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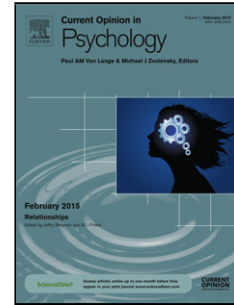
What is a preattentive feature?

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The concept of a preattentive feature has been central to vision and attention research for about half a century. A preattentive feature is a feature that guides attention in visual search and that cannot be decomposed into simpler features. While that definition seems straightforward, there is no simple diagnostic test that infallibly identifies a preattentive feature. This paper briefly reviews the criteria that have been proposed and illustrates some of the difficulties of definition.

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Highlights
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short collection of bullet points that
convey the core findings of the article and should be submitted
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name and include 3 to 5 bullet points
(maximum 85 characters, including spaces, per bullet point)
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- Preattentive features guide attention

- Guidance can be bottom-up (stimulus-driven) or top-down (user-driven).

- Features typically produce efficient visual search and texture segmentation.

- Features may produce visual search "asymmetries", but the issue is somewhat complex.

- It remains unclear if training allows people to learn a new preattentive feature.

About 50 years ago, researchers were doing experiments in which observers needed to look for one type of target among distractor items. For instance, they might have been asked to look for a circle among squares [1]. In some cases, including that search for circles among squares, the reaction time (RT) to declare that the target was present or to declare that all the items were the same did not vary as a function of how many items were presented. The slope of the RT x set size function was near zero. This strongly suggested that the all the items were being processed "in parallel" [2]. In other cases, the RT increased as a roughly linear function of set size, suggesting a serial process [though that need not be the case 3,4]. What made some targets "pop-out"? A leading thought has long been that observers "might have based their decision on a single distinctive *feature*" [p691 of 5]. The idea of a feature took center stage with Anne Treisman's [6] "Feature Integration Theory" (FIT). The theory proposed that a limited set of features

could be identified in parallel across the entire visual field. Any act of object identification that was based on a combination of features would require the deployment of serial attention to the object so that its features could be 'bound' into a recognizable, perceptual whole [7].

While FIT proposed that visual search tasks were either based on parallel detection of a feature or serial binding of features, it became clear that the data produced more of a continuum than a dichotomy [8]. Even when feature information was not adequate to complete a search task, it could be used to *guide* attention toward a target. In a clear example, Egeth and colleagues [9] had observers search for a specific letter among other red and black letters. If observers knew that the target was red, they could restrict attention to the red items, resulting in a search that was more efficient than it would have been if it were not guided by color (Look for the red T in Figure 3, below.). Wolfe et al. [10] argued that you could guide by more than one feature at a time. Thus, in a search for a red vertical, observers could guide to red and to vertical. Triple conjunctions (e.g. find the Big Red Vertical) could be more efficient, given three sources of guidance. See Friedman-Hill & Wolfe [11] for evidence that multiple features guide at the same time.

Not all features guide attention. Many features of the visual stimulus contribute to other aspects of visual perception. Object recognition is, perhaps, the most straight-forward example. Reading this document relies on distinguishing amongst the 'features' of the letters of the alphabet, and subtle properties of shape and texture are used to distinguish one fruit from the next or one make of automobile from others. Some specific examples

of features that do not guide will be mentioned below. A different set of features arise from the convolutional neural networks (CNNs) that have revolutionized object recognition by machine vision. After training, such networks can distinguish between thousands of object classes [12]. These classifications are based on a set of features (typically several thousand) that the network has learned. Those features may turn out to be very similar to the features that support human object recognition. However, it is unlikely that they form a set of guiding features for human visual search. The set of features that can guide human search has been reviewed elsewhere [13,14]. Here, we will briefly review the properties of preattentive/guiding features and how they operate in visual search tasks.

