FREE WILL OR NOT: CAUSALITY PRESERVED BUT ACCESS TO MOTOR DECISIONS OBSCURED

Andrei Gorea, Lukasz Grzeczkowski & Delphine Rider
Laboratoire Psychologie de la Perception
Paris Descartes University & CNRS
45 rue des Saints Pères, 75006 Paris, France

ABSRACT

Empirical studies having addressed the issue of free-will suffer from controversial methodologies and data interpretation. We present a new paradigm involving a synchronization task where the time interval to synchronize with is randomly within and without subject's synchronization capabilities and ask subjects to retrospectively evaluate (Q1) which of the two occurred or (Q2) whether their motor response had had been reactive/speeded or delayed. Contrary to the non-FW view according to which our judgments on the cause of our actions are corrupted by these actions' outcome (here an early or delayed motor response), Q1-judgments correlate with the actual duration of the synchronization interval rather than with subjects' motor response latencies. Instead of postidictively reshuffling their judgment to make it match the outcome of their actions, subjects preserve the causal chain of events having entailed them. When answering Q2 subjects' judgments also correlate with the synchronization interval, proof that they cannot decide on the intentionality of their actions. Hence the present results reveal the intrinsic duality of the free-will concept.

Most, if not all humans have the experience of 'free will' (FW). FW and its corollaries (volition, intentionality), just like consciousness (a poorly defined concept), are strictly private matters: their existence can be asserted by the subject and by no one else. Hence empirical measurements of any FW-related phenomena (such as brain events) must be validated by subject's contention that he *experienced* FW indeed.

The standard contemporary anti-FW allegation of both philosophers and experimenters[1-4] is that FW is but an 'illusion' instantiated by subject's unconscious, postidictive and non-causal interpretation of the chain of events having entailed his action. It is non-causal in that the cause of one's action is judged in the light of this action's outcome rather than for what it actually was. This is not to say that subjects consciously give up with the causal interpretation of the physical chain of events, namely Stimulus (exogeneous or endogeneous) → Decision/Intention → Response (action), but that while consciously sticking with reality, this interpretation is in fact unconsciously based on the non-causal chain S → R → D/I. Most of the empirical approaches to the FW illusion capitalized on the relative timing of D and R to show that the experienced timing of D trails the timing of R as assessed by the neural activity precursory to action[5-7]. In addition to debatable definitions of what is meant by volition, intention, etc.[8], strong qualms have been expressed both about subject's capability of assessing the moment of his decision to act while acting and about the techniques used to allow such assessments[9,10].

Here we capitalize on subject's motor response to (i.e. synchronization with) a temporal interval (stimulus) and of his a posteriori judgment of that interval to find out whether the latter relates to the interval/stimulus itself (causal/objective judgment), or rather to the motor response that this stimulus has prompted (non-causal/postdictive case). As described below, S is manipulated so as to entail speeded ('reactive') or delayed ('intentional') motor responses on a random basis. The causal alternative would give leeway to the possibility that introspective claims of FW are realistic. The non-causal one would raise doubts as to subject's capability of objectively judging, in line with the illusory FW stand.

The operationalization of the question asked draws on a motor synchronization task and on the underlying process of deciding to react or to delay one's motor response depending on whether a randomly drawn temporal interval that a subject must synchronize with (hereafter synchronization interval, SI) is shorter or longer than this participant's Reaction Time (RT). Once the participant has acted his motor response with a given Response Time (RsT), he is asked to provide a binary (Yes/No) response to one of the following three questions:

Q1: Has the current SI been long enough for him to synchronize with?
Q2: Has he reacted or waited to achieve synchronization?
Q3: Has the current SI been short or long?

The first two questions were meant to encourage subject's reliance on introspection (note this well, these questions do *not* bear on whether the RsT had or had not been synchronized). Nonetheless, subjects may base their judgment on the actual SI – an *objective*, *causal* judgment. Alternatively, their response may be contingent on their RsT – a *subjective, non-causal* judgment –, or possibly on the SI-RsT difference – a judgment combining objective and subjective information. A purely non-causal judgment subtending subject's answer to any of the first two questions would rely on an implicit appraisal of his own RT, a capacity known to exist[11,12]. Answering Q3 should not require an appeal to introspection; instead subjects should only appraise the mean of the SI distribution (implicit 'standard') and compare it to the current SI, yet another capacity known to exist and to yield accuracies equivalent to those obtained in the presence of the standard[12,13].

Clearly, very short (i.e. <<RT) and very long (i.e. >>RT) SIs will entail 100% reliable responses to Qs 1 and 2 as such durations will most obviously be respectively beyond and within subject's synchronization capacities independently of this subject's actual synchronization RsT, or even in the absence of any motor synchronization response. Q3 will also entail 100% reliable responses for SIs remote from the mean of the SI distribution. Instead, if the SIs are limited to a narrow time range about the reaction/proaction transition point (presumably close to participant's RT), they will entail much less reliable answers to any of the three questions above. This opens the possibility that participants will appeal to their introspectively estimated RsT as an alternative source of information (even though less reliable than a 'direct' SI estimation[12]).

An additional advantage of using a relatively narrow SI range about each participant's RT is that it should dilute the correlation between SI and RsT, a necessary condition for disentangling (at least partly) participant's reliance on SI from that on RsT. Reliance on RsT should be even more pronounced if the temporal gap between SI and RsT is directly assessable by the subject via a sensory (here visual) feedback. Under such conditions, observers are capable of judging their synchronization response (i.e. whether it had been early or delayed) with an accuracy of less than ±50ms, more than twice better than their perceptual estimation of the SI they had to synchronize with[12].

