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Spotlight Commentary

Is conscious awareness needed for all working memory processes?

David Soto[1,2,*] and Juha Silvanto[3]

[1]Basque Center on Cognition, Brain and Language, San Sebastian, Spain; [2]Basque Foundation for Science, Ikerbasque, Bilbao, Spain; and [3]Department of Psychology, Faculty of Science and Technology, University of Westminster, London, UK

*Correspondence address. Basque Center on Cognition, Brain and Language, Paseo Mikeletegi, 69, 2nd Floor, 20009, San Sebastián - Donostia, Spain; Tel: +34 943 309 300; E-mail: d.soto@bcbl.eu

Abstract

Stein and colleagues argue there is no yet conclusive evidence for nonconscious working memory (WM) and that is critical to probe WM while ensuring null sensitivity to memory cues. While this stringent approach reduces the likelihood of nonconscious signaling for WM, we discuss existing work meeting this null sensitivity criteria, and, related work on nonconscious cognition in keeping with WM/awareness dissociations on the basis of a functional operational definition of WM. Further, because it is likely that WM is a nonunitary functional construct and visual awareness a gradual phenomenon, we propose that delineating the neural mechanisms for distinct WM types across different levels of awareness may prove the most fruitful approach for understanding the interplay between WM and consciousness.

Key words: unconscious processing; working memory; conscious awareness

Stein *et al.* (2016) point out methodological hurdles in assessing the scope of working memory (WM) operations over nonconscious input, and more generally, to bolster alternative views that WM and awareness may be dissociable. Stein *et al.* argue that it is paramount to use bias-free objective sensitivity measures and ensure that observers have null sensitivity of the memory cues (i.e. d' = 0). Stein *et al.* rightly point out that the objective sensitivity measure used in prior studies of nonconscious WM (Soto *et al.* 2011; Dutta *et al.* 2014) was influenced by the individual decision bias in reporting (un)awareness, and therefore was not a pure sensitivity measure but rather a pseudo-d'. The reason for this was that these studies of nonconscious WM aimed to compute a sensitivity measure specific for the trials rated as subjectively unaware (i.e. using the proportion of unaware trials on trials without memory cue as performance hits). Most notably, these initial studies on nonconscious WM were not set to dissociate WM from null sensitivity to the presence of the memory cue, but to explore dissociations between WM performance and subjective measures of awareness, which, according to recent approaches are the most relevant proxy to conscious experience (e.g. Sandberg *et al.* 2010). Signal detection theory (STD)-based sensitivity indices of stimulus processing are excellent measures of performance. But these may not be diagnostic of the state of awareness, because a given level of sensitivity (i.e. d' = 1) may reflect both nonconscious and conscious processes, hence likely overestimating conscious perception (Persaud *et al.* 2007; Dehaene and Changeux 2011; though see Peters and Lau 2015). Further, it turns out that at least in detection tasks, SDT analyses cannot distinguish between sensitivity and decision bias effects (Witt *et al.* 2015), which is to say that decision criteria can reflect actual conscious perception rather than mere response biases. There are grounds therefore to cast doubt on the utility of focusing exclusively on sensitivity measures in the study of visual awareness. We also note that

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Soto et al. (2011) found no correlation between individual perceptual sensitivity of cue and the level of WM performance; but note this correlation is clearly expected if WM performance was coupled with cue sensitivity. A reanalyses of the data from Soto et al. (2011) using the bias-free sensitivity approach proposed by Stein et al. (2016) confirmed again the absence of correlation between cue sensitivity and individual WM performance (Pearson's correlation: -0.24, $t = -1.08$, $P < 0.29$). Further, it is noted that the mean pseudo-d' in Soto et al. (2011) was 0.311 while the d' calculated following the Stein et al. procedure is 0.454; both were highly correlated (Pearson's coefficient: 0. 891, $P < 0.0001$). However, this absence of correlation between WM performance and cue sensitivity is not strong evidence of absence and hence this issue needs to be systematically assessed by high-powered interindividual differences paradigms and within-subject reliability tests across multiple sessions.

Stein et al. (2016) also note that the above findings from Soto et al. (2011) could be instead accounted by the operation of perceptual (rather than WM) processes, wherein observers use a nonconscious or weakly conscious perceptual representations of the masked cue to make a conscious guess which is then held in WM during the delay period. Note this account would also predict a tight interindividual correlation between cue sensitivity and WM performance as better cue sensitivity should elicit conscious guesses of higher fidelity. We agree with Stein et al. that evidence of successful WM given null sensitivity of memory cues would strongly support the view that WM can operate on nonconscious representations. Notably, however, there are a couple of studies meeting this stringent criteria. Pan et al. (2014) asked participants to keep in WM a face cue, which could be conscious or nonconscious (i.e. a 10-ms masked cued associated with null detection d' using the bias-free objective sensitivity measure proposed by Stein et al. 2016). There followed a dichoptic display composed of colored Mondrian-like patterns to one eye, which masked from awareness the information presented in the other eye (i.e. continuous flash suppression; Tsuchiya and Koch 2005). The contrast of the face in the "suppressed" eye ramped up gradually and participants had to detect its location. Reaction times were faster when the target face in the suppressed eye matched the initial cue held in WM, relative to the nonmatch baseline. Memory biases of awareness were driven from both conscious and nonconscious cues, but only when participants were instructed to retain the cues in WM for a later recognition test, and not when participants attended the face cues without memory maintenance requirements; hence ruling out priming accounts of the memory effect (Soto et al. 2008). Thereby, these findings suggest that nonconscious cues were held in WM in order to boost awareness of a matching face during flash suppression.

