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Mapping introspection's blind spot: Reconstruction of dual-task phenomenology using quantified introspection

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ABSTRACT

Psychologists often dismiss introspection as an inappropriate measure, yet subjects readily volunteer detailed descriptions of the time and effort that they spent on a task. Are such reports really so inaccurate? We asked subjects to perform a psychological refractory period experiment followed by extensive quantified introspection. On each trial, just after their objective responses, subjects provided no less than four subjective estimates of the timing of sensory, decision and response events. Based on these subjective variables, we reconstructed the phenomenology of an average trial and compared it to objective times and to predictions derived from the central interference model. Introspections of decision time were highly correlated with objective measures, but there was one point of drastic distortion: subjects were largely unaware that the second target was waiting while the first task was being completed, the psychological refractory period effect. Thus, conscious perception is systematically delayed and distorted while central processing resources are monopolized by another task.

1. Introduction

Performance and response time are common tools in cognitive sciences, but the subject's conscious experience has been largely left aside. Indeed, first-person introspection is usually considered as a suspicious procedure that cannot provide much useful information about internal cognitive processes and must be replaced by third-person objective measurement. For instance, experiments in social psychology indicate that participants can be completely unaware of the true causes of their choice behaviour or of the cognitive processes leading them to the solution of a problem (Nisbett & Wilson, 1977). Ericcson and Simon (1980) stressed that asking subjects for a formal verbal reports of their thought processes could only be informative about a specific subset of non-automatic cognitive processes, and drew attention to the fact that the very act of reporting could alter ongoing processing. Even so, in the history of psychology, introspection never really left the scene as it remained in use both as a debriefing tool and as an essential source of data in psychophysical experiments. With the recent resurgence of interest for consciousness and its determinants, it becomes essential to reconsider whether introspection really is inaccurate and unusable – or whether it is a valid object of cognitive study, like any other, with its valid range of operation and its limits.

We recently introduced a new method aimed at quantifying subjects' conscious introspection of a cognitive task (Corallo, Sackur, Dehaene, & Sigman, 2008). The general concept of quantified introspection involves collecting from subjects, on a trial-by-trial basis, precise quantitative

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data about a subjective variable such as stimulus visibility, location, duration, etc. In particular, the method of introspective response time involves engaging participants in a standard response time task, then collecting, on each trial, a quantitative subjective estimate of the duration of their decision. On each trial, we therefore obtain an objective and a subjective response time, which can be correlated and contrasted. The method implies that subjects monitor their own cognitive operations, register this monitoring in some form of memory, and finally retrieve the relevant information at the end of the main trial in order to perform the requested time estimation. This meta-cognitive measure provides a new opportunity to explore the links between cognitive processes and conscious reports. In our previous work (Corallo et al., 2008), we only studied introspective RT in one or two tasks. In the present study, we show that this method can be dramatically enhanced by asking multiple quantitative questions on a single trial. Our new results indicate that participants can answer no less than four quantitative introspective questions about the preceding RT trial, and that these combined measures can be used to reconstruct a detailed picture of its phenomenology.

Subjective reports have already been used in many magnitude estimation studies. For example, people can estimate the visibility of a target stimulus by using a continuous scale. The visibility rating is strongly correlated with the objective detection performance and is influenced by the same experimental manipulations (Del Cul, Baillet, & Dehaene, 2007; Sergent, Baillet, & Dehaene, 2005; Sergent & Dehaene, 2004). In our recent study, we parametrically examined introspective response times (iRT) and objective response times (RT) in a number comparison task (Corallo et al., 2008). The results showed that introspective and objective RTs were influenced by the same experimental manipulations (numerical distance and notation type) and were strongly correlated. This shows that iRTs are a reliable measure, closely related to standard RTs.

A dual-task paradigm, however, revealed a clear limit of introspective RT. When people have to respond as fast as possible to two successive stimuli, the response time to the second target T2 (RT2) increases as the stimulus onset asynchrony (SOA) decreases, while response time to the first target T1 (RT1) remains unaffected – the so called psychological refractory period (PRP) effect. The PRP shows that part of T1 processing is strictly serial thereby delaying T2 processing (Pashler, 1994; Telford, 1931). The central interference model proposes that only one of three major cognitive stages is delayed in T2 processing (Pashler, 1994; Sigman & Dehaene, 2005, 2006, 2008; Sigman, Jobert, Lebihan, & Dehaene, 2007). Perceptual and motor operations can be processed in parallel but a central decision stage is strictly serial and constitutes the main processing bottleneck (see Fig. 3A for a graphic depiction). Hence, according to this model, other central on-line cognitive operations such as decision making or conscious access might suffer from this bottleneck.

According to dual-stage models of conscious access (Chun & Potter, 1995; Dehaene, Changeux, Naccache, Sackur, & Sergent, 2006; Dehaene, Sergent, & Changeux, 2003; Del Cul et al., 2007; Sergent et al., 2005), conscious perception of T2 relies on the same sort of central processing that is required for the T1 decision, and thus should be delayed until the T2 information is able to access the central processing stage. During the PRP, subjects would therefore suffer from a misperception of external sensory events – their perception would be delayed until T1 processing is completed. In the second experiment of Corallo et al. (2008), we provided a first partial test of this hypothesis. During the PRP interference, a clear dissociation was observed between RTs and iRTs: RTs depended strongly on the SOA between the two stimuli, reflecting the fact that T2 processing had to wait for T1 completion, but iRTs were unaffected by this SOA, compatible with the idea that subjects only had access to T2 processing once they were free from the T1 task.