Some definitions

In this field, definitions have always been open to debate. Ever since William James famously asserted in Chapter 11 of his 1890 Principles of Psychology [15] that "Everyone knows what attention is.", it has been clear that everyone knows but no one agrees on the definition; in part, because the term, attention, covers many processes in the nervous system. Here we are referring specifically to visual selective attention; that aspect of visual attention that allows features of an object to be 'bound' into a recognizable object. That definition requires that we define 'bound' and 'binding' [7,16]. That is, perhaps, best done through a figure like Figure 1.

Visual selective attention is the attention required to determine that there are brown and green N's here. Other factors, like crowding [17] play a role in this illustration but some form of scrutiny would be required in any version of this search for specific letters in particular color combinations [18].

Something is seen at the location of brown and green N's before they are positively identified. That experience of oriented regions colored blue, brown, and green can be called "preattentive" because it is what is available before visual selective attention is deployed to those locations, enabling the colors and orientations to be bound into a recognizable green and brown N. Different properties of a stimulus – here colors and orientations – are processed by different specialized parts of the nervous system. "Binding" refers to the process that creates a representation of the stimulus that registers the relationships between those properties as would be required for most acts of object recognition.

This does not mean that there are no attentional demands when the task involves identifying even a simple color or orientation [19] nor does it mean that only the simplest tasks can be done in the near absence of attention. Quite complex tasks such as the categorization of scenes [20] [21] can be accomplished at above chance levels even if the binding of features into recognized objects is prevented. Such tasks are not attention-free [22] [23]. Some type of attention seems to be required for any conscious perception [24].

Selective attention also improves performance on tasks involving preattentive processes [25] (see Carrasco's review in this issue for an extended discussion). The manner in which selective attention does its work is open to debate. We tend to envision selective attention as being deployed from item to item in series [26] [27]. In other accounts, attentional

resources are spread in parallel across multiple items [28-30]. For the purposes of this brief review, when we say "attention", we mean visual selective attention that is needed for object recognition. Its application, however accomplished, takes some time. Something is visible and processed before attention's work is done. That experience and those processes are what we refer to as "preattentive".

How do preattentive features guide attention?

Some featural information is available preattentively. There are three basic ways in which that feature information guides attention in visual search tasks. Bottom-up, stimulus-based guidance is based on local feature contrast.

Thus, in Figure 2, your attention will be summoned to the red and yellow starburst, without any need for instruction. The item differs from its neighbors in color and shape features like "terminator number" [31]. Indeed, it would be hard *not* to attend to that item. In contrast, once you are told what to look for, top-down, user-driven guidance will rapidly get your attention to a big green vertical item. If you are asked about small purple horizontal items, a new top-down setting will quickly reveal a rough line of three such items, changing your percept without changing the stimulus. There has been much debate about the relative priority of top-down and bottom-up processing with ardent partisans of bottom-up [32,33] and top-down [34]. In fact, each can dominate attentional deployment under the correct circumstances. More recently, it has become clear that a third factor, the history of prior guidance, is important, too. If you randomly select an item in Figure 1, you will quickly be able to find other items sharing those features because the

first selection "primes" subsequent selection [35-38]. Bottom-up guidance is very fast – producing an "exogenous" shift of attention. Top-down takes longer to put into place and can be thought of as producing an "endogenous" shift [39].

Not all guidance in visual search is feature guidance. Scene structure can guide attention very effectively [40-46]. If you are looking for a coffee maker in a kitchen, your search will be highly constrained even though the basic visual features of a coffee maker can vary quite widely. You will tend to look on kitchen counters, not the floor and not on a dining table in the kitchen. Note that you will tend to look in the same places whether or not the coffee maker is present because it is not the coffee maker's features that are relevant in scene guidance. Of course, an observers' understanding of the gist and structure of a scene is based on its visual properties, but those visual features define the meaning of the scene, not the target. Scene features do not behave like preattentive features. Thus, for example, search for a natural scene among urban scenes is not efficient [47].

The characteristics of guiding features

There are a number of properties that are considered diagnostic of preattentive / guiding features. Each has its ambiguities, and none is perfectly diagnostic.

1) A guiding feature should guide.

