



# Visual marking: using time in visual selection

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**Given human capacity limitations, to behave adaptively we need to prioritise the order of visual processing to ensure that the most relevant information is available to control action. One way to do this is to prioritise processing at a particular location in space. However, there are many situations where this strategy is not possible and recent studies have shown that, in such circumstances, observers can use time as well as space to prioritise selection. We propose that selection by time can be influenced by a process of visual marking, involving an active bias applied in parallel against old items in the field. Here we describe the properties of visual marking in relation to other mechanisms of visual selection.**

The visual world contains vast amounts of information, only some of which is relevant to our behaviour. Hence we need mechanisms that enable us to select the most relevant information for our current goals. For example, imagine looking out for the appearance of a predator in a scene containing many objects. There is clearly an adaptive advantage in being able to prioritise the selection of the newly appearing predator at the expense of the other items already visible. In other words, it would be useful if we could select stimuli based on their time of appearance – how might we do this?

## Selection by space, object and time

Visual selection has historically been likened to a spotlight or variable resolution zoom lens [1,2] operating in both 2D and 3D coordinates [3,4] with stimuli falling within the ‘illuminating’ beam receiving enhanced processing. The processing of an item can then be prioritised by ‘selecting’ its location from a background of distractors [5]. Previous research has concentrated on how visual attention might be allocated to a particular location in space [2], a particular object [6,7] or guided to locations that contain specific features or object properties [8,9].

Although space or object-based selection can often be effective, consider our example of looking out for a predator. Attention cannot be consciously applied to a particular location in advance, because we do not know where the target will appear. Likewise, if the visual features of the target are unknown, the attentional system

cannot be set to bias [10,11] or guide attention to items containing particular features [8]. However, several findings suggest that the predator is nonetheless likely to be detected relatively efficiently by default. First, there is evidence that attention is passively biased against returning to previously attended locations, a process called inhibition of return (IOR), applied to each location attended in series [12–14]. Once each old object has been attended and subjected in turn to IOR, selection will be biased to favour new stimuli (at previously unattended locations). Second, Yantis and colleagues over the past fifteen years or so have shown that, by default, new objects can themselves capture our attention in a relatively automatic manner [15–19]. Typically, participants have to detect a target in a display that contains several old objects that change shape when a single, perceptually new object appears. The results suggest that attention is attracted to the new object even if it is not the target.

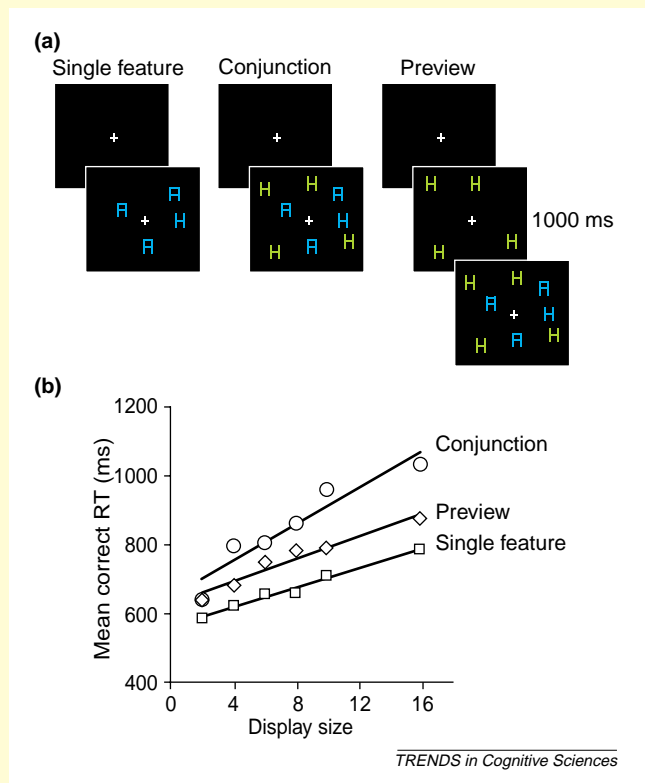
However, there are limits to these passive and apparently automatic processes. For instance, IOR is applied only to the last 4 or 5 examined locations [20]. Similarly, attention seems to be captured by a maximum of ~4 items [19]. On the basis of these processes either only a limited number of objects can be ignored (IOR) or attention can only be prioritised to a subset of several new objects (automatic capture), even if it might be useful to prioritise them all. Furthermore, any prioritisation of new stimuli should ideally not be dependent on changes in low-level properties of the old items – for instance, whether they change luminance (a passing cloud overhead) or move (wind blowing a bush). Processes that respond automatically to low-level dynamic changes (e.g. onsets of new objects) would be vulnerable to similar changes in old objects too. Efficient but flexible selection of multiple stimuli, based on their new temporal occurrence, might require mechanisms other than IOR and automatic attention capture. We argue that one such additional mechanism is ‘visual marking’ (VM). The evidence for VM came originally from studies of visual search over time (‘preview search’), and we outline these studies now to motivate the argument for marking.