However, the introspective questions used in Corallo's study were not sufficient to provide a complete test of our model. In particular, they did not explore the reasons behind the subject's inappropriate reports. Our hypothesis is that T2 itself cannot be perceived until the central stage is freed from T1 processing. An alternative possibility exists, however. Although we insisted that subjects should report the full time elapsed between the objective appearance of T2 and their corresponding response, subjects could have misunderstood these instructions and merely reported the duration of their central decision time only. According to the central interference model, this central duration should be unaffected by SOA, precisely as the subjects reported.

The goal of the present research is to attempt to explain *why* introspection is blind to dual-task interference – we propose and put to a test an actual theory of what introspection can and cannot measure. Our experiment directly probes whether a genuine illusory misperception of time exists during dual-task processing, aiming to show that during the interference period, the conscious perception of the second target is delayed until processing of T1 is completed. To achieve these aims, we investigate the subject's introspections of PRP trials in much greater detail than earlier, asking them no less than four quantitative introspective report which, together, provide a complete picture of how subjective time evolved during a dual task.

The primary task was to respond as quickly as possible to an auditory tone and then to a visual stimulus. In addition to the objective response times, we recorded subject's responses to four subjective questions (see Fig. 1C) asking them to evaluate their response times to task 1 and to task 2 (iRT1 and iRT2), the perceived stimulus onset asynchrony (iSOA), and finally the slack or free time (iSF). The latter variable evaluates the availability of the central stage in between the two tasks. At short T1–T2 SOAs, when T2 has to wait while T1 is being processed, the T2 waiting time is called "slack time". Conversely, we call "free time" the gap that exists, at longer T1–T2 SOAs, between the moment when task 1 is completed, and the moment when task 2 is started.

Our experiment had two goals: (1) to reconstruct the phenomenology of an "average" PRP trial based on introspective data; (2) to test predictions arising from the hypothesis that conscious perception of the second target requires central-stage processing and is therefore delayed during the PRP. Our refined introspective variables allow

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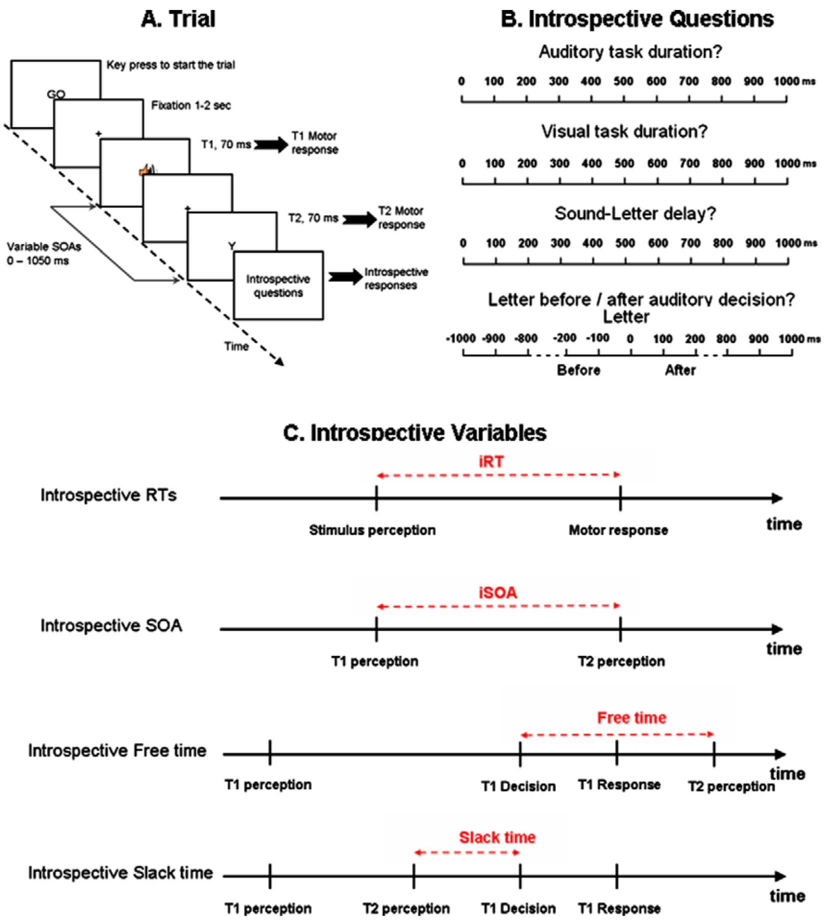

Fig. 1. (A) Experimental paradigm. (B) Continuous scales used to estimate the response times, the SOA and the slack/free time. The lower scale has been shortened (represented by the dots on the scale) for visibility purposes and was originally twice longer than the other scales, so that the time units were the same for all subjective questions. (C) Schematic representation of the introspective variables. The black line represents the time. From top to bottom: introspective reaction times reflect the delay between the perception of a stimulus (T1 or T2) and the related motor response; the introspective SOA reflects the delay between the perception of T1 and the perception of T2; introspective free time corresponds to the delay between T1 decision and the perception of T2 when T2 appeared after T1 decision (long SOAs); introspective slack time corresponds to the delay between T1 decision and T2 perception when T2 was presented before T1 decision (short SOAs).

us to examine when the second target T2 is perceived to occur. Outside the interference period, the estimated SOA should vary with the objective SOA, and subjects should report that free time increases with SOA. Inside the interference period, however, because their central system is constantly occupied, subjects should not be able to detect the overlap between the two tasks and to notice that T2 is waiting. Thus, the iSOA, iSF and iRT2 should remain constant despite decreasing SOA.