In short, the present experiments are designed to test whether subjects' judgments of the cause of their action relies, as it should, on this cause itself or rather on its consequence. This test is performed under conditions that maximize the decorrelation between the timing of their motor responses and the external stimulus that prompted it, on the one hand, and the information expected to enhance subjects' reliance on their response to this external stimulus rather than on the stimulus itself, on the other hand. Finding that, despite the availability of such information, subjects' judgments hinge on the timing of this stimulus rather than on the action it entailed would plead against the non-causality upon which the illusion of FW is seemingly built. In the same time, basing one's response to Q3 (that bears on subject's reactive vs. delayed motor response) on the physical interval having caused his action would support the notion that subjects are not aware of their motor decisions, a stance favoring the FW illusion.

RESULTS

The median and mean RTs assessed with the blocked filled gauge (227.4 ± 15.9ms and 230.6 ± 13.1ms; *Preliminary 1*) and with the randomized filling in durations (230.4 ± 8ms and 242.6 ± 12.1; *Preliminary 2*) were not statistically different.

Figure 2a presents mean RsTs for each participant (different symbols; keep in mind that RT and RsT refer to response times measured in speeded and in a synchronization response mode, respectively) as a function of SI in *Exp. 1*. This representation is not quite legitimate as at least three of the seven RsT means per subject were derived from bimodal RsT distributions (as assessed by Akaike Information Criterion, AIC[14]), with all subjects showing bimodal RsT distributions for SI = 0 and for

SI = 500ms. These bimodal RsT distributions for the two extreme SIs are exemplified in Fig. 2a1 and 2a2 for a typical subject, SL). Averaging RsTs over such bimodal distributions accounts for subjects' too early synchronization responses (i.e. RsTs below the main dashed diagonal) for the longest two SIs (400 and 500ms; for such SIs, subjects show perfect synchronization under blocked SI conditions[12]). While the source of this bimodality is of critical interest in understanding the synchronization process (an issue addressed in an ongoing study), it is of little relevance for the presently asked question. It is worth noting however that the means of the fastest RsT distributions averaged over the 5 subjects for SI = 0 (249 ± 29.8ms) is close to their mean RTs assessed in the two preliminary (RT) experiments (230.6 ± 13 and 242.6 ± 12.1ms) and not significantly different from them. This suggests that in mixed SI blocks including SIs too short to synchronize with, subjects' behavior alternates in about equal proportions between reactive and delayed/intentional response modes.

Fig. 2a3 displays the cumulative Gaussian (μ,σ) fitted to subject's SL 'Yes' responses to Q1 (Neider-Mead simplex algorithm) in *Exp. 1*. The means of such functions fitted to each subject's 'Yes' responses are their PSS_{SI} and have been used as midpoints of the 200ms SI range tested in *Exp. 2* (allowing a new, more accurate PSS_{SI} measure). A first notable observation from Fig. 2 is that the PSS_{SI} averaged over the 5 subjects in *Exp. 1* (246.4 ± 34.2ms) are similar to these subjects' mean RTs assessed in the preliminary experiments and closest to their mean RsTs derived from their fastest RsT distribution for SI = 0 (249.0 ± 29.8ms). This suggests that subjects have an accurate implicit knowledge of their mean RT and use it when answering Q1.

The restricted SI range about each subject's PSS_{SI} used in *Exp. 2* (in-between 117-183 to 317-383ms) ensured that subjects operated in an uncertainty reaction/reflection region and that their RsT were minimally correlated with SI (so as to maximize the disentanglement between subjects' putative reliance, when answering any of the 3 questions, on SI from their reliance on RsT and, as a consequence, on SI-RST). That this was achieved is demonstrated by the very shallow slopes (0.06-0.3; $r \in [.11\text{-}.48]$) of the mean RsT vs. SI functions displayed for each subject in Fig. 2b (same symbols as in Fig. 2a).

Fig. 3 shows the percentages of 'Yes' responses of the same representative subject as in Fig. 2a1-3 for each of the three questions asked (circles, squares and triangles for Q1, Q2 and Q3) together with the corresponding cumulative Gaussian fits as a function of SI (3a), RsT (3b) and SI-RsT (3c). Whatever the question asked, the steepest sigmoids (smallest σ) are obtained when the 'Yes' responses are related to SI ($\sigma_{SI} = 36.9 \pm 1.7$ms), slightly shallower when related to SI-RsT ($\sigma_{SI\text{-}RsT} = 43.1 \pm 3.0$ms) and flat for all practical reasons when related to RsT ($\sigma_{RsT} = 235.8 \pm 102.2$ms). These observations are true for all subjects (with two marginal exceptions out of 15 comparisons for Q1, subjects MD and CR) as shown in Table 1. At a first look, the accuracy of subjects' judgments appears to depend on the question asked ($\sigma_{Q1} = 170.9 \pm 134.1$; $\sigma_{Q2} = 68.3 \pm 23.8$; $\sigma_{Q3} = 76.7 \pm 38.1$ ms) but this is essentially due to the very inaccurate responses to Q1 when related to RsT ($\sigma_{RsT,Q1} = 439 \pm 121.8$ ms). A two-way ANOVA (factors question-type and relevant index, i.e. SI, RsT and SI-RsT) confirms these observations, namely a significant index effect[i] ($F(2,8) = 13.8$, $p = .021$) but no question-type effect ($F = 5.3$, $p = .076$). A partial comparison reveals a significantly steeper SI-related than (Si-RsT)-related slope ($F(1,4) = 3.44$, $p = .02$). Table 1 also displays the point-biserial correlations[15] (r_{PB}) between the binary (Yes/No) and the continuous (SI, RsT and SI-RsT) variables. As it should, the steepness of the fitted functions and r_{PB} show a high negative correlation ($r = -.62$, $p << .001$). In short, the data clearly show that whether asked to provide an introspective (Q1) or 'absolute' (Q3) judgment of SI (Q1 and Q3) or of them having responded in a reactive or reflective/delayed mode (Q2), subjects base their responses on the *actual duration of SI* with practically no 'postidictive' interference from their motor synchronization response. Another way to put it is to say that subjects' interpretation of the past is causal.

