OPINION

What attributes guide the deployment of visual attention and how do they do it?

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As you drive into the centre of town, cars and trucks approach from several directions, and pedestrians swarm into the intersection. The wind blows a newspaper into the gutter and a pigeon does something unexpected on your windshield. This would be a demanding and stressful situation, but you would probably make it to the other side of town without mishap. Why is this situation taxing, and how do you cope?

The world presents the visual system with an embarrassment of riches. Given a brain of any reasonable size, it is impossible to process everything everywhere at one time[1]. The human visual system copes with this problem in a number of ways. Rather than having high-resolution processing at all locations, the best resolution is confined to the fovea, with massive losses in acuity occurring only a few degrees into the periphery. There are restrictions in the wavelengths of light that are processed, the spatial and temporal frequencies that can be detected, and so forth. All of these 'front-end' reductions in the amount of information fail to solve the problem. To deal with the still-overwhelming excess of input, the visual system has attentional mechanisms for selecting a small subset of possible stimuli for more extensive processing while relegating the rest to only limited analysis.

Even though William James famously declared that "Everyone knows what attention is"[2], there is no single, satisfying definition of attention. The term covers a diverse set of selective processes in the nervous system. We can attend to a specific task, attend to tactile stimuli in preference to auditory, attend to a specific visible stimulus that is 2° to the left of fixation, and so on. This article is restricted to consideration of visual attention. Even within vision, there is good evidence that attention has its effects in diverse ways. Attention to a stimulus might enhance the signal produced by that stimulus[3,4]. It might more precisely tune the visual system to a stimulus attribute, excluding other input as noise[3]. Attention might restrict processing to one part of the visual field[5] or to an object[6], or it might restrict processing to a window in time[7].

Faced with this welter of possibilities, we will use an operational definition of one aspect of attention in this paper. We are concerned with the deployment of attention in visual search tasks. It is possible to discuss the role of attention in these tasks while remaining agnostic about distinctions between noise reduction, stimulus enhancement and so forth. In a typical visual search task, an observer looks for a target item among distracting items. In the laboratory, this might be a search for a big red vertical line in a display containing lines of other colours, sizes and orientations. However, visual search is no mere laboratory curiosity. From the search for socks in the laundry to the search for weapons in carry-on luggage, our environment abounds with search tasks. Indeed, these processes of attentional selection, revealed by visual search experiments, are presumably the processes that are used whenever anything in the world becomes the current object of visual attention.

The starting point for any understanding of the deployment of attention in visual search is the observation that some search tasks are easy and efficient while others are not. Consider FIG. 1a. If you are asked to find the red target or the tilted target or the big target, it is intuitively clear that the number of distracting items does not make much difference. The colour, orientation or size attributes that define the targets can efficiently guide attention to the target. On the other hand, among these '5's there is a '2' target. Once it has been found, there is no difficulty in discriminating a 2 from a 5. However, attention cannot be guided by the spatial position information that differentiates those characters. The more 5s that are present, the more difficult the search task will be[8].

The purpose of this article is to review the status of these guiding attributes. What properties can guide attention and what cannot? For about 25 years, the answer to that question has been framed in terms of Treisman's highly influential feature integration theory[9]. Treisman followed Neisser[10] in proposing a two-stage architecture for human vision (FIG. 2a) in which a set of basic features was generated in an initial, parallel, 'preattentive' stage. Other processes, like those that bound features to objects and permitted object recognition, were restricted to one or at most a few objects at a time. Consequently, attention was required to select a subset of the input for this more advanced processing. Later models, such as guided search[11,12], kept the two-stage architecture but noted that the preattentive stage could guide the deployment of attention to select appropriate objects for the second stage. Therefore, a preattentive stage that could process colour and orientation could efficiently guide attention to a target that was defined by the combination of colour and orientation (for example, a red vertical item) even if preattentive stages could not bind colour to orientation in parallel at all locations.