A more subtle set of predictions concern the effect of random fluctuations in the decision times to the T1 task. The delay in the access of T2 to the central stage should be proportional to the duration of the T1 decision. Thus, on trials with a slow RT1, the conscious perception of T2 should be delayed and at long SOA, the free time between the two tasks should decrease. The verification of these subtle predictions would imply that introspection can provide precise, reproducible quantitative measures that are compatible with existing cognitive models of central interference during dual-tasks.

2. Method

2.1. Subjects

Ten normal adults (6 women) aged between 21 and 30 years old (mean age: 22 years) participated in the study. Informed consent was obtained before testing and subjects received a compensation of €10 for their participation. All subjects were naïve with respect to the task and all had normal or corrected to normal vision.

2.2. Calibration task

Prior to the PRP task the subject performed an estimation calibration task. A sound (800 Hz) was presented to both ears through earphones with a duration ranging from 20 to 1000 ms. The sound intensity was not directly measured during the experiment but it was constant across subjects and set to be comfortable. None of the subjects reported any problem hearing the sounds and all performed well at the task. The subject had to estimate the duration of the sound by clicking on a graduated time scale at the end of each trial. Following the subject's response, two feedback numbers were presented for 2 s on the screen, indicating (1) the actual sound duration and (2) its estimation by the subject. Each subject performed 100 trials of this task.

2.3. Dual task

2.3.1. Stimuli and procedure

The first target consisted of a sound presented to both ears (same method as for the calibration task) which could be of high pitch (1100 Hz) or low pitch (1000 Hz), presented for 84 ms. The second target was a black letter (0.8°), either the letter "Y" or the letter "Z", presented on a white black ground for 84 ms (CRT screen with a refresh rate at 60 Hz). In each trial, the subject had to respond to the sound by pressing the "w" key of an AZERTY keyboard with the left middle finger if it was a low pitch and the "x" key with the left index if it was a high pitch. For the second target, the subject had to press the "n" key with the right index or the "," key with right middle finger if a "Y" or a "Z" was presented respectively. Speeded responses were required for both targets (first respond to the sound, then to the letter) and subjects were explicitly instructed to respond as soon as the stimulus appeared in order to avoid "grouped" responses.

Trials began with the word "GO" presented centrally, indicating that the subjects could press a key to start the trial. A fixation cross then appeared immediately, followed after a variable fore period (1–2 s) by the sound target and then, after a variable SOA, by the visual target. SOA could take one of six values: 0, 116, 232, 466, 700 or 1050 ms.

On each trial, 500 ms after their response to T2, subjects also responded to four introspective questions presented in random order and without speed pressure (see Fig. 1). Each question was presented in a short-hand form (French language) in order to decrease the reading time, but each one was precisely detailed during the instruction period to ensure that all subjects performed exactly the same task. (1) "How much time did it take you to respond to the auditory stimulus? i.e. what was the delay between the onset of the sound and your motor response?", presented during the task in the short form "Auditory task duration?"; (2) "How much time did it take you to respond to the visual stimulus? i.e. what was the delay between the onset of the letter and your motor response?", presented in the form "Visual task duration?"; (3) "What was the temporal delay between the onset of the auditory stimulus and the onset of the visual stimulus?", presented in the form "Sound–Letter delay?"; (4) "Did the letter appear before or after your auditory decision? i.e. what was the delay between the moment when you reached your auditory decision and the onset of the letter?", presented in the form "Letter before/after auditory decision?". Each estimate was provided by clicking with the mouse on a continuous time scale (0–1000 ms, or −1000 to 1000 ms for iSF).

Each subject performed 10 blocks separated on two sessions (~1H30 each). For each session, the first block consisted of the calibration task. The second and fifth blocks consisted in a standard PRP paradigm without any introspective questions. In the third and fourth blocks, each trial was followed by introspective questions. Each PRP block included 60 trials. Subjects performed four blocks of the PRP paradigm with introspective questions and four blocks without introspective questions, which gives a total of 40 trials by SOA for each PRP paradigm.

Stimuli were presented on a CRT screen (refresh rate: 70 Hz) at a viewing distance of 50 cm under standard overhead fluorescent lighting. The sequence was controlled by a Pentium IV PC running E-prime 1.1 software (PST Inc.).

3. Results

3.1. Objective measures: the classical PRP

The mean performance across the group was 82.6% ± 3.9 for the auditory T1 task and 90.4% ± 1.6 for the visual T2 task, indicating that in spite of the complexity introduced by the four introspective questions, subjects remained able to perform correctly on the main RT tasks. We tested whether the introspective questions affected the main PRP task by using ANOVAs to compared response times in blocks with or without quantified introspection. We did not find any significant effect neither on RT1 nor RT2, or any interaction with SOA. These results suggest that performing the post-trial time estimation tasks did not interfere with the relatively simple RT tasks used here, consistent with previous findings showing that while performance on time estimation tasks is often affected by a concurrent task, the converse need not be true (Brown, 1997).

Fig. 2A shows the mean introspective and objective response times as a function of SOA during the Quantified Introspection blocks. Several aspects of the objective results support the by-now classical central interference model of the PRP (Pashler, 1994; Sigman & Dehaene, 2005). In this model, processing is strictly serial, without resource sharing, and thus processing time for the first target should not be affected by the SOA. Indeed, we did not find any significant effect of SOA on RT1 (Fig. 2A). However, the model predicts that T2 processing should be delayed until T1 processing is completed, which implies an effect of SOA on RT2. We found that RT2 (as measured from the T2 onset) increased as SOA decreased, thus revealing the classical PRP effect, $F(5, 45) = 47.08$, $p < 0.001$. A significant quadratic contrast on SOA, $t = 3.29$, $p < 0.01$, reflected the fact that RT2 decreased with a slope close to −1 at short SOAs and became constant at long SOAs (Fig. 2A). The effect of SOA on RT2 defines an interference regime, mainly between 0 and 700 ms SOA, during which T1 processing impacts strongly on T2 processing. For SOAs above this limit, the SOA effect on RT2 was much reduced (54 ms difference between SOA 700 ms and SOA 1050 ms), although still significant, $F(1, 9) = 10.02$, $p < 0.01$, suggesting that T2 was now moving out of the interference regime on most trials.