Additional support for this conclusion transpires from a closer look at subjects' Points of Subjective Synchronization (PSS) and RTs. As already noted, RTs were practically identical when directly measured in the preliminary RT experiments with the gauge instantaneously filled (SI=0) or filling over 0 to 500ms intervals or when derived from the fastest RsT distribution to the instantaneously filled gauge in the synchronization Exp. 1 (black circle, square and triangle in column "RT" of Figure 4). To answer the introspective Qs 1 and 2, subjects must, in principle, refer their responses to their introspected RT. The fact that the PSS_{SI} (column "PSS_SI" in Fig. 4) derived from their answers to these questions (Q1, solid red and open blue circles for Exps 1 and 2, respectively; Q2, open blue square, *Exp. 2*) are about equal to their RTs, while the corresponding PSS_{RsT} (column "PSS_SI"; same colors and symbols) differ markedly from the RTs as well as across experiments (circle vs. square) and subjects (error bars) support the notion that subjects' introspection was based on the SIs rather than on their own RsT. As the mean of the SIs used in *Exp. 2* was by construction equal to the PSS_{SI} obtained in *Exp. 1* (red solid circle), the PSS derived from subjects' responses to Q3 (that bore on the SI itself) should coincide with the mean SI. This is the case for the PSS_{SI} but not for the PSS_{RsT} implying once again that subjects have judged, as they should have for Q3, the SI and not their own RsT. Hence, subjects base their judgments on the objective duration of the interval they have to synchronize with whether in response to an introspective (Q1, Q2) or "objective" (Q3) question. Finally, the possibility that subjects calibrated their responses (whatever the question asked) relatively to their average RsT is not supported by the data as these averages ("AV_RsT" column in Fig. 4) are significantly above subjects' RT and PSS_{SI}.

DISCUSSION AND CONCLUSION

The present experiments demonstrate that despite being given full feedback on their motor synchronization response with a random time interval, subjects' introspective judgment of the length of this interval relative to their synchronization capacity (Q1) or of them having been in a reactive or reflective motor response mode (Q2) are poorly related, if at all, to their actual synchronization response time but strongly related to the physical duration of the interval. In fact, the accuracy of such introspective judgments is no different from that assessed when subjects are asked to judge the 'absolute' duration of these same intervals (Q3). The statistical analysis also shows that the accuracy of subjects' judgments is higher when these judgments are referred to the time interval itself rather than to the difference between this interval and the timing of their synchronization response. The data also show that subjects' Point of Subjective Synchronization is not significantly different from their mean reaction time and less variable (over experiments and subjects) when derived from subjects' answers (to any of the three questions asked) as a function of the actual duration of the synchronization interval than as a function of their synchronization response time. While it has been shown that judgements of a stimulus having entailed an action (such as a target and a saccade to it) are not biased by putative motor errors [16-18] at least in healthy subjects[18], the present study is the first to show that introspection on one's actions is based on these actions' physical cause rather than on their outcome. In the same time, such introspection appears to be calibrated relatively to subjects' introspected reaction time. The specific observation that responses to Q2, that bears on subjects' past decision to react or to delay action, do not correlate with their actual response time implies that, at least in the present experimental conditions, subjects do not have conscious access to or, alternatively, do not remember *what* this decision has been. This observation raises serious doubts about the experimental paradigm used in many studies where subjects were asked to specify *when* their decision to act had been taken[5,9,10].

Despite their fuzzy definition[8], reactive and intentional movements are known to reflect[19-22] and actually be triggered by[23] the activity of distinct neural networks. Yet, such anatomo-physiological distinction does not appear to sustain subjects' introspective judgments, specifically their knowledge of having reacted or delayed their action (Q2). This is so even though, in contrast with previous laboratory manipulations of volition (of the kind "Have free will now!" – see Haggard[7]), subjects' switch from a reactive to an intentional response mode was entirely under their own control. The conundrum appears to be solved, though not conceptually, by Desmurget et al.'s [23] astonishing findings that stimulation of distinct cortices may trigger the 'intention and desire' to move a limb or the lips together with the feeling of having done so in the absence of any corresponding electromyographic activity (inferior parietal regions) and reciprocally, an overt movement without the 'feeling' of having executed it (premotor area). Inasmuch as the 'consciousnesses' of acting and the action itself appear to be dissociated (or at least dissociable), it is not more remarkable to admit that reactive and intentional actions might not be consciously dissociable either. Such dissociations are actually amply documented in amputees and anosognostic patients (for the first type of dissociation) and in patients with utilization behavior or with delusions of control (for the second type of dissociation)[24]. Temptingly, one would take such intention/action dissociations as evidence favoring the notion that free will is but an illusion[3]. The present results provide paradoxical denotations in this respect. On the one hand, subjects' incapacity of retrospectively classifying their reactive vs. delayed motor response (Q2) based on the actual latency of this response comforts the view of an illusory free will. On the other hand, the fact that subjects judge their capacity of synchronizing a motor response with a random time interval based on their estimation of this interval rather than on their introspected response time (Q1) implies that their retrospective evaluation of the chain of events having caused their actions is causal, a prerequisite of the free will stand. Hence, not astonishingly, the present experiments and results reveal the intrinsic duality of the free will concept debated since the antiquity[25,26] and most recently formulated mathematically[27].

