)^2 + (y - y_F)^2 = R^2 \ . \tag{1}$$

The solutions of Eq. 1 are given by:

$$\begin{cases} x = R\cos(\theta) + x_F \\ y = R\sin(\theta) + y_F \end{cases} \quad \text{with} \quad \theta \in [0, 2\pi[\ . \tag{2}$$

To obtain random locations on the virtual circle, we uniformly sample values in the interval $[0, 2\pi[$ using the Matlab command `2*pi*rand`. This provides one angle θ which then gives us one position (x, y) using

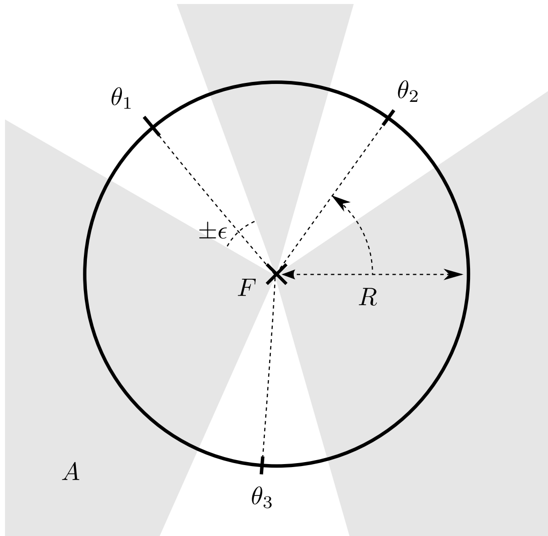


Figure 5: Illustration of the random location of gabor positions θ_1, θ_2 and θ_3 on a virtual circle centered on a fixed point F with a radius R and the free-zone A. The free-zone A is the set of points ouside intervals located at $\pm\epsilon$ from the gabor positions θ.

Eq. (2). With this method, we obtain random positions uniformly distributed on $[0, 2\pi[$. We want gabors not to overlap during a given period of time T. Each time a position is sampled, an area where the next positions can only be sampled, a free zone area, is updated. The method can be described as follows:

- Initiate the free zone area: $A = [0, 2\pi[$
- Initiate the history of gabor positions: $P = \emptyset$
- Initiate current time: $t_{curr} = 0$
- Repeat
  - Sample a new position $\theta_{curr} \in A$
  - Add the new position to the history of gabors positions: $P = P \cup \{(t_{curr}, \theta_{curr})\}$
  - Delete old positions in the history of gabors positions: $P = \{(t_{pre}, \theta_{pre}) \in P$ such that $(t_{curr} - t_{pre}) < T\}$
  - Update the free zone area: $A = [0, 2\pi[\Big\backslash \bigcup_{(t,\theta)\in P} [\theta - \epsilon, \theta + \epsilon[$
  - Update the current time: $t_{curr} = t_{curr} + dt$

B Estimation of the parameters of psychometric functions

In our problem, we have N observations (x_i, y_i), for $i = 1, \ldots, N$. The variable x_i represents a parameter of our experiment (for instance, the angle orientation difference) and y_i probabilities for a given response (for instance, the probability of answering correctly on the orientation task). Our purpose is to fit a function to the observations, i.e., to find a function that explains the observations but is also able to predict probabilities for different values of the experimental parameters. In our problem, we consider three parametric functions (namely, the *erf*, *logistic* and *Weibull*) defined by two parameters μ and σ: μ is a shift parameter that represents the mean of the psychometric function and σ is a scale parameter that is taken as the standard deviation of the psychometric function. The three psychometric functions are respectively defined by:

$$f_{\mu,\sigma}^{(erf)}(x) = \gamma + (1-\gamma)\frac{1}{2}erf\left(\frac{x-\mu}{\sigma}\right) \tag{3}$$

$$f_{\mu,\sigma}^{(logistic)}(x) = \gamma + (1-\gamma)\frac{1}{1+\exp\left(-\frac{x-\mu}{\sigma}\right)} \tag{4}$$

$$f_{\mu,\sigma}^{(Weibull)}(x) = \gamma + (1-\gamma)(1-\exp\left(-\left(\frac{x}{\mu}\right)^s\right) \ . \tag{5}$$

where $0 \leq \gamma < 1$. All these functions have values between γ and 1. The first two functions are defined for all real values x while the *Weibull* function is only defined for positive real values. Figure 6 gives an illustration of such a fitting function and with its parameters μ, σ and $\gamma = 0.5$ for $N = 5$ observations.

