Trends in
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Spotlight

About time: modelling dynamic voluntary attention

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Goal-directed behaviour requires flexible prioritisation of relevant sensations in space and time. A recent paper by Denison *et al.* brings time into a canonical model of voluntary selective attention. We reflect on this breakthrough and consider the opportunities it offers for future research on the dynamic fabric of mind.

Goal-directed behaviour relies on voluntary selective attention to flexibly prioritise sensations that are most relevant to current and anticipated goals. To date, theoretical models of voluntary selective attention have predominantly considered static contexts where sensory representations compete only in space. However, in real-life situations our minds are immersed in a dynamically unfolding world in which continuous streams of sensory inputs compete for processing also across time. Hence, voluntary selective attention cannot be fully captured without accounting for its temporal dynamics (also Box 1). In a recent article, Denison, Carassco, and Heeger [1] provide a pivotal step forwards by adapting an influential 'normalisation model' of attention [2] to formalise and quantify how voluntary selective attention is deployed over time.

Modelling and quantifying voluntary selective attention across time

Denison *et al.* used an innovative visual discrimination task to investigate how voluntary selective attention can flexibly prioritise one of two stimuli that appear in sequence, separated by an interval between 100 and 800 ms. After seeing both stimuli, a response cue instructed participants to report the tilt of either the first or the second stimulus. Crucially, before presenting the two stimuli, an auditory pre-cue indicated which stimulus would be 75% likely to become probed for report later, allowing participants to voluntarily prioritise this stimulus over the other in time. When pre-cues directed voluntary attention to the first stimulus they conferred a behavioural benefit – at the expense of a cost to visual discrimination of the second stimulus. Thus, foreknowledge led to an attentional trade-off ('biased competition') between the two stimuli in time. This trade-off depended on the interval that separated the stimuli, and showed the largest benefits through voluntary attention when both stimuli occurred within 200–400 ms.

Behavioural data from this task were used to constrain the novel dynamic normalisation model of attention. In this model, voluntary attention is instantiated as a transient increase in neural gain at the attended moment, followed by a depletion of resources and a gradual, linear recovery. Although other models previously described temporal trade-offs in attention (e.g., [3]), Denison *et al.* provide a direct link to a canonical normalisation model of spatial attention [2] and focus specifically on voluntary control over temporal trade-offs in attention.

The new model provides – and enables – two major advances. First, it provides a theoretical formalisation for voluntary trade-offs over time in a widely used model that is neurobiologically grounded. Second, it allows researchers to estimate latent variables relating to the temporal parameters ('time constants') of attention. For example, the authors estimated that it took ~1 s for attentional gain to recover.

Because all behaviour is constrained in time, the formalisation and estimation of dynamic voluntary attention may have broad relevance beyond the specific task employed in [1]. In the following we therefore first reflect on the findings in light of the unique task properties, before outlining promising future directions opened by this landmark demonstration.

Temporal task properties and their theoretical relevance

First, the participants in [1] were required to temporarily store two stimuli in memory

Box 1. What is the 'time' in temporal attention?

The term 'temporal attention' has been used in relation to various related but distinguishable phenomena that we break down below.

First, since the early studies of attention, researchers have considered the time-course of spatial attention – in other words, how long it takes for observers to plan and execute shifts of attention.

Other studies (e.g., [1,6]) predominantly focus on the dynamics of temporal gating mechanisms and study the selective temporal filtering – or the integration – of information that appears in close temporal succession.

Further studies have focused on the anticipatory deployment of attention, guided by temporal structures that afford temporal predictions [5]. Unlike studies on temporal filtering, these studies typically consider the processing of a single perceptual target that occurs at a more/less anticipated moment.

Another line of research is dedicated to continuous attention – the intrinsic dynamics and limitations of attention deployment over time at longer timescales [10]. How the model presented in [1] may apply to such timescales is another interesting open question.

Ultimately, the above elements in this non-exhaustive list are interrelated. Computational models such as that in [1] may provide one avenue to foster integration between these flavours of temporal attention that are still rarely considered together.

until a cue instructed which stimulus to report. Accordingly, the trade-off in performance may occur (i) during stimulus processing, and/or (ii) at a post-perceptual stage when consolidating or later prioritising either of the two items in working memory [4]. Although the observed temporal specificity argues for a perceptual effect, additional contributions from memory-related processes cannot be entirely excluded. Relatedly, the process of consolidation into working memory – that may itself take additional time and resources – may influence the estimated 'temporal parameters' attributed to selective attention.

Second, both targets in [1] were always fully predictable in time. It therefore remains open whether voluntary temporal trade-offs resulted from (i) differential anticipation before the two stimuli, and/or (ii) differential prioritisation of the two stimuli during (or after) sensory encoding. This pertains to the relevant distinction between 'temporal anticipation' (orienting attention to relevant moments) and 'temporal filtering' (prioritising among stimuli that compete in time) [5] (Box 1). Indeed, one can benefit from anticipating a single stimulus at a particular moment in time without needing to filter it from another – but one can also prioritise one stimulus over another in time without being able to anticipate the timings of either. Additional manipulations of onset predictability could disentangle the relative contributions of both processes and charter how temporal anticipation may change the filtering of stimuli in time [6].

Future directions

Flexibility is a hallmark of voluntary attention. Denison *et al.* demonstrate and formalise how attentional trade-offs in time are under voluntarily control. An important next step is to address to what extent the specific parameters that define voluntary attention, such as its temporal distribution, can also be flexibly adapted to task demands – akin to the adaptation of the spatial distribution of attention by spatial task demands [7]. For example, voluntary attention may be deployed differently across time when anticipating a target followed by a distractor [6] instead of two potential targets. Akin to spatial selection [8], observers may strategically prepare to reject irrelevant information at particular moments. This might be achieved by a proactive reduction of gain at the anticipated distractor time – a possibility that remains to be tested and modelled.

Second, temporal anticipation of the most relevant stimulus in [1] was instructed via explicit cues. Cued associations are one of several 'temporal structures' that may guide attention in and across time [5]. It remains to be tested whether different results and model parameters would be obtained when temporal anticipation is driven, for example, by rhythmic regularities which may rely on distinct mechanisms [9].

Finally, Denison *et al.* have elegantly demonstrated how the canonical computational model of attentional competition in space can be adapted to similarly account for voluntary control over competition in time. Ultimately, attention must handle sensory competition not in either space or time, but both space and time. The work presented in [1] provides a crucial first step towards a next generation of models that will help us understand how attention enables flexible behaviour in the rich and dynamic environments that we face in everyday life.

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Declaration of interests

The authors declare no competing interests.

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