In an initial study, Watson and Humphreys adapted a classic colour–form conjunction task [21] so that one set of distractors (the old items) appeared for 1 s before the other (new) items [22]. When present, the target always appeared with the new items. Search was as efficient in

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### Box 1. The basic preview paradigm

In visual search tasks observers indicate the presence or absence of a pre-specified target among a varying number of distractors [21,50] (Fig. 1a). In difficult search tasks it takes longer to determine if the target is present as a function of number of items in the display (the display size). Thus the slopes of reaction-time vs. display size can also be used to determine how many items are being searched. In the preview condition, one set of distractors is previewed before the remaining items. If search can be restricted to just the new items then the preview search slope should match that of the single-feature baseline (as shown in Fig. 1b). By contrast, if old items cannot be ignored then it should match that of the conjunction baseline. In the first papers on visual marking, the preview condition was called the gap condition and the resultant increase in search efficiency was called the gap effect. In more recent papers, the term gap condition has been replaced with preview condition and gap effect with preview benefit. These new terms are more descriptive of the task and less confusable with other uses of the word gap in the psychological literature. It is also important to distinguish between the observation of improved search efficiency in the preview condition – the preview benefit – and the possible mechanisms for achieving this, such as inhibitory visual marking.



**Fig. 1.** Visual search and preview paradigm. (a) Search for a single feature (a blue H), a colour-form conjunction search, and a preview search in which one set of distractors is seen before the search display. (b) Results showing that the slope for the preview search (corresponding to an average 16.2 ms/item) matches that of the single feature search (14.0 ms/item) rather than the conjunction search (26.1 ms/item). This indicates that the previewed items can be ignored in the search. (Data redrawn from Ref. [22] Experiment 1).

this *preview* condition, as it was in a condition in which only the second set of stimuli was presented, and it was considerably more efficient than in the standard conjunction baseline (in which all the stimuli appeared together) (see Box 1). This improvement in search has been labelled the *preview benefit*. The characteristics of the preview benefit are listed in Table 1.

The preview benefit does not require a simple feature difference between old and new items [23–25] and it is found with moving and stationary stimuli alike [23,25,26]. Importantly it occurs with up to 30 or more old stimuli [27], and 15 new items [24] and so is not subject to the capacity constraints that limit automatic attention to new objects [19] or IOR [20]. Furthermore, the benefit is slow-acting; old and new items have to be separated by ~400 ms or more for efficient preview search to occur [22] – an interval considerably longer than the time difference necessary for any automatic capture of attention by new items (~100 ms [28]).

In addition, the benefit is reduced if participants carry out a secondary task during the preview period [22,29,30]. Both auditory and visual secondary tasks are disruptive if presented when the preview first appears, whereas only visual secondary tasks are disruptive when time is allowed first to encode old stimuli [29]. These effects of secondary tasks suggest that, to optimise selection of new stimuli, active processes must be engaged when the old items are present. Furthermore, the differential disruption depending on secondary task modality indicates that these processes can be separated into an initial encoding of the old items (affected by visual and auditory secondary tasks alike), followed by the maintenance of this representation (affected more by visual tasks).

#### VM: an active bias against old stimuli

One reason why it might be useful to encode and maintain a representation of old stimuli is that it allows an active bias to be used against them – the process of VM. Old items, encoded as a group, can be rejected in parallel, unlimited by capacity constraints. Evidence for this active bias comes from studies using ‘probe-dot’ detection tasks. Watson and Humphreys [31] had participants engage in a search for new targets on a majority of trials, interspersing occasional trials where a probe (a small dot in the display) had to be detected. Probes at the locations of old items were particularly difficult to detect, compared to probes at the locations of new items. Interestingly there was little

