

## Towards a neurobiology of internal selective attention

Freek van Ede<sup>1</sup> & Anna C. Nobre<sup>2,3</sup>

<sup>1</sup>*Institute for Brain and Behavior Amsterdam, Department of Experimental and Applied Psychology, Vrije Universiteit Amsterdam, The Netherlands*

<sup>2</sup>*Department of Experimental Psychology, University of Oxford, United Kingdom*

<sup>3</sup>*Oxford Centre for Human Brain Activity, Wellcome Centre for Integrative Neuroimaging, Department of Psychiatry, University of Oxford, United Kingdom*

Correspondence to: [freek.van.ede@vu.nl](mailto:freek.van.ede@vu.nl) (F. van Ede), [kia.nobre@psy.ox.ac.uk](mailto:kia.nobre@psy.ox.ac.uk) (A.C. Nobre)

-----  
Keywords: Working memory, Visual, Retrocue, Selection, Prioritisation, Spatial

**A recent study in non-human primates by Panichello and Buschman brings the investigation of selective attention within visual working memory to the systems and cellular neuroscience levels. We reflect on this breakthrough in light of nearly twenty years of related research in humans and highlight some of the lessons to help frame future work.**

It is now widely appreciated that selective attention continues to operate on sensory representations maintained ‘in mind’ (in working memory), to select and prioritise these in service of behaviour [1]. This may seem a straightforward and foundational principle to those less familiar with the classical literature. Yet, for a long time, since its early empirical study, visual working memory was considered to be impervious to selective attention. In 1960, Sperling [2] showed that attentional post-cues, presented after a brief visual display, were ineffective at boosting access to encoded information, unless presented immediately (within ~500 ms) after encoding – suggesting no role for selective attention beyond the iconic sensory buffer. This longstanding tenet was only challenged in 2003 when it was shown that attention-directing retrocues – this time targeting representations that had already been consolidated into working memory up to seconds earlier – can be utilised to improve ensuing memory-guided behaviour (reviewed in [1]). Such benefits become especially clear when retrocues are followed by an interval during which attention can access and influence cued memory content to prepare for the upcoming task.

Over the past ~20 years, we and others have extensively studied such ‘internal selective attention’ in humans. We have learned that internal attention is a rich and multifaceted phenomenon (**Figure 1**) that can be driven by multiple voluntary and involuntary sources [3], target various representational contents [4], and act through multiple stages – including orienting, selection, (re)prioritisation, and transformation – to optimise internal representations for behaviour [1,5].

### ***Taking the study of internal selective attention into the brain***

Using cellular recordings in non-human primates (NHPs), Panichello & Buschman (P&B) [6] launch the investigation of the cellular and systems-level mechanisms of internal selective attention. They offer proof of principle that NHPs can (be trained to) use retrocues to deploy selective attention within working memory, providing a foothold for a neurobiologically grounded understanding of internal selective attention.

In their task, P&B used symbolic cues to direct NHPs to report the colour of either the upper or the lower visual item after a working-memory delay. The cue occurred either as a precue, before memory encoding (enabling *external* selective attention; “attention” in P&B) or, critically, as a retrocue, during the memory delay (enabling *internal* selective attention; “selection” in P&B).

P&B report three central findings. First, the spatial focus of internal selective attention – mediated through the memorised item location – could be decoded from firing-rate patterns in each recorded area: Lateral Prefrontal Cortex (LPFC), Frontal Eye Fields (FEF), Parietal cortex, and Visual area 4 (V4). Decoding emerged

first in LPFC, where a ‘shared code’ was identified that generalised between external and internal selective attention. Second, internal attention boosted colour information associated with the cued memory item across frontal and parietal areas (but, interestingly, not V4). Third, internal attention transformed the cued item into a new neuronal subspace that was invariant to the item’s original location. In line with previous proposals [1], P&B suggest the transformation prepares the selected item for the upcoming task. Future studies directly manipulating task demands can test this interpretation.