FIGURE LEGENDS

Figure 1. Spatial (a) and temporal (b) display of the stimulus. Note the different ranges of the Synchronization Intervals used and h different questions asked in *Exps 1 and 2*.

Figure 2. Synchronization Response Times (RsT) as a function of SI in *Experiments 1* (a) and *2* (b) of all 5 participants (different symbols) together with representative bimodal RsT distributions of participant SL for SI = 0 (a1) and SI = 500ms (a2) as well as a representative cumulative Gaussian fitted to this subject's 'Yes' responses to Q1 as a function of SI (a3). The dashed main diagonals in a and b show perfectly synchronized RsTs. The double arrowed right-angle lines in a3 point to this subject's RsT at 50% 'Yes' responses (i.e. the mean of the fitted Gaussian) which is referred to as his Point of Subjective Synchronization referred to SI (PSS_{SI}).

Figure 3. Percentage of 'Yes' responses to Qs1-3 (circles, squares and triangles, respectively) of a representative subject (SL) as a function of SI (a), RsT (b) and SI-RsT (c) together with the best cumulative Gaussian fits (sigmoids of corresponding colors). Insets show the respective means and SDs of the fits.

Figure 4. Reaction Times (RT; black symbols), Points of Subjective Synchronization derived from the cumulative Gaussian fits of the 'Yes' responses as a function of the Synchronization Interval (PSS_SI) and as a function of subjects' synchronization response time (PSS_RsT) and the means of these RsT (Av_RsT) as measured or derived from the different experiments. RTs measured in response to the instantaneously filled (SI=0) gauge and to a gauge filling over 0 to 500ms intervals are shown as the black circle and square, respectively. RT derived from the fastest RsT distribution to the instantaneously filled gauge in the synchronization Exp. 1 is shown a the black triangle. PSS and Av_RsT derived from responses to questions 1, 2 and 3 are shown as circles, squares and triangles with their colors referring to the Experiment where they have been assessed (red, *Exp. 1*; blue, *Exp. 2*). The solid red circle is the PSS_{SI} from *Exp. 1* used as the midpoint of the SI range tested in *Exp. 2*. Each symbol is the average over the 5 participants with the vertical bars showing 1SE.

ACKNOWLEDGMENT

Thanks to Patrick Cavanagh, Pascal Mamassian and Florian Waszak for helpful discussions. This work was supported by grant ANR-06-NEURO-042-01 from Agence Nationale pour la Recherche.

AUTHOR CONTRIBUTIONS

A.G. designed the experiments, performed part of the analysis, supervised the project, and wrote the paper. L.G. carried out the experiments and analyzed part of the data. D.R. wrote the stimulus presentation and data collection and analysis code and suggested new statistical tools.

METHODS

Stimulus

It was a 1° thick virtual annulus (the 'gauge') with a 3° external edge radius (Figure 1a) that started to fill in (randomly at one out of 8 locations marked by a radial bar) either in white (100 cd/m²) or in black (0.05 cd/m²) on a 50 cd/m² grey background. Polarity was swapped on each trial to prevent adaptation effects. The filling gauge was displayed on a 19'' E96f+SB ViewSonic screen (1024x768 pixels, 100 Hz refresh rate) 40 cm away from observers' eyes. The filling in was always counterclockwise (Fig. 1b) and occurred randomly within one out of 7 (0, 100, 200, 250, 300, 400, 500 ms; Experiment 1), or out of 21 synchronization time intervals (SIs, 10 ms apart within a range of 200 ms centered about each observer's Point of Subjective Synchronization; Experiment 2; see Procedure). Stimulus presentation and response recording were controlled using the Psychtoolbox[28,29].