**Table 1. Summary of the characteristics of the preview benefit**

- Requires ~400 ms between old and new stimuli
- Is effective with at least 30 old and 15 new items
- Requires the commitment of limited capacity resources
- Contains dissociable set-up and subsequent maintenance components
- Occurs with stationary and moving stimuli
- Is disrupted by shape and motion but not by colour or luminance changes to old items
- Is affected by separate grouping of old and new stimuli (based on time, motion, colour)
- Is disrupted by colour similarity between the old and new stimuli
- Survives occlusion
- Can be ‘topped up’ by the earlier presentation of the preview within the same trial [53]
- Is mediated by earlier and increased activation in the superior parietal lobule/precuneus and associated with a sustained negative waveform in ERP
- Is reduced when new stimuli are isoluminant with their background
- Shows an age-related deficit with moving stimuli [54] but not with stationary stimuli [54,55]

### Box 2. Using probe-dots to investigate the preview benefit

Evidence that old items are ignored by inhibiting them has been found using a probe-dot detection paradigm (Fig. 1). In one study [31] observers searched for a blue H target on the majority of trials and, on the remaining trials (signalled by a brief tone), they had to indicate whether a probe-dot was present or absent (data from 'present' trials only shown here). Probe detection was much worse at the location of an old previewed green item than at the location of a new blue item. By contrast, there was a much smaller difference in accuracy between

probe-dots presented at green and blue item locations when (i) all items appeared simultaneously, preventing the old items from being marked (conjunction condition), or (ii) when all trials were probe trials, removing the rationale for inhibiting any of the old items (but keeping the timing relations between the items constant). This type of paradigm provides converging evidence that the preview benefit involves inhibition of old items and that it is under voluntary control of the observer (see also [30]).

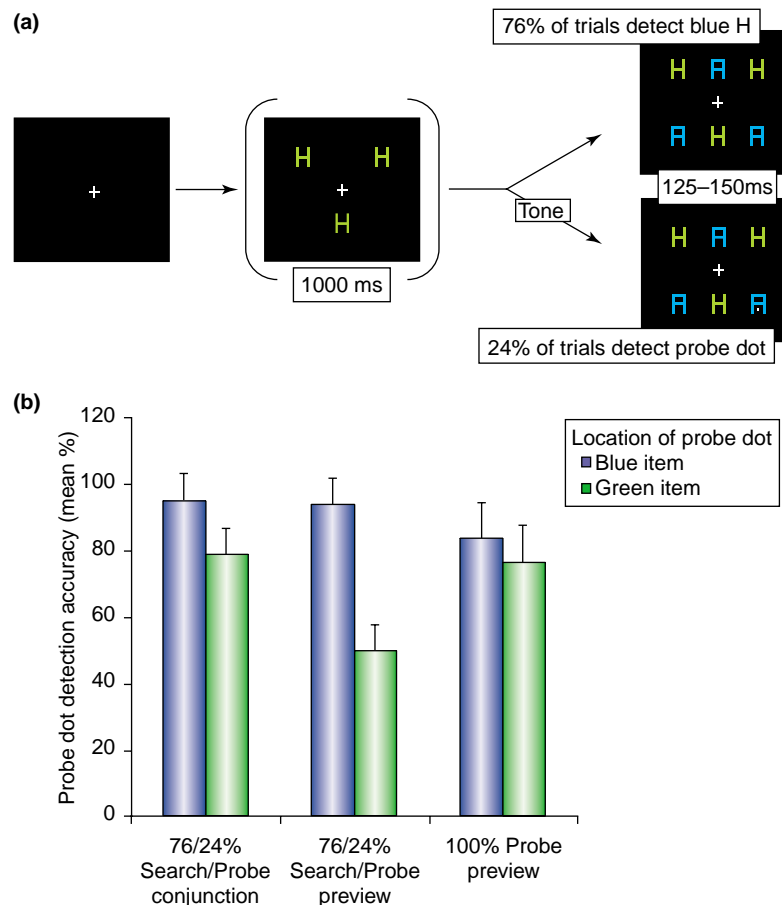


Fig. 1. Probe-dot detection paradigm. (a) In some trials, a tone indicates to the subject that they should signal the presence or absence in the display of a probe dot. (b) Results of an experiment showing the dependence on preview (see text for discussion). (Data redrawn from Ref. [31]).

difference in probe detection at new and old locations when probe detection rather than search was the dominant task (see also [30]; Box 2). Thus poor detection at old locations was not simply due to the time relations between the displays, but rather to an active intentional bias used in search over time. Recent studies have shown further that probe detection at old locations actually improves if participants engage in a secondary task when the old items are first presented [30]. Apparently the bias against old locations is most effective when there is no interference during the initial encoding process.