If a target is defined by a unique feature, it should not matter how many distractors are present, the slope of the RT x set size function should be near zero. As Duncan and Humphreys [48] describe, this will be true only if the unique target feature is sufficiently different from the distractor feature. The required target-distractor

difference that will support efficient search tends to be much greater than the just noticeable difference for that feature [e.g. color 49], [orientation 50]. If the distractors are heterogeneous, the efficiency of search will decline as a function of the degree of distractor variation [48]. Efficiency will be especially impacted if the target and distractors are not "linearly separable" [51] meaning that a line can be drawn, separating the target from the distractors in the feature space. Yellow among orange and red is linearly separable and search is efficient. Orange among yellow and red is not [52]. Similar rules apply, for example, in orientation [53].

Sometimes search is efficient even if no single feature defines the target. Targets defined by conjunctions of highly salient features can produce RT x set size slopes near zero. For instance, Theeuwes & Kooi [54] showed that a search for a black O among black Xs and white Os was very efficient. It would be a mistake to think of the "black O" conjunction as a basic feature in its own right because it is composed of two other more basic features: shape and luminance polarity. They simply combine in this case to guide conjunction search particularly efficiently. This occurs for higher order conjunctions as well [e.g. things like vertical green crescents 55]. This point can be and has been debated. For instance, people are very good at detecting the presence of an animal in a scene in brief glimpse [56,57]. One argument would be that animals are defined by a particular, perhaps probabilistic conjunction of basic features, but others argue that low level visual features cannot explain the behavior [58].

2) Search asymmetries: Detecting the presence of a feature is easier than detecting its absence.

Treisman introduced the idea of a search asymmetry as "A diagnostic for preattentive processing of separable features" [59]. A search asymmetry is a situation where search for A among B is more efficient than search for B among A. In a truly diagnostic case, A among B will be very efficient while B among A will be inefficient. Perhaps the clearest instance of this is motion [60] where finding the presence of a moving item among stationary is much easier than finding the presence of a stationary item among moving items. Treisman's useful idea was that the presence of a feature (e.g. motion) is easier to detect than its absence [61]. Thus, orange among yellow is easier than yellow among orange because orange is defined by the presence of the feature of "redness" while, in comparison to orange, yellow is defined by the absence of redness. Asymmetries are not completely unambiguous as evidence for the presence of preattentive features. Stimulus factors like target eccentricity that might be thought to be irrelevant to the status of a candidate feature, will modulate the strength or even the presence of an asymmetry [62] and, in some cases, the task, itself, may be asymmetric. For example, as Rosenholtz [for a set of important cautions about asymmetries see 63] pointed out, in the classic motion asymmetry, the harder case is search for a stationary target among heterogeneous, randomly moving distractors while the other side of the asymmetry is the easier search for a moving item among homogeneous, stationary distractors.

Search asymmetries have been also used as evidence for preattentive features that are not simple visual properties. For example, it has been proposed that emotionally

valent (e.g. 'angry') objects (notably, faces) are found more efficiently among neutral distractors than vice versa, suggesting the existence of preattentive processing of "emotional features" [64]. Asymmetries are important here because the search tasks tend to produce relatively inefficient searches. It can be argued that the steep RT x set size slopes come from low stimulus salience [48], leaving the asymmetry between two inefficient searches as the evidence for featural status for emotional valence [65]. However, asymmetries can also be produced if one type of distractor is harder to reject than another. Thus, for example, if each face is processed in series and it takes longer to move away from an angry face than from a neutral face, then search for neutral among angry will be less efficient. Asymmetries are most convincing when one of the two searches is efficient. The point is arguable, but, in the case of emotional valence, the asymmetry probably does not reflect featural status [66].

3) Groups or regions, defined by a unique preattentive feature, segment from a background defined by other features

As a negative example, Figure 3a shows that intersection type (here T vs "plus" intersections) does not behave like a basic feature [67]. The evidence is that attentional scrutiny is required to notice that the bottom third of the figure is composed of plus intersections.