Procedure

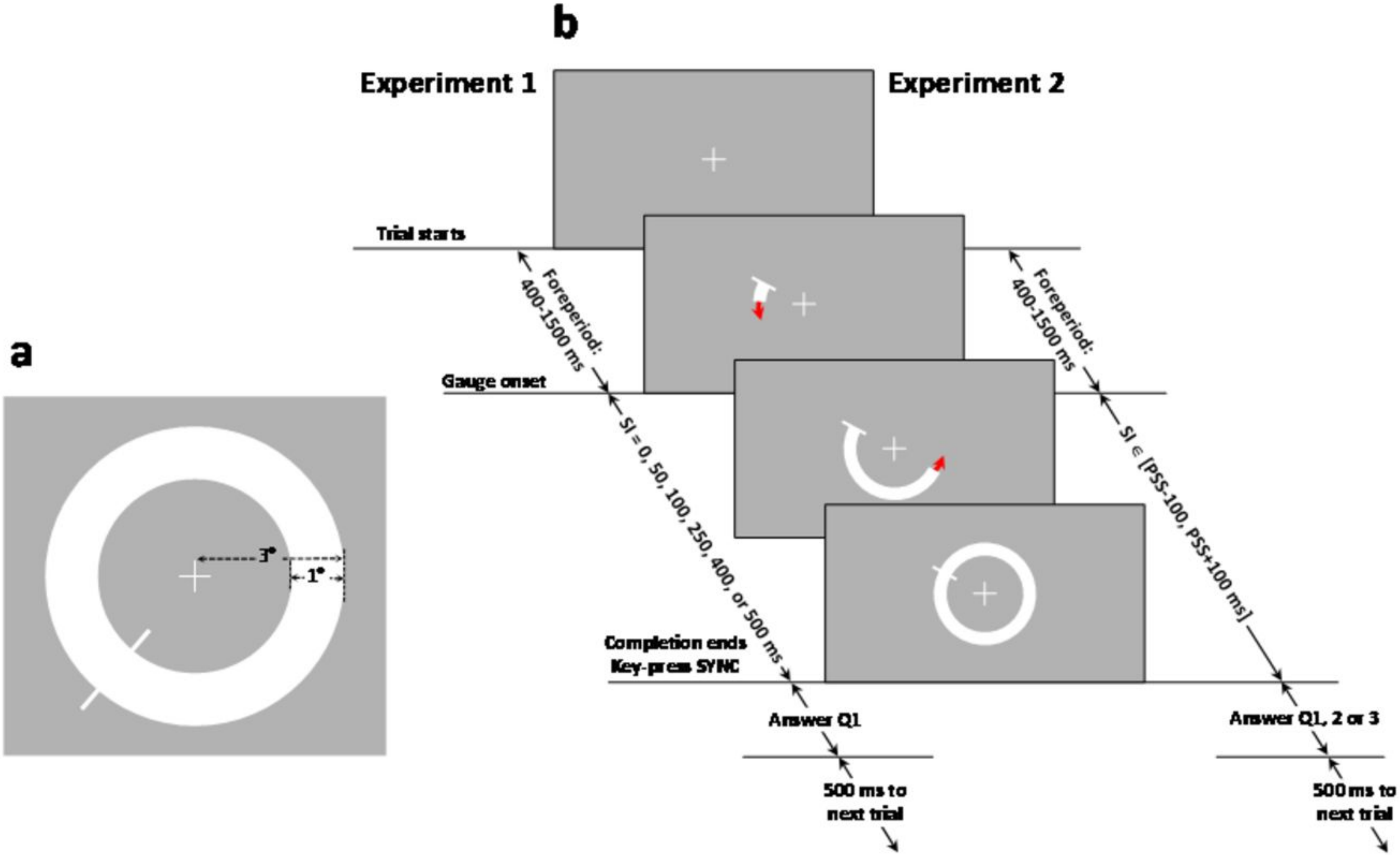
The experiment was performed in three stages. In a *preliminary* stage participants were asked to react (press a keyboard) as soon as possible to the appearance of the annular gauge that was either (a) fully filled from the start (SI = 0; one blocked session of 100 trials per subject; *Preliminary 1*) or (b) whose filling duration (hence speed) was randomly chosen across trials out of 7 possible SIs over a range of 0 to 500 ms (see above; *Preliminary 2*). In the latter case, 80 reaction times (RTs) were collected for each duration and observer in two sessions. The measure of these RTs was meant to be compared with subjects' Points of Subjective Synchronization (PSS) derived from their binary responses in *Experiments 1* and *2*. In both these experiments participants were asked to synchronize their motor responses (key-presses) with the moment the filling of the gauge was completed. In *Exp. 1* this range was the same as in the second preliminary experiment (i.e. 7 SIs spanning 0 to 500ms). After each motor synchronization response subjects had to provide a Yes/No response to Q1, i.e. *whether or not the SI had been long enough for them to synchronize their key-press with* (independently of whether or not they believed having provided an accurate synchronization response). The mean of the cumulative Gaussian fit to the frequency of 'Yes' responses as a function of SI is referred to as participant's PSS_{SI}. The PSS_{SI} corresponded to the mean of the SI range to be used in *Exp. 2*. There were 40 trials per SI and per session (i.e. 40x7 = 280 trials/session) repeated four times (i.e. 160 trials per SI total). At least 5 s breaks were imposed after every 20 trials. *Exp. 2* was run in three versions that differed only in the question asked after the synchronization key-press, i.e. Q1, 2 or 3. All versions consisted in repeating *Exp. 1* but this time with 21 SIs 10 ms apart within a total range of 200 ms centered on each participant's PSS_{SI}. Q1 and Q2 were intended to bias subjects toward a subjective appraisal of the SIs *relatively* to their own (introspected) RT. Instead, Q3 was meant to bias subjects toward an objective appraisal of the SIs; to answer it subjects had to implicitly estimate the mean SI.