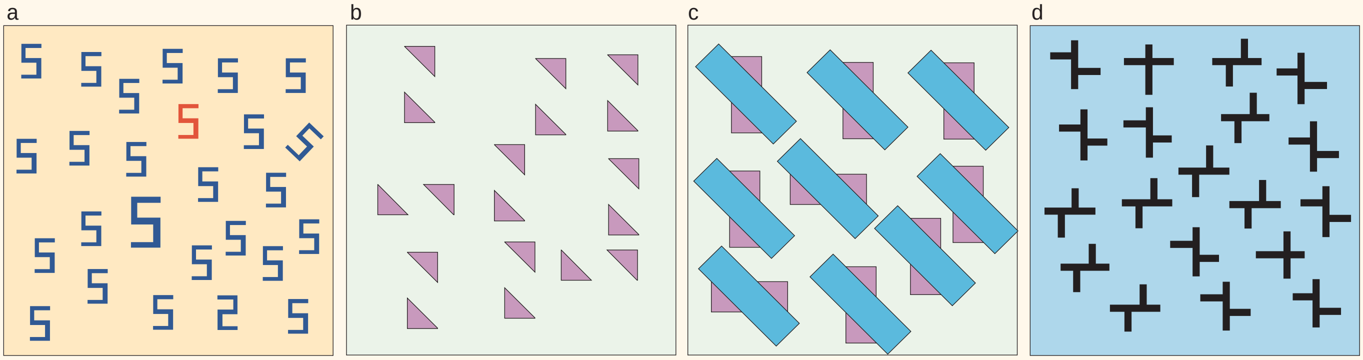

Figure 1 | **Easy and difficult examples of visual search. a** | It is easy to find the red, tilted or big '5'. It is not easy to find the '2' among the '5's. **b**,**c** | It is difficult to find the horizontal pairs of triangles in **b**, but in **c** it is easy because the early visual system can use intersection information to infer that the blue items occlude pink rectangles. **d** | In this panel, search for the 'plus' is inefficient because the intersection information here does not guide attention.

The original account was appealing. Simple features such as size and motion were extracted preattentively. More complex properties required attention. However, the accumulation of information about guiding attributes over the past 20 years makes it clear that this two-stage, linear approach will not work. Several lines of objection have been raised[13,14], but the core problem for us is that there are multiple examples of 'features' that are available early in visual processing and also in attentive vision, but that are not available to guide the deployment of attention. At the same time, there are properties of guiding attributes that are not reflected in attentive vision. This makes it difficult to envision the guiding representation as a stage in a linear sequence of visual processes, like a filter — even a tunable filter — between early vision and the attentional bottleneck.

As an example, consider intersections. In FIG. 1b, it is not easy to find the two horizontal pairs of triangles. In FIG. 1c, it is quite easy because early visual processes can handle occlusion information[15]. Interpreting occlusion requires that the early visual system successfully interprets intersections. Clearly, later object recognition processes can use intersection information. However, as shown in FIG. 1d, intersection does not serve as a source of guidance[8]. The linear model would have to explain how intersection information could be present, then absent, then present again.

It might be better to think of a 'guiding representation' as a control device, sitting to one side of the main pathway from early vision to object recognition (FIG. 2b). Its contents are abstracted from the main pathway and it, in turn, controls access to the attentional bottleneck. However, it would not, itself, be part of the pathway.

Departure from the linear model has been a feature of several recent theoretical approaches to the guidance of attention. Hochstein and Ahissar[16] offer a 'reverse hierarchy' model in which properties that are abstracted late in visual processing feed back onto early stages. In an approach that more closely resembles the architecture of FIG. 2b, DiLollo and colleagues[13] propose that "Initial processing is performed by a set of input filters whose functional characteristics are programmable under the control of prefrontal cortex." For our purposes, there are two important points to be made about a guidance control module — wherever it is located in the brain. First, as the intersection example illustrates, it does not have access to all of the information that is available in the visual pathway that runs from early vision through the bottleneck to object recognition. Second, as DiLollo *et al.* note, when the control module exerts its control over access to the bottleneck, it is not acting as a filter in the simple physical sense of that term.