Concerning trial-by-trial fluctuations, the central interference model proposes that T2 accesses the central stage only after T1 decision is completed. As a result, during

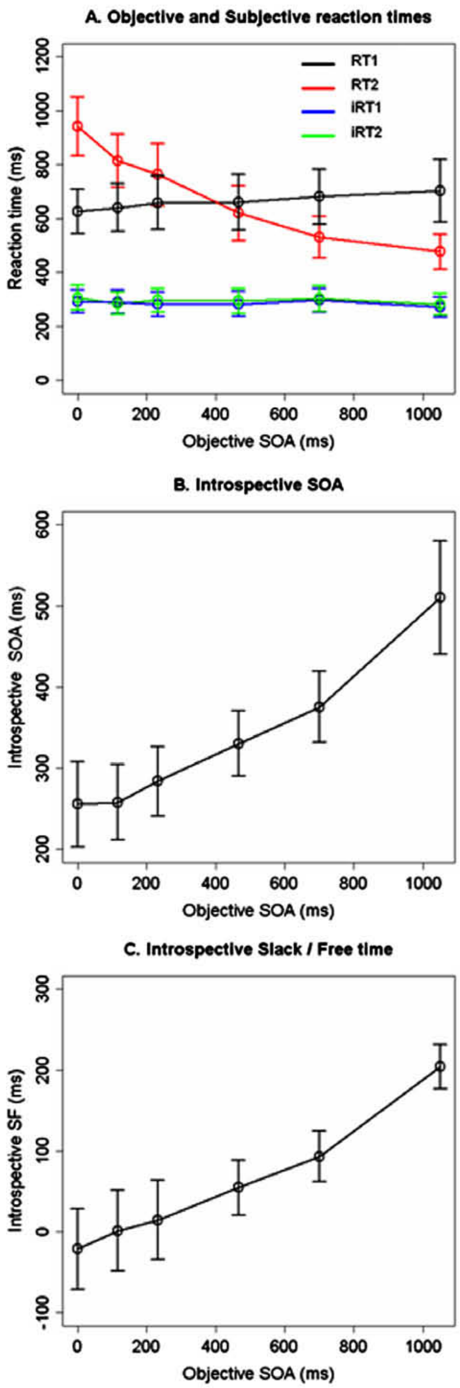

Fig. 2. (A) Mean objective response time (ms) for T1 and T2 (black and red respectively) and introspective response time for T1 and T2 (blue and green respectively). Error bars represent the standard error of the mean. (B) Introspective SOA (mean (ms) ± sem.) as a function of objective SOA. (C) Introspective slack/free time (mean (ms) ± sem.) as a function of SOA (ms).

the interference regime, the slowing of RT2 should increase with the duration of T1 processing. Indeed, we found a strong positive correlation between RT1 and RT2 in the interference regime, which varied across SOAs, $F(5, 45) = 18.35$, $p < 0.001$, and became weaker (but still significant) outside the interference regime (Fig. 4A).

In summary, these analyses indicate that our experiment shared all of the classical properties of the PRP phenomenon – at short SOAs, task 1 processing delayed task 2 processing. We now turn to how this effect was subjectively perceived.

3.2. Subjective measures: illusion in T2 conscious perception

Prior to the main dual-task experiment, subjects were trained to estimate short time intervals on a calibration task. We found a strong correlation between the estimated and the objective duration of the sound (mean $r = 0.90 \pm 0.07$). The average slope across subjects was 0.92 ± 0.02 with an intercept of 63.06 ± 10.20. When the duration of the sound was inferior to ~800 ms subjects estimated the duration without any tendency of over- or under-estimation. However, subjects underestimated the duration of the sound when it was superior to 800 ms ($F(14, 126) = 2.91$; $p < 0.001$). This under-estimation is consistent with what we observed during the estimation of reaction times (see below), but smaller since the biggest difference was about 100 ms at a sound duration of 1000 ms while iRT1, for instance, was on average 300 ms smaller than RT1. The main conclusion of the calibration task was that subjects were able to estimate short time intervals with good precision.

Introspective response times, on the other hand, showed a systematic under-estimation of the objective response times (Fig. 2A) – suggesting that subjects introspected only about a subset of the total processing time. In agreement with this notion, the results replicated the lack of introspection of the PRP as previously shown (Corallo et al., 2008). For introspective measures, neither iRT1 nor iRT2 showed any effect of SOA. The latter result is particularly striking, as the mean objective RT2 varied twofold (from about 1000 ms to about 500 ms) with SOA, but this variation was not perceived subjectively.

Correlation analyses demonstrated that this constancy of the subjective RTs with SOA was not due to a lack of sensitivity of these introspective measures. First of all, we verified that iRT1 was correlated with RT1 (mean $r = 0.38 \pm 0.09$) (Fig. 4B) except for the longest SOA where the mean correlation was positive but did not reach the significance threshold. Second, iRT2 was also correlated with RT2 (Fig. 4C). This correlation was highest at long SOAs, which is understandable if subjects merely report as iRT2 the duration of the central decision stage of the T2 task, whereas during the PRP interference, RT2 is the sum of this stage plus the corresponding decision stage for T1 (see model on Fig. 3). According to this interpretation, within the interference regime (short SOAs), iRT2 should be better correlated with the difference RT2–RT1. We verified that this is the case. We found a significant correlation between RT2–RT1 and iRT2 that was significant at all SOAs except at the longest SOA 1050 ms (Fig. 4D).