The nature of the bias itself seems to depend upon the characteristics of the old stimuli. For instance, VM can apply to old locations when the stimuli are stationary [22,31], or maintain a set configuration [25], but it can also be applied to a common feature if the old items move (e.g. to their colour

[26]). This fits with ecological and computational constraints on visual processing. A location-based bias is useful because it allows old items to be rejected even if they do not share features. However, a bias against common features could be adaptive when objects move because it removes the need to simultaneously track the changing old locations – a process likely to be computationally expensive and limited to a few items [32]. There is also evidence of a bias against common features even when the old items are stationary [33], presumably because grouping by common feature supports suppression of the old set as a single entity [34].

#### What if old items change?

If VM provides a useful means of prioritising attention to new stimuli outside of the laboratory, then we would expect it to be sensitive to ecological constraints. For example,

changes to old objects should be important primarily if they are relevant to current behavioural goals, and they should be less important if they reflect transitory changes in the environment. When the task is to identify a target based on its shape (remember our example of looking for a predator), then changes in shape should be important but not changes in the colour or brightness of old items. This turns out to be the case [35]. Indeed, even having the old items disappear and re-appear with the new stimuli is not crucial, provided any disappearance is consistent with the old items being occluded [36].

Taken together, the results indicate that an active, intentional bias against old stimuli can contribute to the efficient selection of new items as a single group. In **Box 3** we outline a functional architecture for VM.

### *Neural mechanisms*

What brain areas might be involved in implementing a bias in selection against old items? Recent studies using ERP [37] and fMRI [38] provide some indications. For example, there is ERP evidence of a sustained negative waveform under conditions of an active bias against old items in search [37], with this being most pronounced over fronto-parietal regions. fMRI evidence shows earlier and more pronounced activation in superior parietal cortex (precuneus) in preview search relative to baseline search conditions where old items are present but not actively ignored [38]. Interestingly, this early activation in the superior parietal lobe is distinct from the activation in the temporo-parietal junction region associated with the ease of selecting new items [39]. The superior parietal activation apparent in fMRI might reflect the coding of a spatial map of old locations or the operation of the bias in selection itself.

### **Alternative accounts**

Do we need to propose a new mechanism of selection, VM, to explain performance? Certainly it is possible (and even likely) that other mechanisms contribute to the efficient selection of new stimuli, but we suggest that none can provide a complete account of known results.

### *Inhibition of return*

As detailed earlier, IOR is a passive mechanism that biases attention and eye movements away from locations that have previously been attended in series [12–14]. However, the capacity of IOR seems too small to account for preview search. Moreover, recent work has shown that any preview benefit is greatly reduced if participants conduct a serial search on the first set of items (although this ought to produce maximum IOR) [40]. The efficient bias against old items does not come about through the serial application of IOR to old locations. Nevertheless, there are grounds for arguing that IOR is not a single process, and that there are distinct object-based and spatial components [41]. It is possible that object-based IOR, biasing selection against previously attended objects, is similar to VM, although the studies of marking indicate that the process would need to be applied intentionally [30,31] and to be sensitive to different factors depending on the properties of the stimuli [23,26]. The evidence from

functional brain imaging also suggests that distinct brain regions might modulate VM and IOR (compare Refs [38] and [42]).

### *Automatic onset capture*

Donk and Theeuwes [43] have argued that the preview benefit can be explained fully by automatic attention capture by the onsets created by new stimuli. They based their argument on a failure to find a preview benefit when new items appeared under isoluminant conditions. This suggests that new stimuli need to be accompanied by a luminance change to be selected with high priority, although it should also be noted that search for isoluminant stimuli is often difficult, perhaps because the locations of such items are not accurately coded. Factors such as this, rather than isoluminance *per se*, might be critical; for example, marking might require that the locations of old and new items be clearly segregated. It could also be that luminance onsets are critical for prioritising search to new objects because marking acts on a location map sensitive to luminance change. Moreover, the capacity limits of automatic attention capture [19], its relatively fast time course (compare Ref. [22] with [28]), and its sensitivity to local luminance change (unlike preview search; [35,36]) indicate that it cannot provide a full explanation. The automatic, new-onset account also fails to predict secondary task interference on the preview benefit, and the positive effects of secondary tasks on probe detection [22,29,30]. In one recent study, previews were also shown to reduce attentional capture by a salient singleton in the new display, when the singleton shared features with the old items [33]. This should not occur if attention was automatically drawn to the new stimuli simply by virtue of their being new onsets.