REFERENCES

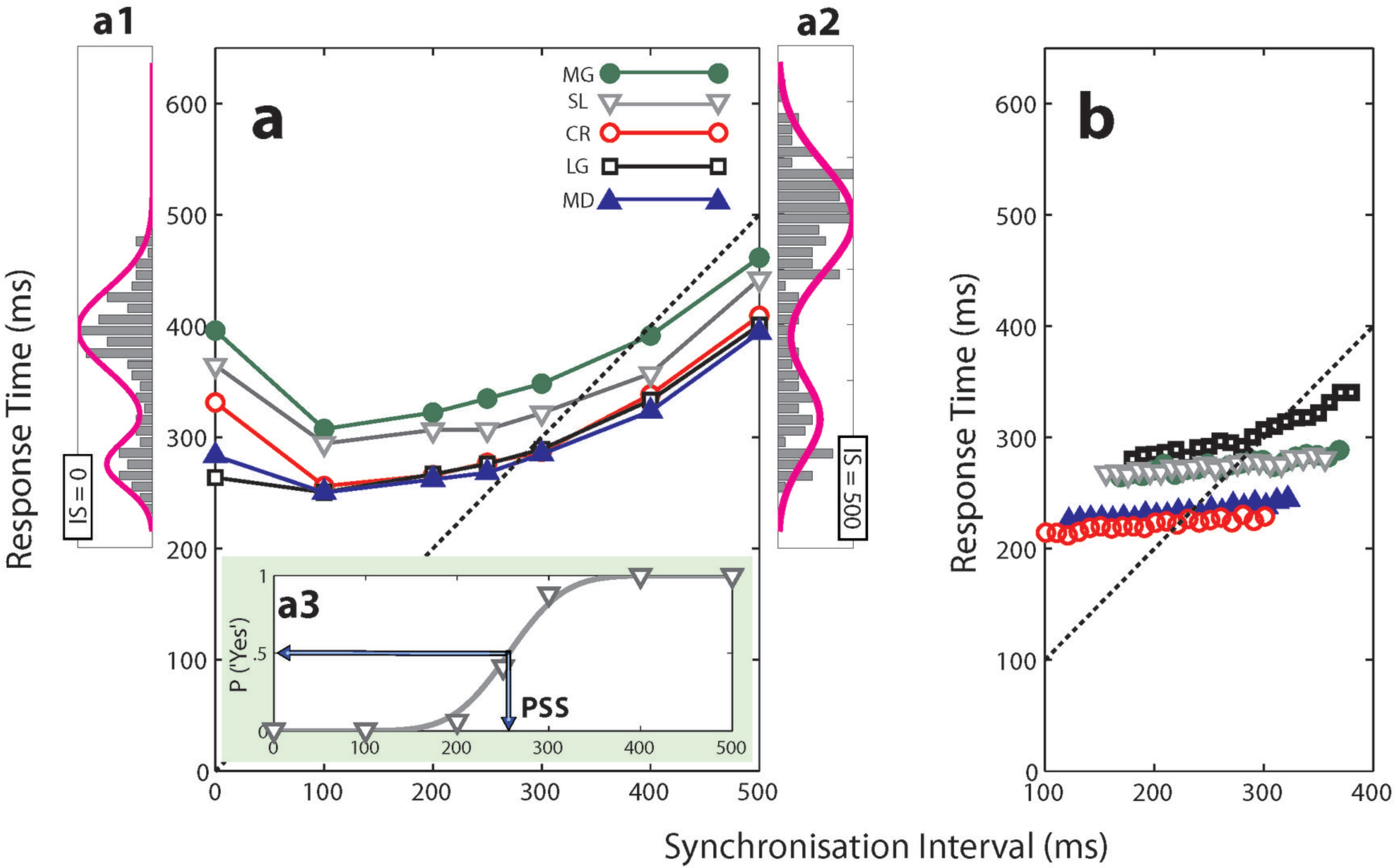
1. Dennett, D.C. *Consciousness explained*. London/New York: Penguin Books (1991).
2. Wegner, D.M. *The Illusion of Conscious Will*. Cambridge, MA: MIT Press (2002).
3. Wegner, D.M., Wheatley T. Apparent mental causation, sources of the experience of will. *Am. Psychol.* **54**(7), 480-492 (1999).
4. Hallett, M. Volitional control of movement: The physiology of free will. *Clin. Neurophysiol.* **118***,* 1179-1192 (2007).
5. Libet, B. *Neurophysiology of consciousness: Selected papers and new essays by Benjamin Libet*. Boston/Basel/Berlin: Birkhauser (1993).
6. Lau, H.C, Rogers, R.D. & Passingham, R.E. Manipulating the Experienced Onset of Intention after Action Execution. *J. Cognitive Neurosci.* **19**(1), 1-10 (2007).
7. Haggard, P. The Sources of Human Volition. *Science* **324**, 731-733 (2009).
8. Nachev, P., Husain, M. & Kennard, C. Volition and eye movements. In C. Kennard & R.J. Leigh (Eds), *Progress in Brain research Vol. 171*, Elsevier (pp 391-398) (2008)
9. Pockett, S. On Subjective Back-Referral and How Long It Takes to Become Conscious of a Stimulus: A Reinterpretation of Libet's Data. *Conscious. Cogn.* **11**, 144–161 (2002).
10. Danquah, A.N., Farrell, M. J., & O'Boyle, D. J. (2008). Biases in the subjective timing of perceptual events: Libet et al. (1983) revisited. *Conscious Cogn, 17*(3), 616-627.
11. James, W. *The principles of psychology*. Vol. 1, Chapt. 15: The perception of time. New York: Holt (1890).
12. Gorea, A., Mamassian, P. & Cardoso-Leite, P. Introspective Duration Estimation of Reactive and Proactive Motor Responses*.* *Acta Psychol.* **134**, 142-153 (2010).
13. Morgan, M. J., Watamaniuk, S.N.J. & McKee, S.P. The use of an implicit standard for measuring discrimination thresholds. *Vision Res.* **40**, 2341–2349 (2000).
14. Akaike, H. A new look at the statistical model identification. *IEEE T. Automat. Contr.* **19**(6), 716-723 (1974).
15. Lev, J. The Point Biserial Coefficient of Correlation. *Ann. Math. Stat.* **20**(1), 125-126 (1949).
16. Collins, T., Rolfs, M., Deubel, H. & Cavanagh, P. Post-saccadic location judgments reveal remapping of saccade targets to non-foveal locations. *J. Vis.* **9**(29), 1–9 (2009).
17. Munuera, J., Morel, P., Duhamel, J.R. & Deneve, S. Optimal sensorimotor control in eye movement sequences. *J Neurosci* **29**, 3026–3035 (2009).
18. Ostendorf, F., Liebermann, D. & Ploner, C.J. Human thalamus contributes to perceptual stability across eye movements. *Proc. Nat. Acad. Sci. USA,* **107**(3), 1229-1234 (2010).
19. Frith, C. D., Friston, K., Liddle, P.F. & Frackowiak, R.S.J. Willed Action and the Prefrontal Cortex in Man: A Study with PET. *Proc. R. Soc. Lond.* **244**, 241-246 (1991).
20. Jahanshahi, M., Jenkins, I.H., Brown, R.G., Marsden, C.D., Passingham, R.E. & Brooks, D.J. Self-initiated versus externally triggered movements. An investigation using measurement of regional cerebral blood flow with PET and movement-related potentials in normal and Parkinson's disease subjects. *Brain* **118***,* 913-933 (1995).
21. Jenkins, I. H., Jahanshahi, M., Jueptner, M., Passingham, R.E. & Brooks, D.J. Self-initiated versus externally triggered movements. II. The effect of movement predictability on regional cerebral blood flow. *Brain* **123**, 1216-1228 (2000).
22. Brass, M. & Haggard, P. To do or not to do: The neural signature of self control. *Journal of Neuroscience* **27**(34), 9141-9145 (2007).
23. Desmurget, M., Reilly, K.T., Richard, N., Szathmari, A., Mottolese, C. & Sirigu, A. Movement Intention After Parietal Cortex Stimulation in Humans. *Science* **324**, 811- 813 (2009).
24. Frith, C.D, Blakemore, S.J. & Wolpert, D.M. Abnormalities in the awareness and control of action. *Philos. Trans. R. Soc. Lond B Biol. Sci.* **355**, 1771-1788 (2000).
25. Bobzien, S. (1998). *Determinism and freedom in stoic philosophy*. Oxford University Press, Oxford, UK.
26. O'Keefe, T. (2005). *Epicurus on Freedom*. Cambridge University Press, Cambridge, UK.