Mathematically, the optimal parameters μ and σ can be obtained by solving the least squares problem, i.e., by minimizing the sum squared error between $f_{\mu,\sigma}(x_i)$ and y_i defined by:

$$\sum_{i=1}^{N}(f_{\mu,\sigma}(x_i) - y_i)^2 \ . \tag{6}$$

The errors between the observed probability y_i and the prediction given by $f_{\mu,\sigma}$ at positions x_i are represented on Figure 6. The solution (m, s) of such an optimization problem is the point at which the differentials of the sum squared error equal to zero (i.e., the solution of the following system):

$$\begin{cases} \frac{\partial}{\partial\mu}\sum_{i=1}^{N}(f_{\mu,\sigma}(x_i) - y_i)^2 & = 0 \\ \frac{\partial}{\partial\sigma}\sum_{i=1}^{N}(f_{\mu,\sigma}(x_i) - y_i)^2 & = 0 \end{cases} \ . \tag{7}$$

For our psychometric functions, such a system cannot be solved analytically. Instead, we choose to map the problem to a linear regression problem, for which an analytic solution can be obtained (see next sections). This solution does not minimize Eq. (6) but another least square problem. However, we assume it is close

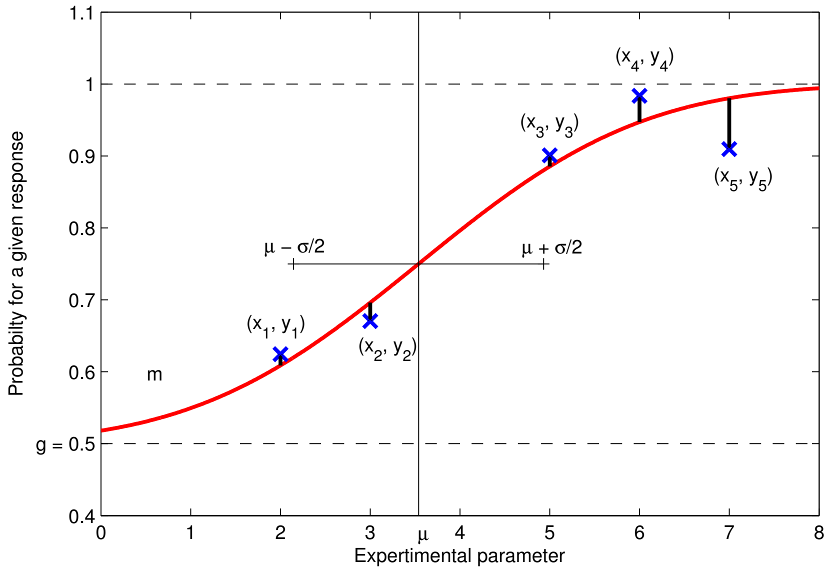


Figure 6: Representation of an *erf* psychometric function $f_{\mu,\sigma}$ fitting the 5 observations (x_i, y_i). The mean μ and the standard deviation σ are indicated as well as the errors of prediction on the observations: $y_i - f_{\mu,\sigma}(x_i)$.

enough to the optimal solution, and then can be used to initialize an iterative gradient descent to solve the orginal optimization problem:

$$\begin{cases} \mu_{t+1} = \mu_t - \rho \frac{\partial}{\partial \mu} \sum_{i=1}^{N} (f_{\mu,\sigma}(x_i) - y_i)^2 \\ \sigma_{t+1} = \sigma_t - \rho \frac{\partial}{\partial \sigma} \sum_{i=1}^{N} (f_{\mu,\sigma}(x_i) - y_i)^2 \end{cases} \tag{8}$$

where t is the current time index during the gradient descent and $\rho > 0$ is the descent step.

B.1 The case of the *erf* psychometric function

We are looking for the values of σ and μ such that for all observations i:

$$y_i = f_{\mu,\sigma}^{erf}(x_i) = \gamma + (1-\gamma)\frac{1}{2} erf\left(\frac{x_i - \mu}{\sigma}\right) . \tag{9}$$

We can show that solving the problem in (9) is equivalent to solving the following:

$$x_i = s\hat{y}_i + \mu \tag{10}$$

$$\text{where} \quad \hat{y}_i = erf^{-1}\left(\frac{2y - 1 - \gamma}{1 - \gamma}\right) . \tag{11}$$

Estimates of σ and μ are then obtained by minimizing a linear least squares problem in the set of observations $(\hat{y}_i, x_i)$ which can be performed easily with the Matlab function `polyfit`.