We interpret these results as showing an inability to introspect about the duration of the T2 task while being occupied with the first. As noted in the introduction, however, it could be argued that all of these results, including

Fig. 3. (A) Schematic representation of the central bottleneck model. Black, dark grey and light grey represents the perceptual, central and motor stages respectively associated with the integration of T1. T2 onset is depicted by a red segment, and the dark, medium and light blue bars represent the perceptual, central and motor stages of T2 processing. The green line represents the end of the central stage for T1, which determines the limit between slack and free time, i.e. T2 integration will be delayed if the central stage is occupied by T1 (Slack time = white space below the green line), otherwise it will access the

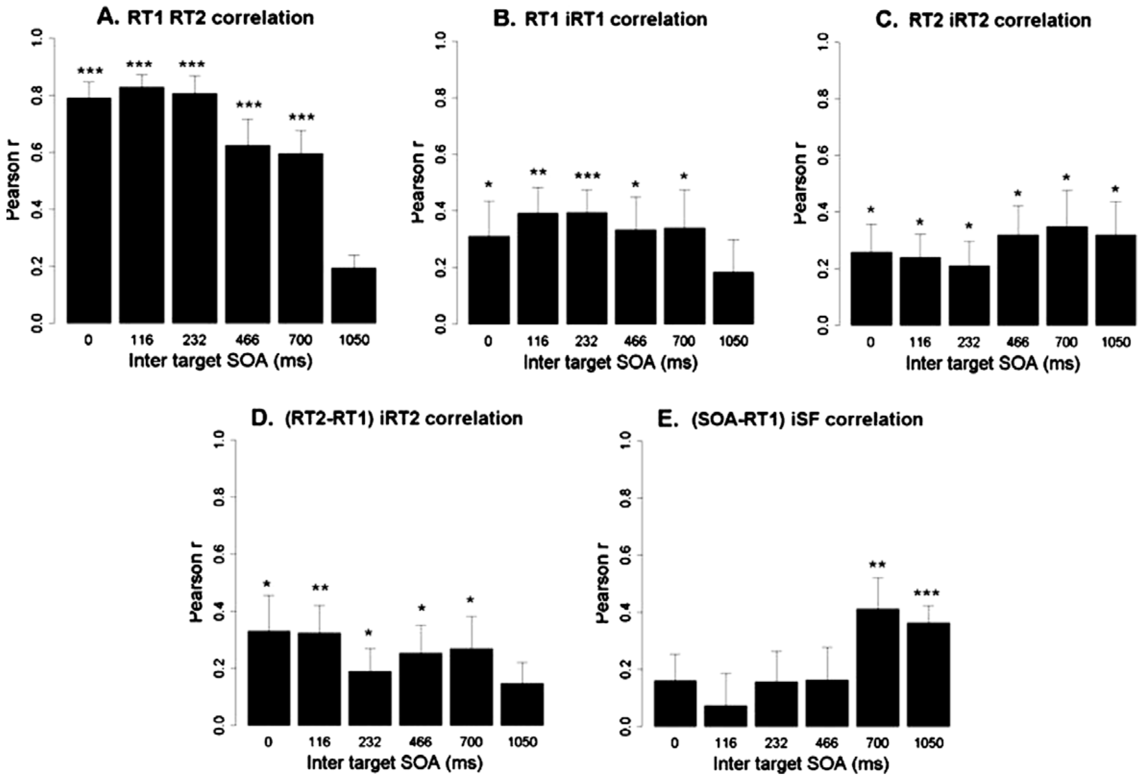

Fig. 4. Correlations between the different measures recorded simultaneously on a given trial. The bars indicate the Pearson r, first calculated within each subject and each lag, and then averaged across subjects (mean ± standard error). Stars indicate correlations significantly different from zero (between-subject *t*-test; ∗, $p < 0.05$; ∗∗, $p < 0.01$, ∗∗∗, $p < 0.001$). (A) Correlation between RT1 and RT2. (B) Correlation between RT1 and iRT1. (C) Correlation between RT2 and iRT2. (D) Correlation between the difference RT2 – RT1 and iRT2. (E) Correlation between the difference SOA – RT1 and iSF.

Corallo et al. (2008), simply mean that subjects misunderstood the task – they merely reported their subjective perception of central decision time, which according to the central interference model indeed does not vary with SOA, both for task 1 and for task 2. However, our two new introspective measures, iSOA and iSF, refute this alternative interpretation and show that subjects experience a real illusion of misperception of T2 presentation time.

We first analyzed introspective SOA, by which subjects reported the perceived time of T2 presentation. As expected, iSOA increased with objective SOA duration, $F(5, 45) = 12.24$, $p < 0.001$ (Fig. 2B). However, in this linear regression, the intercept was highly significant (241.82 ± 45.37 ms, $t = 5.33$, $p < 0.001$), implying that at short SOAs, within the interference regime, subjects failed to perceive the simultaneity or brief temporal lag of the two stimuli. Instead of simultaneity, subjects perceived T2 as arising much later than it actually did, by about 250 ms. The interference regime is the only period where subject's introspective time judgments were actually *over*-estimated, thus going strongly against the general tendency, noted above, for subjective temporal judgements to underestimate objective durations. Furthermore, a significant quadratic contrast indicated that the variation of iSOA was non-linear with SOA, $t = 2.81$, $p < 0.01$. Outside the interference regime, the iSOA increased by 135 ms ($F(1, 9) = 6.53$, $p < 0.05$) when the SOA increased from 700 to 1050 ms. During the interference period, however, the SOA effect was much reduced: the iSOA increased by only 45 ms between the SOAs 466 and 700 ms ($F(1, 9) = 10.30$; $p = 0.01$), and by only 28 ms between SOA 0 and 232 ms ($F(1, 9) = 3.47$; $p = 0.05$).