### ***Comparison to human literature***

When comparing the study by Panichello and Buschman to internal-attention studies in humans, three aspects are worth highlighting.

First, human studies standardly include control conditions necessary for assessing behavioural benefits (conditions with no, neutral or invalid retrocues). In P&B, retrocue utilisation is evident from the neural data, yet the degree and quality of behavioural benefits remain unclear, making direct comparisons to the human literature difficult.

Second, in P&B, after selecting the cued memory item, the other item could be dropped from memory altogether. One of the most interesting and distinguishing properties of internal attention revealed by human studies is the ability to prioritise items flexibly and reversibly [5,7]. One item can be selected for imminent use while other items can be retained (unattended but not forgotten), and re-prioritised subsequently when needed. Clarifying the neurobiological mechanisms of such flexible (re)prioritisation, and the transformations involved, is a major possible contribution of future neurophysiological studies. One can envision, for instance, that while transformation to a spatially invariant code may be effective when the non-cued item can be dropped from memory, a different transformation may support the more delicate act of (re)directing priority among multiple memoranda.

Third, P&B controlled for eye movements by including in their analyses only trials in which gaze remained within two degrees from fixation. Our recent work, using highly similar tasks, has revealed robust microsaccadic biases toward the memorised location of attended memory items [8] that reside almost completely under the two-degree threshold. It will be informative to test whether similar gaze biases accompany internal attention in NHPs, and how these relate to cellular signatures of internal attention.

### ***Future opportunities***

The P&B study makes a pivotal step toward a neurobiological understanding of internally directed selective attention. In closing, we share considerations and directions for building on this landmark demonstration.

First, it will be important to consider the richness of the phenomenon under investigation. Mechanisms, such as the reported frontal-to-parietal cascade of neural recruitment, may well be different when internal attention is involuntarily captured by sensory events [3] or driven by internal states [7], as opposed to when explicitly instructed by a cue. Relatedly, how might internal attention operate when directed at feature dimensions across multiple items [4]? It will also be important to adopt consistent nomenclature, as ‘internal selective attention’ encompasses multiple stages of which “selection” is but one (**Figure 1**).

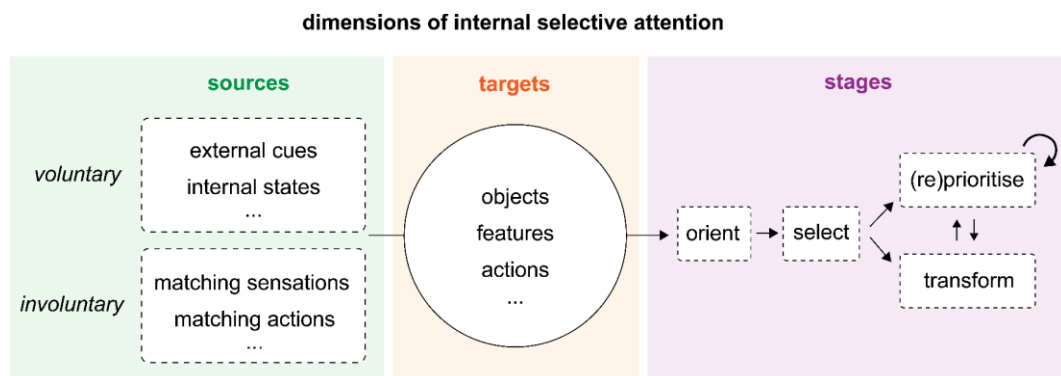
Second, in future work, it would be valuable to conduct analyses of network dynamics (local field potentials and inter-areal connectivity), and to record from additional areas (including sub-cortical structures like the superior colliculus given the aforementioned link between internal focusing and microsaccades [8]).

Third, like the reported comparison between internal and external sensory selection, the comparison between internal selection of sensory representations and action plans may yield important insights – not least since action selection is another form of ‘internal attention’ with a strong tradition in neuroscience [9]. Considering sensory and motor selection together [10] can help integrate fields and redirect research focus from ‘how memories are maintained’ to ‘how memories serve behaviour’.