### *The temporal asynchrony account*

One other account [44] attributes the preview benefit to the separate temporal grouping of old and new stimuli, which can then be attended selectively (without any need to propose a further inhibitory bias). However, this fails to explain factors such as: differences in probe detection on new and old items under search conditions, why secondary tasks disrupt preview search, and why some but not other changes to old stimuli disrupt search [35].

### **Relationship to other high level mechanisms**

It is also important to review the relations between VM and other aspects of visual cognition. Here we consider the relations between VM and the phenomena of change blindness, inattentive blindness and the attentional blink.

### *Change blindness*

People are very poor at detecting changes to sequentially presented scenes if the transients that would normally accompany the change are masked ('change blindness'; [45,46]). Rensink [45] proposed that, at one time, we process only a limited amount of information, held in a dynamic temporary representation (the nexus). Only changes to information represented in the nexus can be detected. The template representation, which we suggest

### Box 3. A functional architecture for visual marking

We propose that visual marking (VM) is dependent on the adoption of an inhibitory goal state (Fig. 1). This supports the encoding and maintenance of a representation of the old items (the inhibitory template), which is used to coordinate the rejection of old items from the subsequent search process. Inhibition is location-based for stationary stimuli or for moving items that maintain a fixed configuration, in which case a motion-transform could be applied to maintain the alignment of inhibition to the old items [25]. For moving stimuli that do not maintain a fixed configuration, inhibition could be applied to a neural map involved in coding a feature in common across the old set [51]. Inhibition reduces the salience of all items coded by that map, making them less likely to compete for attention. Certain types of changes to old items effectively reset

inhibition at the level of location or feature map depending upon their match to the template representation [35]. Other goal states set up to perform additional tasks interfere with VM by (i) competing for control of behaviour when the inhibitory template is encoded and (ii) competing for common visual representations (e.g. maintaining positions in the location map) [29]. Studies of secondary task interference have shown that both auditory and visual secondary tasks disrupt search when they begin at the same time as the preview. We attribute this to competition for the initial control of behaviour, disrupting the encoding of the old items. However, when sufficient time has elapsed to encode the preview, only visual secondary tasks interfere [29]. We attribute this to modality-specific disruption to the maintenance of the representation of the old items.

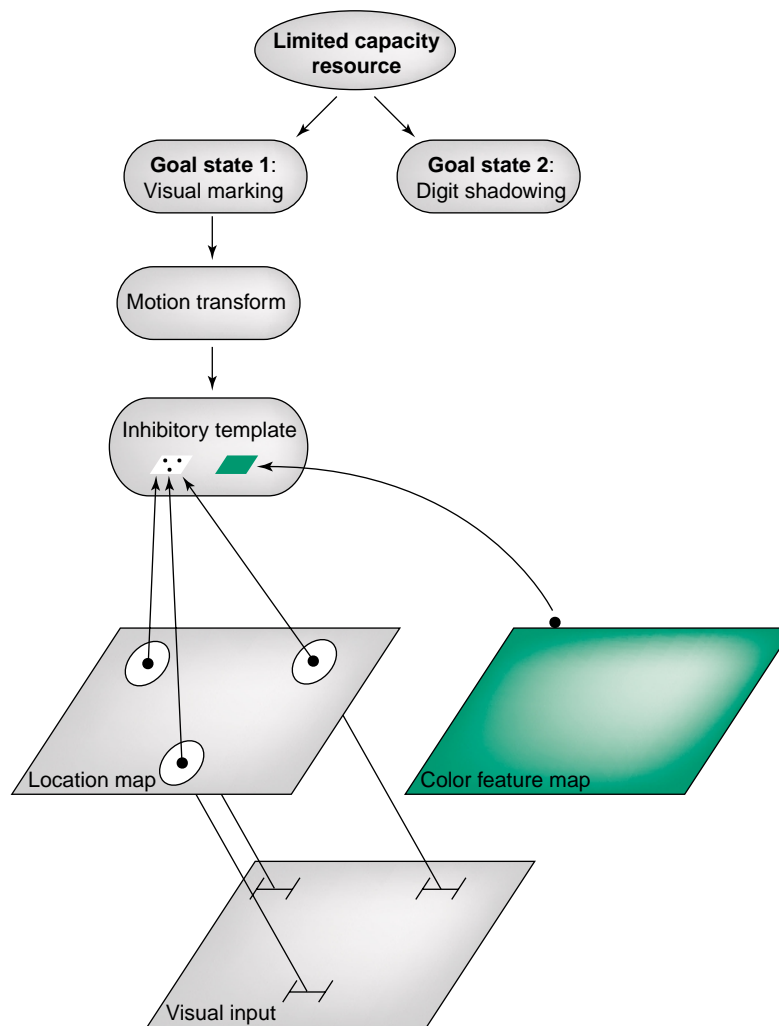


Fig. 1. A model for visual marking, where an inhibitory goal state is adopted that allows old items to be rejected from subsequent search (see text for details).