Additional relevant evidence comes from recent work by Rosenthal and colleagues (2010, 2016) using a visuospatial learning protocol in which a complex sequence of targets occurred repeatedly across four placeholders (i.e. locations 1-2-3-4). The sequence (i.e. 3 4 2 3 1 2 1 4 3 2 4 1) was based on a 12-element second-order conditional rule. There were 4 monocular placeholders: 1 and 2 were presented to the left eye, while 3 and 4 were presented to the right eye by means of stereoscopic presentation. This triggered binocular fusion of the 4 monocular placeholders from left and right eyes, leading to conscious perception of 2 placeholders only. Hence the four monocular locations in which the sequence was embedded were continuously masked from visual awareness. Following the study phase, sequence knowledge was assessed by means of a surprise old/new recognition test composed of trained (old) and untrained (new) recognition sequences, which critically differed only at the level of the (masked) monocular sequential order but were otherwise identical when viewed at a conscious binocular level. While participants could not perceive the monocular locations of the sequence, as confirmed by the null sensitivity in forced-choice location discrimination tests, performance in the recognition memory test revealed that nevertheless the sequence was learnt. In particular, memory confidence was higher for old (trained) than for new sequences during recognition. These results demonstrate successful acquisition of nonconscious higher-order sequence knowledge and later recognition without awareness. Crucially, in order to learn the spatiotemporal serial order of the 12-element sequence of targets, spatial information had to be maintained and integrated across several seconds, which is in keeping with the operational definition of WM. The learned sequences also biased other cognitive processes, namely, later memory-guided behavior and retrieval in the subsequent recognition test, which also involves the interplay between WM and long-term memory systems (Baddeley 2003).

The above evidence for WM operations on nonconscious input also aligns with other evidence that higher-order cognitive processes such as executive control during conflict (van Gaal et al. 2012), arithmetic computations (Ric and Muller 2012), and sentence processing (Sklar et al. 2012) can be performed on information that is nonconscious, confirmed also by stringent tests of perceptual sensitivity. Functional operations involved in executive control, arithmetic and processing of sentences (e.g. during reading) are also within the functional operational definition of WM.

Stein et al. argue that it is difficult to imagine a situation in which we are not consciously aware of the stimuli that enter WM. However, masked distracters that go undetected can nevertheless enter WM and modulate the fidelity of the representations that are consciously maintained in WM (Silvanto and Soto 2012). There are also demonstrations that conscious awareness of WM content does not accurately track the fidelity of WM contents (Bona et al. 2013), indicating that the phenomenology of WM does not always reflect the actual WM content. There are thus several lines of evidence which, taken together, lead to a theoretical reevaluation of the putatively close link between consciousness and WM (Soto and Silvanto 2014).

By no account, however, experimental data supporting a dissociation between WM processes and conscious awareness should be strictly taken to suggest that WM and conscious awareness are independent cognitive systems, but that they can be partially segregated in different contexts. Because WM is a nonunitary psychological construct, the distinct WM types may relate differently to conscious awareness, also, considering that awareness is likely not an all or none phenomenon (Kouider et al. 2010; Windey et al. 2014) and may be best conceived as a gradual property. There are at least a few neural mechanisms for WM functions, including: synaptic mechanisms for information maintenance (i.e. through calcium kinetics in task-relevant neural substrates) (Mongillo et al. 2008), persistent neural firing (Sreenivasan et al. 2014), and oscillatory network coherence (Palva and Palva 2012). One could hypothesize that persistent neural activity could reflect the *conscious* use of memory contents for cognitive control, conscious reflection, or manipulation of relevant memoranda. Synaptic memory mechanisms or specific states of functional connectivity (e.g. frequency-specific network coherence), on the other hand, can provide alternative (silent) coding scheme for WM in the absence of persistent neural firing (cf. Stokes 2015), which could support the maintenance of "nonconscious" information over short periods of time. The expression of these neural mechanisms for WM and how they relate to awareness is also likely to be modulated by the complexity of the information and/or the computations required to solve the task. Hence, it is unlikely there is a binary response to the question of whether WM can operate outside awareness.

In summary, the development of new psychophysical protocols to probe WM processes stemming from cues associated with null sensitivity may be useful but, notably, constraints due to weakening the cue signal may only reduce the likelihood of nonconscious signaling for WM and hence little WM effects on behavioral measures. We believe that a more fruitful avenue for future research is to take the subjective reports of awareness at face value and test the neural differentiation of WM processes across the different states of (un)awareness, while considering the diversity of WM types, task contexts, and object-level domains in which WM and awareness operate. In this vein, a recent MEG study combined the nonconscious WM paradigm from Soto *et al.* (2011) with cutting edge decoding analyses to track moment-to-moment changes in the neural representations of conscious and nonconscious memoranda and demonstrate the existence of qualitatively distinct, selective mechanisms for keeping information in WM across different states of (un)awareness (King *et al.* 2016).

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