It could be argued that subjects are simply unable to perceive the quasi-simultaneity of two events, independently of any PRP phenomenon. However, examination of the fourth introspective variable, the introspective slack/free time showed that, in fact, subjects did not properly evaluate the temporal overlap of the two tasks. We found a significant SOA effect, $F(5, 45) = 12.31$, $p < 0.001$ (Fig. 2C), indicating that subjects did take variations of SOA into account in their subjective estimations of iSF. The quadratic contrast was significant, $t = 2.74$, $p = 0.01$, and indeed, at short lags, iSF varied little with SOA (SOAs 0, 116, 232 ms: $F(2, 18) = 4.00$; $p < 0.05$) and remained close to zero rather than being negative. The fact that iSF never became strongly negative indicates that on average, subjects did not notice that T2 ever had to wait before being processed in the second task (contrary to what the objective PRP phenomenon indicates). In fact, iSF did not differ from zero for the first three SOAs, a trend appeared at 466 ms SOA ($t = 1.60$, $p = 0.1$), and the iSF was significant for SOAs 700 and 1050 ms ($t = 2.95$, $p = 0.02$ and $t = 7.56$, $p < 0.001$, respectively).

Correlations between objective and subjective measures confirmed that iSF was an accurate measure outside the interference regime, but not during it. We computed the subtraction between the SOA and RT1 to obtain, on a single trial basis, an estimate of the objective slack/free time, i.e.

the delay between the motor response to T1 and the time of T2 appearance. At the two longest SOAs, outside the interference regime, this objective measure of free time correlated strongly with the subject's introspective reports iSF. Inside the interference regime, however, this correlation dropped to a non-significant value (Fig. 4E). In summary, free time was properly perceived, but not slack time.

Overall, analyses of iSF confirmed the conclusions obtained from the introspective report of SOA. Both measures indicated that, during the PRP interference, subjects are confused about the presentation time of T2, and make reports that are (a) highly noisy (b) systematically over-estimating T2 presentation time (c) uninformed of the T2 slack time.

3.3. Reconstructing the phenomenology of a PRP trial

The availability of four introspective measures on each trial allowed us to tentatively reconstruct the phenomenology of a PRP trial, as seen from the subject's introspection. In Fig. 3C, we combined the iRT1, introspective SOA, introspective slack/free time, and iRT2 in order to obtain a schematic representation of the subjective unfolding of a PRP trial, which could be directly compared with the objective data (Fig. 3B) and with the classical central interference model (Fig. 3A). This subjective reconstruction was based on several simple assumptions. First, we placed a red segment at the location of the introspective SOA, assuming that this value faithfully reflects the moment when subjects perceived the onset of T2. From this subjective T2 reference location, we first placed a grey bar proportional to iSF and whose direction is either positive or negative according to whether participants experienced slack or free time, ending with a green segment representing the subjective end of the T1 decision. Second, we placed a blue rectangle, of length proportional to iRT2, directly above the perceived T2 subjective onset time (iSOA).

In spite of a global change of scale, due to subjects' overall under-estimation of temporal intervals, there was an excellent consistency between the objective and subjective events at long SOA. Subjects were able to record and to store the "time stamps" of the sensory and internal events throughout the trial as if they were using a mental clock. However, a glaring anomaly appeared in subjects' introspection during a PRP trial (Fig. 3B and C). The "time stamps" applied to T2 did not correspond to when T2 really occurred. Instead, during the PRP, it corresponded to the completion of the central processing of T1. At short SOAs, subjects' estimations of RT2 thus started with the conscious perception of T2 and ended with the motor response, leaving iRT2 constant despite the variations caused by the PRP. At longer SOAs, outside the interference regime, introspection became accurate again: subjects correctly recognized that RT2 is unaffected by RT1, could estimate the relative timing of T1 and T2 (despite an overall under-estimation), and even the free time separating the tasks (Fig. 3C).

3.4. Fluctuations in T1 processing time influence T2 introspection

As a final test of these ideas, we examined the pattern of introspective results as a function of the duration of the T1 decision. We used a median split to separate the trials into fast RT1 (mean = 561 ms) versus slow RT1 (mean = 797 ms). We then examined the impact on objective and subjective T2 measures (Fig. 5). According to the central interference model (see Fig. 3A), once T2 is presented during the interference period, any fluctuation in RT1 translates into a corresponding slowing down of RT2. The "elbow" in the curve relating RT2 and SOA indicates the SOA where RT2 becomes independent of RT1 and thus the duration of the interference regime. Thus, this elbow should be shifted toward longer SOAs when RT1 is slow. Indeed, when we examined the objective measures, we found significant effects on RT2 of both SOA, $F(5,45) = 46.24$, $p < 0.001$ and RT1 speed, $F(1,9) = 35.93$, $p < 0.001$, and crucially, a significant interaction compatible with the predicted shift in elbow location, $F(5,45) = 13.58$, $p < 0.001$. We determined the location of the elbow as the largest SOA value where RT2 + SOA did not vary significantly with SOA. When RT1 was fast, this elbow was at 232 ms whereas for slow RT1 trials, it was 466 ms.