modulates VM, could well be similar to the nexus (Box 3), except that, under conditions of preview search, observers are biased against selecting stimuli with properties represented in the template; by contrast, observers presumably attend to the nexus to detect change. Capacity limits in the template representation might be minimized by grouping and treating the old items as a single entity.

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#### Inattentional blindness

When we ignore one set of stimuli on the basis of a common property, we are poor at detecting new items with this ignored property – so-called inattentional blindness [47]. Inattentional blindness could well be brought about by VM, and indeed the effect of VM on attentional capture by new singletons [33] seems similar in kind to inattentional blindness.

#### Box 4. How robust is the preview benefit?

If visual marking (VM) is to have any useful role in real world selection tasks then we would expect it to be observable in a variety of tasks. To date, VM has been studied using detection [22], localization [30] and orientation discrimination tasks [27]. Effects have been observed in conditions where the number of old and new stimuli are varied together equally [22], varied orthogonally [24] or when the number of new items remain fixed [44]. Effects also arise in both easy and difficult search tasks, and they might even be stronger under more difficult search conditions [52]. The robustness of the effects across several selection tasks and conditions points to the likely utility of VM for cases where search is across time as well as space.

#### Box 5. Questions for future research

- It is likely that visual marking operates *in addition* to other more passive mechanisms that help to prioritise the selection of new items. What is the relative contribution of the passive mechanisms and how do they interact with visual marking?
- What are the common elements of visual marking to other high-level processes, such as the representations involved in change detection and in object tracking?
- Old stationary items can be ignored purely by location-based inhibition and moving items purely by feature-based inhibition. However, recent work shows that sometimes feature-based inhibition can play a role in ignoring stationary items and that, in some circumstances, moving items can be ignored even when feature-based inhibition is not possible. Sometimes it will be adaptive to use only one type of inhibition whereas in other situations it might be useful to use both. Is the type of inhibition applied under top-down control? If so, how can we measure it, and in what situations will people use each type?
- Changes in the shape and identity of old items seem to re-set marking at those locations. Is this caused by a simple change in shape or does the object also have to change its identity? Can periodic/predictable changes be ignored more easily than random or unexpected changes? What ecological factors modulate these 'change effects'?
- What is the role of visual short-term memory in visual marking? Are 'to-be-ignored' items actively represented in visual short-term memory, and, if so, what are the interactions with the representations of 'to-be-found' items?

#### Attentional blink

After identifying a first target (T1) in a stream of rapidly presented digits, observers are poor at detecting a subsequent target (T2) presented as long as 400 to 500 ms later – this is the 'attentional blink' [48,49]. This time course is similar to that required for an optimal preview benefit [22], which, we suggest, reflects in part the time taken to encode a representation of old items into visual short-term memory (VSTM). The worsening of search performance with short previews might be because this representation is still being consolidated, and the time needed to consolidate targets in VSTM could give rise to the attentional blink. However, once consolidated, we hold that VM involves an extra process of intentional bias against the representation.

#### Conclusion

What has this line of research achieved? We have made the case that selection in time might often be essential for

efficient selection of information, which in turn is necessary for adaptive behaviour. Work on visual marking has shown the extent to which time-based selection is possible and helped to define how it is achieved. This work has provided evidence for a specific mechanism we have called visual marking. Unlike attentional capture by new items and IOR, VM is an active process, applied in parallel to old stimuli, and sensitive to the most useful properties that discriminate old and new items. VM also remains sensitive to changes in old objects that are behaviourally relevant. The wide range of conditions under which marking has been observed (see Box 4), and its ecological properties, attests to the likely importance and robustness of this selection mechanism in the real world, where stimuli are defined by their temporal as well as their spatial properties. We have argued that visual marking is distinct from other selection mechanisms, but it remains a goal for future research to determine the interplay between visual marking and other high level selection mechanisms (see Box 5), and to establish the extent to which visual marking might account for other findings in the field (e.g. sustained inattention blindness).

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