In Figure 3b, adequate variation in orientation and/or size produces clear texture segmentation, as basic features should. Conjunctions, though they can support efficient search, do not support texture segmentation [68], more evidence that the conjunction,

itself, is not a guiding feature. Turning to grouping, in the lower left quadrant of Figure 3b, four orientation oddballs form a rough diamond. The colored items in the upper left quadrant may seem to form more of a red triangle with an added blue oddball [69].

Different types of features can be governed by somewhat different rules. Recent studies showed that even the most conventional features do not always support global display segmentation. In displays mixing many colors or orientations, observers are very efficient at selecting the subset of items based on hue. They are much less efficient at doing so based on color saturation or line orientation [70,71], although both features can pop-out in visual search [72]. Therefore, easy segmentation of groups and regions and target pop-out do not always unambiguously converge to diagnose basic features.

4) Features are organized into modular dimensions.

This point requires a bit of care about terminology. "Red", for this purpose, would be a feature. "Color" is the dimension. "Vertical" is a feature. "Orientation" is a dimension, and so forth. The distinction is useful because it is possible to guide attention to a dimension as well as to a feature [73,74]. Thus, you could give someone the instruction to find orientation oddballs and ignore color. Moreover, as Treisman [75] suggested, in *disjunctive* search, it is harder to search for features in two different dimensions (find red or vertical) than in the same (find red or green). In conjunctive search, where two features are attached to one item, it is more efficient to search for an item that is red AND vertical than one that is red AND green [18].

5) Adaptation is not a distinctive property of basic features.

It is tempting to think that features should produce featural aftereffects. After all, for instance, orientation is a feature dimension and there are orientation (tilt) aftereffects [76,77]. The same is true for size, motion, and others [78]. However, lack of an aftereffect does not disqualify a candidate feature. For example, line terminations [31] and topological properties like the presence and absence of holes [79] are probably guiding features without having associated aftereffects. Moreover, presence of an aftereffect is not clear evidence for feature status. Contingent aftereffects like the McCollough effect [80,81] occur for many conjunctions of features [82] even though the conjunctions are not features in their own right. Other stimuli like faces show clear adaptation effects [83] [84] but properties like Asian vs European that do produce aftereffects are unlikely to serve as guiding features. On balance, it seems that adaptation effects are not diagnostic of guiding feature status.

6) Preattentive features are derived from but not the same as early vision features. Treisman [85] originally suggested that her preattentive features were the same as the features that electrophysiologists were finding in primary visual cortex [86]. For a modern version of this thought see Zhaoping [87]. We presume that the features that guide attention are derived from early visual processes. Thus, in Figure 4, one of the target "T"s is composed of vertical and horizontal lines. The others are tilted. Knowing that does not help you to find it. The 10 deg differences in orientation, while readily detectable, are not able to guide attention [50,88] because guiding features are coarsely coded. In contrast, as noted earlier, knowing that one of the Ts is red helps considerably.

Guiding features are also appear to be coded categorically. Semantic categories like "number" vs "letter" probably do not serve to guide search [89,90]. However, more perceptual categories have a role to play. If we define vertical as "0 deg", it is easier to search for a -10 deg target among -50 and 50 deg distractors than it is to search for a 10 deg target among -30 and 70 deg distractors. In the first case. Wolfe et al. [53] concluded that the important difference was that target was the only "steep" item in the first condition. The second condition is a simple 20 deg rotation of the first but now the target is merely the "steepest" item. Even though the relative geometries are the same in the two conditions, the first condition is the easier search (see also [91]). Similar effects have been reported in color [92] [93] but see [94].

One way to summarize this section would be to argue that attention is guided by a set of coarse, perhaps categorical, features, abstracted from early visual processes. In this view, you do not *see* guiding features, you use them [95]. This view leaves unclear the relationship of guidance to texture segmentation and grouping. Clearly, in those cases, what we are calling guiding features also shape what we see.

Can you learn a new feature?