We next examined how these variations were perceived introspectively. There was a significant effect of RT1 speed on iRT1, $F(1,9) = 22.55$, $p = 0.001$, confirming that subjects correctly estimated the duration of T1. Importantly, however, we did not find any effect of SOA, RT1 speed or their interaction on iRT2 which shows that subjects were again insensitive to objective variations in the time elapsing between T2 and their second motor response, including variations induced by fluctuations in T1 task duration.

The iSF was affected by both RT1 speed ($F(1,9) = 5.37$, $p < 0.05$) and SOA ($F(5,45) = 15.46$, $p < 0.001$), with a significant interaction, $F(5,45) = 2.56$, $p < 0.05$. This means that at long SOAs, subjects correctly estimated having more free time when RT1 was fast compared to when RT1 was slow. However, at short SOAs (0116, and 232 ms), there was no effect of RT1 speed on iSF ($F(2,18) = 2.89$, $p = 0.12$), showing that no matter the speed of RT1, subjects were unaware of the corresponding gain or loss in slack time – they again appeared blind to variations in task overlap inducing by fluctuating RT1.

Finally for iSOA, the central interference model predicts that it should be longer with fast RT1 at long SOAs – the shorter T1 processing is, the more time is available to estimate T2 onset. We observed an effect of SOA ($F(5,45) = 14.71$, $p < 0.001$) and a tendency for iSOA to be longer for fast RT1 than for short RT1 (+10 ms at 700 ms SOA, and +48 ms at 1050 ms SOA) but this effect did not reach the threshold of significance.

3.5. Interactions between introspection measures

The present analyses are based on four introspective questions that were asked in random order after each trial. One might think that the ability to introspect about a past event would degrade with elapsing time. We therefore used ANOVAs to analyze, for each subjective variable, the putative impact of its rank order in the query list. No significant effect was found, however. Within the range of times that were tested (<20 s in total), answering introspective questions was equally accurate regardless of whether they came

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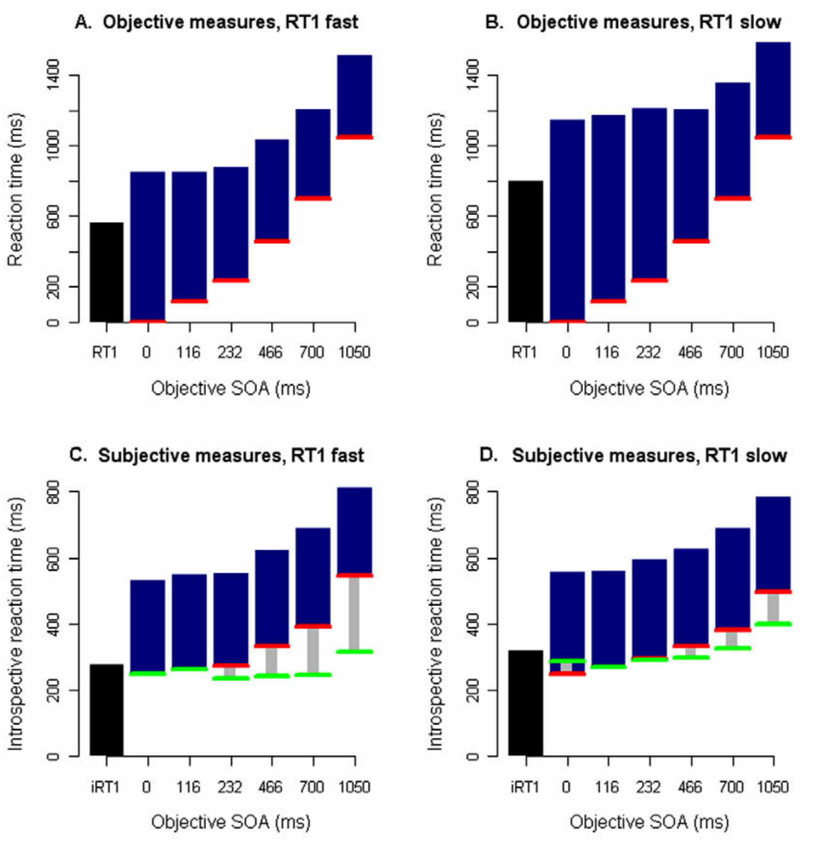

Fig. 5. Objective and introspective results, after subdivision of the data into two halves according to the objective speed of the T1 decision (same format as Fig. 3). All trials with RT1 shorter than the median were classified as fast (panels A and C) while trials with RT1 superior to the median were classified as slow (panels B and D). Values are means (ms) across subjects. The objective time spent to complete the first task influenced both the objective timing and subjective perception of PRP events.

first or last – subjects appeared to remember equally well all of the different details of the last trial.

4. Discussion

The present study shows that introspection brings new information inaccessible with classical behavioural measures. For the first time, we were able to reconstruct the sequence of conscious events in a PRP trial based on subjects' introspection. Participants' introspection partially reflected the objective parsing of the task, while diverging on some aspects. As we shall discuss, most deviations can be explained by a single hypothesis: in a dual-task setting, introspection is tied up by the first task and cannot focus on the second target until decision on the first target is resolved. This explains not only the disappearance of the PRP delay effect in introspective response times, which was already observed by Corallo et al. (2008), but also the misperception of SOAs and of slack time. Thus, these results suggest that during dual-task experiments, introspection only has access to a central serial processing stage.

Overall, introspective measures appear both consistent with and complementary to objective measures. Outside the interference regime, introspective RTs, iSF and iSOA were well correlated with the corresponding objective variables, meaning that subjects were able to correctly estimate their behavioural performance. In addition, subjects correctly estimated having less free time between the two tasks when they were slower to respond to T1. However, inside the interference regime, a completely different pattern appeared for introspective measures. Estimation of SOA was poor and subjects seemed unaware of the existence of slack time. According to the central interference model, if introspection was able to gain access to perceptual stages and their durations, then the subjective onset of T2 would be tightly related to its objective onset. Instead, if introspection was related to the central stage, the bottleneck induced by T1 processing would postpone conscious access to T2 and increase RT2. The observed pattern of results fits with the latter hypothesis: introspection was distorted during the PRP, and conscious perception of T2 was delayed until T1 processing was completed.