Finally, while P&B emphasized the ‘shared nature’ of internal and external selective attention, one should not overlook the fascinating differences between them [1]. The lack of generalisation in neuronal decoding of attention (that P&B observed in all areas except LPFC) is one pointer in this direction. External and internal attention share the purpose of prioritising task-relevant information, but they operate on different representational substrates. In working memory, attention must operate on information that has already been extracted from the sensory stream. The properties of these representations may be optimised for separation and protection from other items, and may endow internal representations with the unique ability to shift flexibly in and out of focus to serve behaviour in a dynamically unfolding world.

## References

1. Nobre, A.C., and Stokes, M.G. (2020). Memory and attention: the back and forth. In *The Cognitive Neurosciences*, M. Gazzaniga, ed. (Cambridge: MIT Press).
2. Sperling, G. (1960). The information available in brief visual presentations. *Psychol. Monogr. Gen. Appl.* 74, 1–29.
3. van Ede, F., Board, A.G., and Nobre, A.C. (2020). Goal-directed and stimulus-driven selection of internal representations. *Proc. Natl. Acad. Sci.* 117, 24590–24598.
4. Niklaus, M., Nobre, A.C., and van Ede, F. (2017). Feature-based attentional weighting and spreading in visual working memory. *Sci. Rep.* 7, 1–10.
5. de Vries, I.E.J., Slagter, H., and Olivers, C.N.L. (2019). Oscillatory control over representational states in working memory. *Trends Cogn. Sci.* 24, 150–162.
6. Panichello, M., and Buschman, T. (2021). Shared mechanisms underlie the control of working memory and attention. *Nature*. Available at: <https://doi.org/10.1038/s41586-021-03390-w>.
7. van Ede, F., Niklaus, M., and Nobre, A.C. (2017). Temporal expectations guide dynamic prioritization in visual working memory through attenuated  $\alpha$  oscillations. *J. Neurosci.* 37, 437–445.
8. van Ede, F., Chekroud, S.R., and Nobre, A.C. (2019). Human gaze tracks attentional focusing in memorized visual space. *Nat. Hum. Behav.* 3, 462–470.
9. Cisek, P. (2007). Cortical mechanisms of action selection: the affordance competition hypothesis. *Philos. Trans. R. Soc. B Biol. Sci.* 362, 1585–1599.
10. van Ede, F., Chekroud, S.R., Stokes, M.G., and Nobre, A.C. (2019). Concurrent visual and motor selection during visual working memory guided action. *Nat. Neurosci.* 22, 477–483.



**Figure 1. Dimensions of internal selective attention.** Left: similar to external selective attention, internal selective attention can be mediated by both voluntary and involuntary sources [3] and driven by external cues (as in P&B, [6]) as well as by internally generated states such as temporal expectation [7]. Middle: internal selective attention may target memoranda at various levels of representations including items (objects) at specific locations (as in P&B), features shared across multiple items [4], and item-specific action plans [10]. Right: internal selective attention may help prepare internal representations for upcoming behaviour through multiple stages including orienting to relevant aspects of representations, as well as their selection, flexible (re)prioritisation, and transformation to action-ready states [1,5–7,10].

**Acknowledgements**

The authors were supported by an ERC Starting Grant from the European Research Council (MENTICIPATION, 850636) to F.v.E., a Wellcome Trust Senior Investigator Award (104571/Z/14/Z) and a James S. McDonnell Foundation Understanding Human Cognition Collaborative Award (220020448) to A.C.N, and by the NIHR Oxford Health Biomedical Research Centre. The Wellcome Centre for Integrative Neuroimaging is supported by core funding from the Wellcome Trust (203139/Z/16/Z).

**Declaration of Interests**

Anna C. Nobre is a member of the advisory board of Trends in Neurosciences. The authors declare no other competing interests in relation to this work.