Is the set of preattentive features fixed or can new features be learned? Most tasks improve with practice. In search, some inefficient searches can become efficient, as in the pioneering work of Schneider and Shiffrin [96] or the work of Carrasco et al. on conjunctions of two colors [97]. After some reports of failures to train efficient search,

another group managed to make previously inefficient conjunction searches efficient [98,99]. Efficient searches for categories like "vehicle" have also been taken as evidence for learned features [57,100]. Have these conjunctions and vehicles become features? The alternative is that observers have learned to use basic features in a way that permits efficient search [101], similar to the account we offered for efficient search for salient conjunctions earlier.

If a new feature was behind newly efficient search, we would expect the new feature to behave like a feature in other tasks (e.g. texture segmentation). Evidence for such transfer has been weak [102], but in recent work, we obtained some transfer of a quite arbitrary property from one type of stimulus to another [103]. In part because the criteria for feature status, discussed above, remain unclear, it is hard to definitively determine if a new feature has been created by training.

Conclusions

At the end of the brief review, we find ourselves with an essentially pragmatic, operational answer to the question: What is a preattentive feature? A preattentive feature is a feature that guides attention in visual search and that cannot be decomposed into simpler features. Thus, color and orientation are features. A color X orientation conjunction, even if it supports efficient search, is not a feature because the efficient search can be attributed to guidance by color and orientation, acting independently. There are other phenomena that go along with feature status; e.g. search asymmetries and texture segmentation, but there is no airtight set of diagnostics to rule one attribute into preattentive feature status

and others out of that status. From the days of Treisman's "feature maps", one approach has been to reify features into building blocks with their own separate existence. One of us, for example, keeps publishing tables of these features [13] [14] that could lead to the expectation that there will be specific pieces of the brain that *embody* the feature. A more nuanced way to think of preattentive features might be to think of them as the way that basic visual information is used by the mechanisms of selective visual attention. There are restrictions on the guidance of selective attention. One way to think of those restrictions is to describe attention as guided by a limited set of coarsely coded visual properties. We might not need to imagine that these exist as separate modules, defining a physical stage of processing. They might be what emerges when the human search engine makes use of the human visual system.

Both authors state that they have no Declarations of interest.

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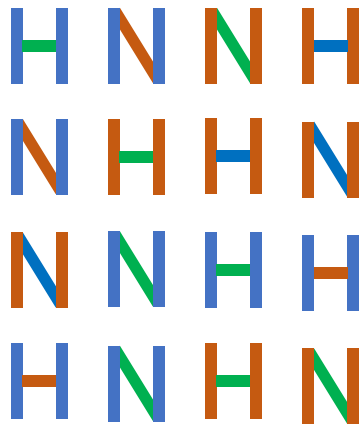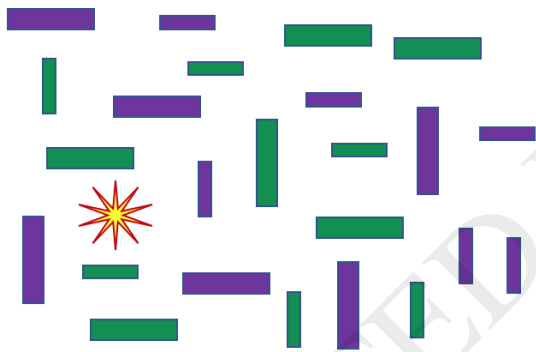
Figure 1: Find the two brown and green "N"s