27. Conway, J.H. & Kochen, S. (2009). The Strong Free Will Theorem. *Notices Am. Math Soc.* **56**(2), 226-232.
28. Brainard, D.H. The psychophysics toolbox. *Spatial Vision* **10**, 433-436 (1997).
29. Pelli, D.G. The VideoToolbox software for visual psychophysics: Transforming numbers into movies. *Spatial Vision* **10**, 437–442 (1997).

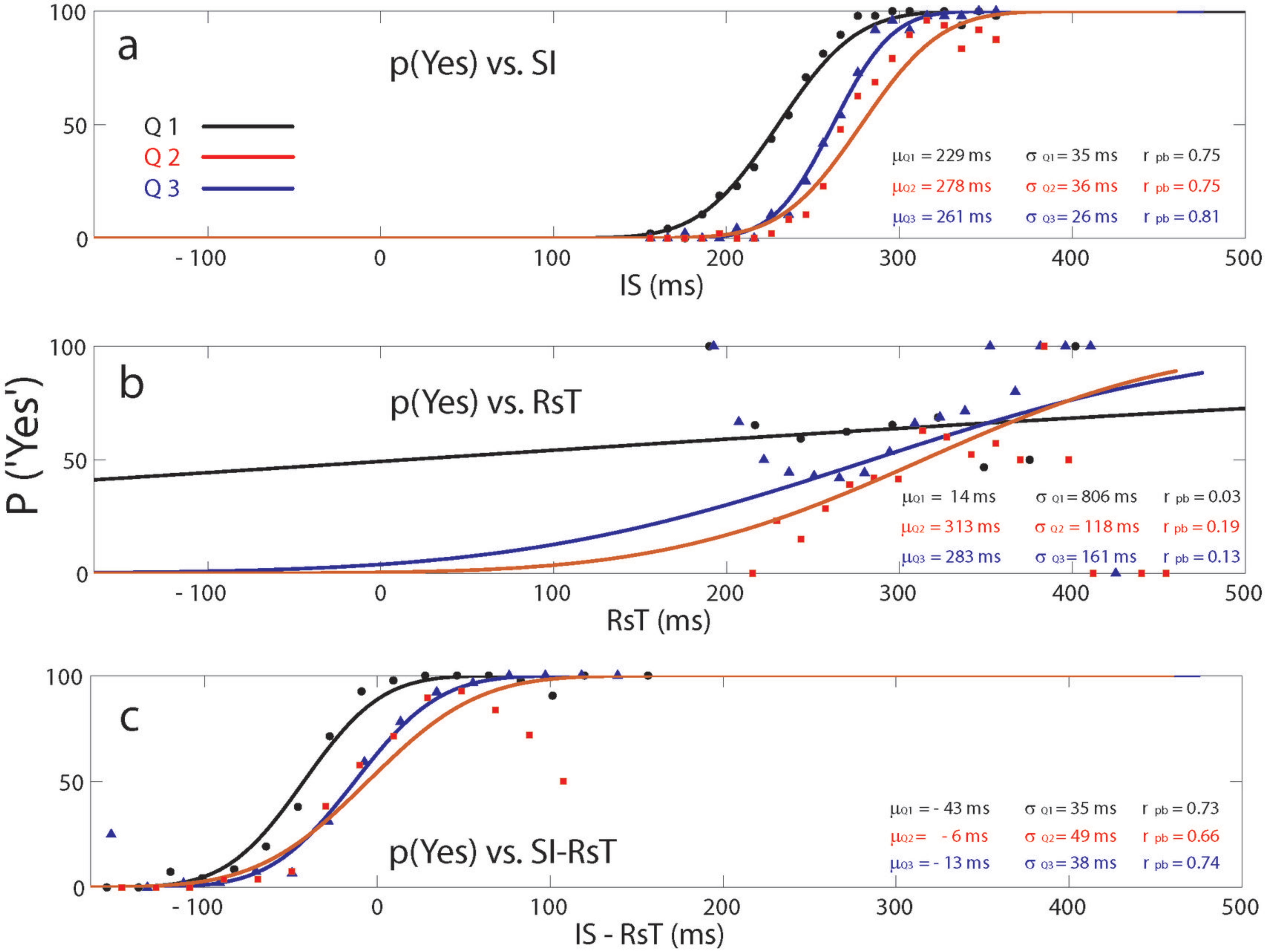
[i] All effects are corrected for sphericity – Greenhouse-Geisser.