One possible model for the results assumes that, during slack time, when T2 is presumably waiting in a perceptual buffer before getting access to the central stage, the information relative to the precise timing of the perceptual events is lost or modified. This hypothesis would explain that SOA was better estimated outside the interference regime than inside it. Once the T1 decision is completed, the subjects would regain a faithful perception of internal events relating to T2. This is indeed reflected in iRT2, which always reflects accurately the delay between the onset of T2 access to the central stage and the motor response, independently of the SOA and of RT1 speed. Overall, these results suggest that subjects' introspection of perceptual timing is distorted only during the interference regime.

Alternatively, it might be suggested that the "timer" used to monitor sensory and internal events is itself subject to the bottleneck and that it might slow down or even stop during the interference period. Note however that subjects never really ceased to be accurate at measuring durations. When T1 and T2 were overlapping, participants were blind to the ongoing slack time of T2, but could still accurately estimate the trial-by-trial fluctuations of RT1. Hence, it seems more accurate to suggest that the "timer" is limited to a single task, rather than ceases to operate during dual-task interference. In addition, the latter hypothesis would predict that during the interference period, the variance of the estimated appearance of T2 (and of the variables that depend on T2 estimated onset, i.e. iSOA, iRT2 and iSF) should strongly increase. However, this is not what we observed. Instead, the estimated appearance of T2 was systematically delayed by more than 250 ms. The introspective RT2 was comparable across lags and not specifically increased or more variable during the interference period.

Prior to the main PRP experiment, we trained subjects to estimate short sound durations in order to ensure that they were able to estimate time interval at the same scale as their own response time. We found a strong correlation between the estimated and the actual sound duration. However, during the PRP experiment, subjects systematically underestimated their response times, an effect also found by Corallo and collaborators (2008). This suggests that performing a task does affect time estimation. Indeed, previous studies indicate that when attention is allocated to another concurrent task, the estimation of time tends to be shorter compared to when attention is allocated to the timing task (Champagne & Fortin, 2008; Kladopoulos, Hemmes, & Brown, 2004; Zakay & Block, 2004; Zakay & Shub, 1998). Other studies showed that when attention is attracted by a specific stimulus, its subjective duration is increased (Tse, Intriligator, Rivest, & Cavanagh, 2004). Also, if a perceptual event closely follows a motor action, such as a sound presented a few hundred milliseconds after pressing a button, the temporal interval between the action and the stimulus is subjectively shorter (Eagleman & Holcombe, 2002; Haggard, Clark, & Kalogeras, 2002). Performing time estimation, however, do not always affect the performance on a concurrent non-temporal task. Many studies did not find any influence of temporal tasks on the execution of non-temporal tasks, except for highly demanding tasks which seem to be more susceptible to bidirectional interference (Brown, 1997, 2006). In our experiment, we did not find any effect of time estimation on the response times. This suggests that subjects actually performed time estimation but that the effect of introspection on reaction times was either undetectable or completely absent. The dual-task paradigm enables us to virtually monopolize attention on one task, leaving a second one with few, if any attentional resources. In this situation, even the conscious perception of a stimulus can be delayed and the subjective timing of its onset becomes heavily distorted.

Under the appropriate masking conditions, the dual-task paradigm can lead to a downright inability to achieve conscious perception. In the attentional blink, two targets are successively presented, as in PRP experiments, but embedded in a temporal series of distractors. When the inter-target SOA is less than half a second, subjects' perception of the second target can be strongly impaired (Duncan, Ward, & Shapiro, 1994; Raymond, Shapiro, & Arnell, 1992). Two-stage models of the AB share common features with the central interference model, inasmuch as they propose a parallel perceptual processing stage, which is preserved, and a central serial stage which is absent during AB (Chun & Potter, 1995; Duncan et al., 1994; Marois, Chun, & Gore, 2000). Moreover, some studies suggest that the PRP and the AB are deeply related and could be explained by a single common model (Jolicoeur, 1998; Wong, 2002). Indeed, paralleling the present results, two recent studies of the AB have shown that during the interference regime, temporal attention is delayed, distorted and diffused (Vul, Hanus, & Kanwisher, 2008; Vul, Nieuwenstein, & Kanwisher, 2008). Vul and collaborators (2008) showed that inside the interference period, T2 can be misperceived and substituted by distractors presented within a broad time interval around the true T2 onset, indicating that the timing of the perceptual events is strongly distorted during AB. At long SOAs, the erroneous reports frequently came from distractors presented *after* T2 onset, again pointing to a parallel between AB and the present findings.

Overall, the present study showed that quantified introspection is a powerful tool. After each trial, participants can answer multiple questions that provide remarkably coherent data which are not always objectively true, but can be used to paint a consistent picture of the subjective phenomenology of an average trial during a cognitive task. Perhaps the most surprising finding is that participants can answer such questions at no apparent cost to the main PRP task, as if they were merely inspecting, after the fact, a detailed episodic record of what had happened on the preceding trial. The relation of introspection to episodic memory is just one of many aspects of quantified introspection that are left to be explored. Above all, introspection appears as a reliable tool which can be used like any other behavioural performance variable, along perhaps with time-resolved neuroimaging methods, in order to explore the links between sequences of subjective events and sequences of brain activities during a cognitive task.

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