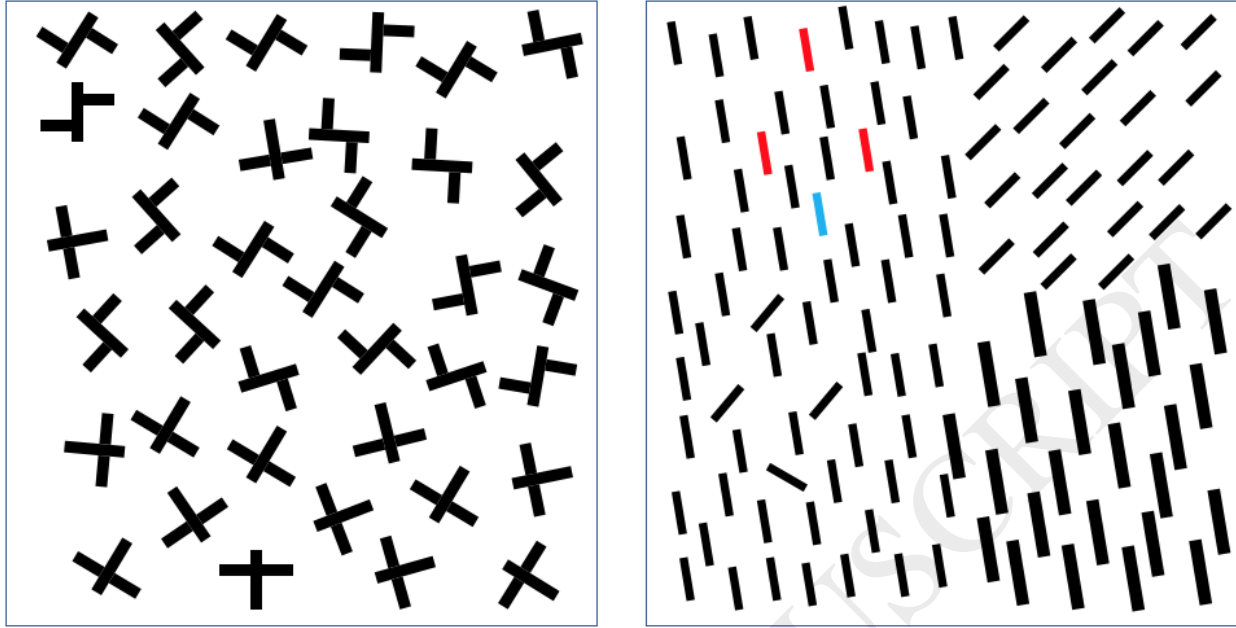**Figure 2: Find a big green vertical target.**

Figure 3a: Plus intersections do not support texture segmentation (find the plus region). 3b: Size and orientation do support texture segmentation.
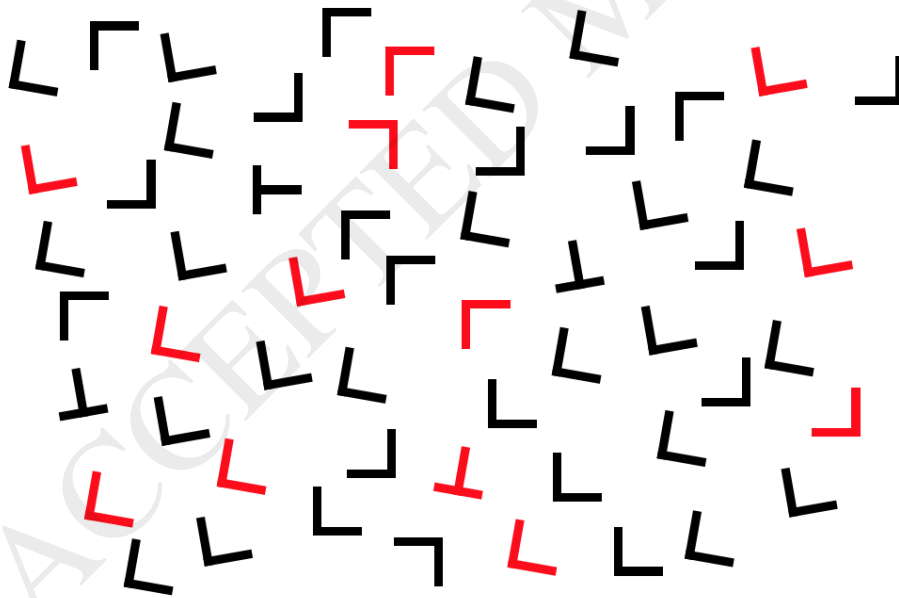

Figure 4: Look for the red T. Look for the untilted T.