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Invited reply

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Rapid switching and complementary evidence accumulation enable flexibility of an all-or-none global workspace for control of attentional and conscious processing: a reply to Wyble *et al*.

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Although *attentional* (e.g. [1]) and *conscious* (e.g. [2]) processing limitations have been widely acknowledged as interdependent (e.g. [3–5]), a unifying theory has been lacking. As an attempt to bridge these domains, we recently proposed the *Theory of Attention and Consciousness* (TAC; [6]). TAC provides a unified neurocognitive account of several phenomena associated with visual search, attentional blink (AB), and working memory (WM) consolidation. Wyble *et al*. [7] commented on our TAC proposal, focusing on WM consolidation and AB effects.

With respect to WM consolidation, which corresponds to short-term memory (STM) encoding in their framework, Wyble *et al*. [7] observe that there is mounting evidence for parallel processing of multiple targets. In the *lag-1 sparing* condition of the AB paradigm, two targets are apparently encoded together [8]. Global workspace (GW) models (e.g. [2]) face particular difficulties in accounting for such evidence, given that their processing limitations are based on a strict winner-take-all principle (however, see [9] for a neural model enabling parallel target encoding in the GW). Wyble *et al*. [7] acknowledge that while retaining the notion of GW, TAC attempts to go beyond such models, in particular by introducing an 'intermediate buffer' mechanism. This mechanism operates in tandem with a winner-take-all competition in the GW between higher order executive routers for attentional selection and consolidation in WM. Instead, in their previously proposed *Episodic Simultaneous Type Serial Token* (*eSTST*) model [10–12], competition for resources between encoding in STM and attentional selection is not winner-take-all but leads to attenuation of these processes. Wyble *et al*. [7] emphasize that, unlike TAC, the eSTST model permits parallel encoding of multiple targets into STM.

First of all, we note that the TAC as described in Raffone *et al*. [6], in spite of the claims in Wyble *et al*.'s [7] comment, is in principle neutral with respect to serial versus parallel consolidation in WM. These issues are not explicitly addressed in the current, first formulation of the theory, which is to be developed further in order to account for a broader set of data, including *divided attention* and multitasking paradigms (e.g. [13]). Wyble *et al*. [7] claim that parallelism favours encoding of multiple targets in WM in discrete attentional episodes. TAC enables a form of parallel 'episodic' representation for encoding in WM. Specifically, multiple targets represented in the intermediate buffer may be consolidated through repeated shifts in the processing priority of different targets, each of which lasts a few tenths of milliseconds, with a mechanism based on nested slow and fast processing cycles. This mechanism would be revealed electrophysiologically through phase–amplitude coupling. The role of this mechanism in AB conditions has recently been demonstrated [14]. This mechanism reconciles winner-take-all and seriality of fast processing cycles with parallel representation of multiple targets within slow processing cycles.

TAC would thus entail a universal mechanism at multiple processing levels: attentional filtering, WM consolidation and WM maintenance.

Some recent evidence has emerged from a visual search task in which multiple items need to be remembered, thus requiring resources for both attentional selection and WM consolidation [15]. Eye-tracking data from this study suggest that these processes cannot be achieved in parallel, but need to be handled sequentially. Eye-movements to the next target were delayed when visual WM capacity was exceeded, which suggests that when extra resources were needed for memory representation, this competed with attentional selection. Consistently with the above-mentioned mechanism, the delay is of the order of tenths of milliseconds.

Let us now consider the first empirical benchmark that Wyble *et al*. [7] consider unattainable for TAC, namely that providing a cue during the deepest part of the AB has a facilitatory effect on the following target (T2) [16] and no effect on accuracy of reporting the first target (T1) in the rapidly presented series. Although TAC proposes a winner-take-all or all-or-none competition between higher-order executive routers for consolidation in WM and attentional selection in the GW, it also includes complementary graded and ongoing evidence accumulation processes driving such competition, and assumes the possibility of rapid and reversible switches between the ignition (activation) of either the attentional selection or the WM consolidation router. In TAC, such reversibility is central to account for trials in which the AB does not occur even with lags such as lag-2 and lag-3, in terms of a *sparing recovery* process [6]. Because of these mechanisms, the model is able to account for the first empirical benchmark. For our part, we are worried about the apparently rigid notion of 'attentional episode' in the eSTST model, which would appear to face difficulty in accounting for this sparing recovery.

In reference to the second specific empirical benchmark that Wyble *et al*. [7] deem unattainable for TAC, i.e. the observation that, in event-related potentials (ERP), the onset of P3 (a component assumed to be related to WM consolidation) is not delayed at lag-1 when compared with lag-8 (fig. 2 in Wyble *et al*.'s comment [7], from [17]). However, the effect permits an alternative account, motivated by the more persistent positivity of the P3 wave in lag-1 when compared with lag-8 conditions in fig. 2 [7]. In terms of the GW mechanisms assumed in TAC, this effect would reflect a prolonged activation of the GW router for WM consolidation. This prolonged activation is needed in the competition for resources with the router for attentional selection. This explanation is in accordance with the observation that the effect of spatio-temporal selection decreases with practice in the AB task [18]. This alternative account appears also more consistent with the electrophysiological evidence of late conscious access markers [19], with a latency of about 300 ms, which in our view suggests that consolidation for encoding in WM (STM) is initiated rather than completed around that time. Furthermore, in the same fig. 2 [7], we observe a pronounced difference in amplitude of the P3 component for T1 and T2 with lag-8. In our view, such evidence can be hardly explained if not in terms of a higher-order competition mechanism between routers for WM consolidation and attentional selection. Specifically, TAC would predict a lower accumulation of evidence (cortical inputs) needed to reactivate the router for WM consolidation for T2, related to a reduced P3 amplitude for T2 when compared with T1 with lag-8, owing to the earlier activation of the same router for T1. Thus, a priming effect would be established between T1 and T2 presentations with lag-8, in terms of residual (slowly decaying) graded activation feeding the (all-or-none) higher-order router for WM consolidation in the GW, implicated for the consolidation of both targets.

We agree with Wyble *et al*. [7] that conscious processing and WM encoding for relevant targets need to be completed as fast as possible. The occurrence of multiple stages of processing in TAC ensures that relevant processing steps for target perception occur before consolidation for encoding in WM. Moreover, the processes of evidence accumulation and ignition driving attentional selection and WM consolidation in the GW should enable prioritarization of the most relevant processing operation at any given time in a task.

Wyble *et al*. [7] conclude their comment by asking about the adaptive utility of suppressing attention during encoding, and observe that preventing interference from feature and proto-object representations as claimed in TAC seems an insufficient answer, also in the light of the evidence of parallel target processing with lag-1 sparing. First of all, we note that processing two targets with lag-1 sparing may implicate costs and errors [20], also depending on the relative strength of the targets. Moreover, given the strong amplification assumed to take place in the GW during conscious access, with a strong selective feedback towards neurons in posterior cortex involved in the representation of the accessed target and its features (e.g. [2]), any concomitant amplification for attentional selection in posterior cortex could give rise to spurious activations and target detections when incoming task-irrelevant stimuli share features with the accessed target.

Finally, the processes, mechanisms and computations proposed in TAC need to be specified and evaluated in working model implementations and simulations, in the light of behavioural, electrophysiological and neurophysiological data. These simulations will also enable a detailed comparison with other simulation-based models of the AB and WM encoding, including eSTST [10–12] and ViSA [9]. Given the broad explanatory scope of TAC, the simulations also need to deal with a range of other phenomena and effects, such as in visual search and dual-performance tasks.

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