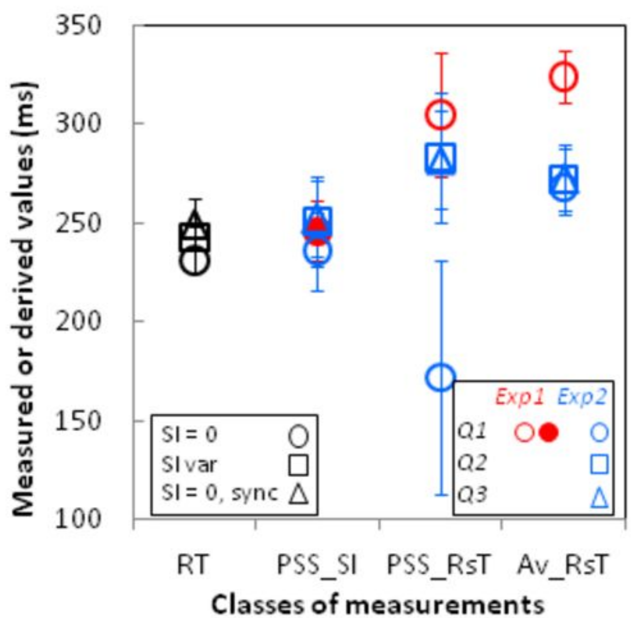
a
3°
1°
b
Experiment 1
Experiment 2
Trial starts
Foreperiod: 400-1500 ms
Gauge onset
SI = 0, 50, 100, 250, 400, or 500 ms
SI ∈ [PSS-100, PSS+100 ms]
Completion ends
Key-press SYNC
Answer Q1
Answer Q1, 2 or 3
500 ms to next trial



a1
a2
a
b
a3
MG
SL
CR
LG
MD
IS = 0
IS = 500
Response Time (ms)
Synchronisation Interval (ms)
P ('Yes')
PSS



a
p(Yes) vs. SI
Q 1
Q 2
Q 3
μQ1 = 229 ms σ Q1 = 35 ms r pb = 0.75
μQ2 = 278 ms σ Q2 = 36 ms r pb = 0.75
μQ3 = 261 ms σ Q3 = 26 ms r pb = 0.81
IS (ms)
b
p(Yes) vs. RsT
μQ1 = 14 ms σ Q1 = 806 ms r pb = 0.03
μQ2 = 313 ms σ Q2 = 118 ms r pb = 0.19
μQ3 = 283 ms σ Q3 = 161 ms r pb = 0.13
RsT (ms)
P ('Yes')
c
p(Yes) vs. SI-RsT
μQ1 = - 43 ms σ Q1 = 35 ms r pb = 0.73
μQ2 = - 6 ms σ Q2 = 49 ms r pb = 0.66
μQ3 = - 13 ms σ Q3 = 38 ms r pb = 0.74
IS - RsT (ms)



350
300
250
200
150
100
Measured or derived values (ms)
RT
PSS_SI
PSS_RsT
Av_RsT
Classes of measurements
SI = 0
SI var
SI = 0, sync
Exp1
Exp2
Q1
Q2
Q3

Table 1. Standard deviations of the cumulative Gaussians fitted to subjects' 'Yes' responses to each of the three Questions asked in *Exp 2* as a function of the Synchronization Interval (σSI), Response Time ($\sigma P\sigma T$) and SI-RsT($\sigma SI\text{-}RsT$) (odd cols) together with the corresponding Point Biserial correlations (rPB; even cols).

	Q1 *Has the current SI been long enough for you to synchronize with?*						**Q2** *Have you reacted or waited to achieve synchronization?*						**Q3** *Has the current SI been short or long?*					
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Sjs	σ_{SI}	$r_{PB,SI}$	σ_{RsT}	$r_{PB,RsT}$	$\sigma_{SI\text{-}RsT}$	$r_{PB,SI\text{-}RsT}$	σ_{SI}	$r_{PB,SI}$	σ_{RsT}	$r_{PB,RsT}$	$\sigma_{SI\text{-}RsT}$	$r_{PB,SI\text{-}RsT}$	σ_{SI}	$r_{PB,SI}$	σ_{RsT}	$r_{PB,RsT}$	$\sigma_{SI\text{-}RsT}$	$r_{PB,SI\text{-}RsT}$
LG	37	0.76	154	0.18	39	0.68	47	0.70	60	0.42	56	0.55	32	0.77	53	0.45	39	0.64
SL	35	0.75	806	0.03	54	0.68	36	0.75	118	0.19	49	0.66	26	0.81	161	0.13	38	0.74
MD	32	0.78	229	0.07	32	0.76	35	0.76	66	0.21	41	0.71	41	0.74	114	0.17	45	0.69
CR	34	0.75	622	0.03	28	0.75	60	0.62	219	0.08	62	0.60	41	0.74	75	0.19	42	0.70
MG	36	0.77	384	0.07	41	0.71	44	0.67	218	0.11	53	0.60	38	0.74	361	0.07	44	0.69
μ	**34.8**	**0.76**	**439**	**0.08**	**38.8**	**0.72**	**44.4**	**0.70**	**136**	**0.20**	**52.2**	**0.62**	**35.6**	**0.76**	**153**	**0.20**	**41.6**	**0.69**
σ	*1.92*	*0.01*	*272*	*0.06*	*10.0*	*0.04*	*10.11*	*0.06*	*78.4*	*0.13*	*7.85*	*0.06*	*6.50*	*0.03*	*123*	*0.15*	*3.05*	*0.04*