B.2 The case of the *logistic* psychometric function

We are looking for the values of σ and μ such that for all observations i:

$$y_i = f_{\mu,\sigma}^{logistic}(x_i) = \gamma + (1-\gamma)\frac{1}{1+\exp\left(-\frac{x_i-\mu}{\sigma}\right)} \ . \tag{12}$$

We can show that solving the problem in (12) is equivalent to solving the following:

$$x_i = s\hat{y}_i + \mu \tag{13}$$

$$\text{where} \quad \hat{y}_i = \log\left(\frac{y-\gamma}{1-y}\right) \tag{14}$$

Estimates of σ and μ are then obtained by minimizing a linear least squares problem in the set of observations $(\hat{y}_i, x_i)$ which can be performed easily with the Matlab function `polyfit`.

B.3 The case of the *Weibull* psychometric function

We are again looking for the values of σ and μ such that for all observations i:

$$y_i = f_{\mu,\sigma}^{weibull}(x_i) = \gamma + (1-\gamma)(1-\exp\left(-\left(\frac{x_i}{\mu}\right)^s\right) \ . \tag{15}$$

We can show that solving the problem in (15) is equivalent to solving the following:

$$\log x_i = \frac{1}{\sigma}\hat{y}_i + \log\mu \tag{16}$$

$$\text{where} \quad \hat{y}_i = \log\left(-\log\left(1-\frac{y-\gamma}{1-\gamma}\right)\right) \tag{17}$$

Estimates of σ and μ are then obtained by minimizing a linear least squares problem in the set of observation $(\hat{y}_i, x_i)$ which can be performed easily with the Matlab function `polyfit`.

C Supplementary information

Table 3: Number of responses per correct, incorrect, high-, and low-confidence modalities per probe duration (n)

		Duration of Std (ms)														
	n	300					400					500				
		"- 34%"	"- 17%"	"+ 0%"	"+ 17%"	"+ 34%"	"- 34%"	"- 17%"	"+ 0%"	"+ 17%"	"+ 34%"	"- 34%"	"- 17%"	"+ 0%"	"+ 17%"	"+ 34%"
Sure	jh*	119	115	108	115	108	114	109	108	115	118	123	116	117	114	118
	total			565					564					588		
	ag	56	61	58	51	48	67	60	56	50	53	61	65	55	54	54
	total			274					286					289		
	cad	85	80	80	77	81	82	76	81	86	81	80	86	84	84	81
	total			403					406					415		
	np	3	2	0	0	2	0	1	2	3	3	3	0	0	1	1
	total			7					9					5		
	sc	42	33	34	29	38	50	41	44	38	30	38	45	40	37	35
	total			176					203					195		
	md	66	68	63	61	63	62	60	61	72	55	47	60	61	63	65
	total			321					310					296		
Not sure	jh	25	29	36	29	36	30	35	36	29	26	21	28	27	30	26
	total			155					156					132		
	ag	44	39	42	49	52	33	40	44	50	47	39	35	45	46	46
	total			226					214					211		
	cad	15	20	20	23	19	18	24	19	14	19	20	14	16	16	19
	total			97					94					85		
	np	97	98	100	100	98	100	99	98	97	97	97	100	100	99	99
	total			493					491					495		
	sc	58	67	66	71	62	50	59	56	62	70	62	55	60	63	65
	total			324					297					305		
	md	34	32	37	39	37	38	40	39	28	45	53	40	39	37	35
	total			179					190					204		
Correct	jh	130	124	112	119	125	123	116	122	119	113	123	117	127	122	124
	total			610					593					613		
	ag	86	86	87	85	84	84	84	92	87	93	86	82	89	86	88
	total			428					440					431		
	cad	81	86	79	80	85	78	80	78	82	83	77	87	76	79	78
	total			411					401					397		
	np	79	83	74	81	74	75	78	78	77	83	65	71	69	74	76
	total			391					391					355		
	sc	89	86	84	83	84	86	83	84	81	81	86	86	88	88	80
	total			426					415					428		
	md	93	91	86	92	90	90	92	93	98	87	88	90	89	88	93
	total			452					460					448		
Incorrect	jh	14	20	32	25	19	21	28	22	25	31	21	27	17	22	20
	total			110					127					107		
	ag	14	14	13	15	16	16	16	8	13	7	14	18	11	14	12
	total			72					60					69		
	cad	19	14	21	20	15	22	20	22	18	17	23	13	24	21	22
	total			89					99					103		
	np	21	17	26	19	26	25	22	22	23	17	35	29	31	26	24
	total			109					109					145		
	sc	11	14	16	17	16	14	17	16	19	19	14	14	12	12	20
	total			74					85					72		
	md	7	9	14	8	10	10	8	7	2	13	12	10	11	12	7
	total			48					40					52		