The problem with filters is that they remove information. Consider the following: as we discuss below, guidance by attributes such as colour and orientation seems to be coarse and categorical. Attention is guided to 'red' and 'steep', not to 640 nm or 23° left of vertical. Suppose that a target is known to be categorically 'red'. Filtering for 'red' would pass what was red and reject what was not. However, imagine a task in which observers must determine whether a red object has a green spot on it, and not a black or a blue one. Introspection will tell you that this is a straightforward task, but a filter that eliminated the 'not-red' would make it impossible. Rather than altering the stimulus, as a filter might, the hypothetical control module guides selection like a security screener at an airport. Based on a rather abstract representation of the notion of 'threat', the screener selects some individuals for more attention than others. Although attending to an object or location might have perceptual consequences[17], guidance itself should not.

Conceiving of guidance as a control module also avoids a potential pitfall in models of the reverse hierarchy[16] variety. It is reasonable to assume that attention can be guided by some 'late' information (see, for example, Torralba's theoretical work on guidance by scene properties[18]). If that information fed back onto early visual processes and acted as a filter, one could imagine odd recursive problems where feedback about a scene reduced the ability to see the scene. Torralba's model, for example, generates images where only the ground plane is visible during a search for people, but we are not meant to suppose that this is what is seen. As with the search for 'red', it seems more plausible that late information could inform the guidance of attention by altering the representation in a guiding module placed outside the main pathway to object recognition.

In the remainder of this article, we discuss the attributes that are abstracted from early vision that can guide attention. In keeping with the hypothesis that guidance is separate from the the main pathway to object recognition, we avoid the use of the term 'preattentive' and its associated theoretical implications. Attributes will be discussed in terms of their ability to guide the deployment of attention.

Identifying 'guiding' attributes

One of the most productive ways to study the differences between visual search tasks is to measure reaction time (RT) — the time that is required to say that a target is present or absent — as a function of the set size (the number of items in the display). The slope of the RT × set size function indexes the cost of adding an item to the search display. So, varying the set size in the colour search task in FIG. 1 will produce little or no change in RT. The slope will be near zero and we can label such a search as efficient. By contrast, in the search for a 2 among 5s, the slope will increase at a rate of about 20–40 ms per item for trials when a target is present. The slope will be a bit more than twice that steep when the target is absent. We can label such tasks as inefficient. Note that this assumes that the stimuli are large enough and sparse enough that it is not necessary to fixate each one. If search is limited by the rate of eye movements, slopes are in the range of 150–300 ms per item.

If the world were simple, search tasks would fall into two dichotomous groups, as originally proposed by Treisman[9]. There would be parallel tasks, where a guiding feature defined the target, and serial tasks, where no adequate guiding feature was present. We could then use some objective slope criterion (such as 10 ms per item, which has often been proposed in the search literature) as the marker for the presence of a guiding feature. However, when we pool data from many different subjects in many different tasks (as in FIG. 3), the resulting histogram makes it clear that there is no obvious division that splits search tasks into different categories based on slope[19]. Note that this does not mean that the distribution in FIG. 3 could not be the sum of two or more distinct, underlying distributions[20]. But it does mean that no simple slope criterion defines the presence of a guiding feature.

If a simple slope value is not definitive, what can define a guiding attribute? There are several measures, none of which is completely definitive by itself. An accumulation of converging evidence makes the most convincing case. Note, for the remainder of this paper, that a 'feature' will generally refer to a specific value (such as red) on a specific 'dimension' (such as colour).

Simple feature searches are generally very efficient. Although features cannot be defined by applying a simple criterion slope value, the closer the slope is to 0 ms per item, the more likely it is that the target is defined by a guiding feature. A shallow slope is not perfectly definitive because combinations of features can produce shallow slopes. For example, as shown in FIG. 4a, it is easy to find a black 'X' defined by a conjunction of shape and luminance polarity[21]. In this case, luminance or colour processes can guide attention to the black items and some shape process can guide attention to the item with line terminators[22]. These guiding signals are strong enough that attention can be swiftly guided to the intersection of the two sets of items[11,12].

Other criteria. Efficient search is, therefore, a necessary but not sufficient property for showing the presence of a guiding feature. There are at least four other indicators that can provide converging evidence.

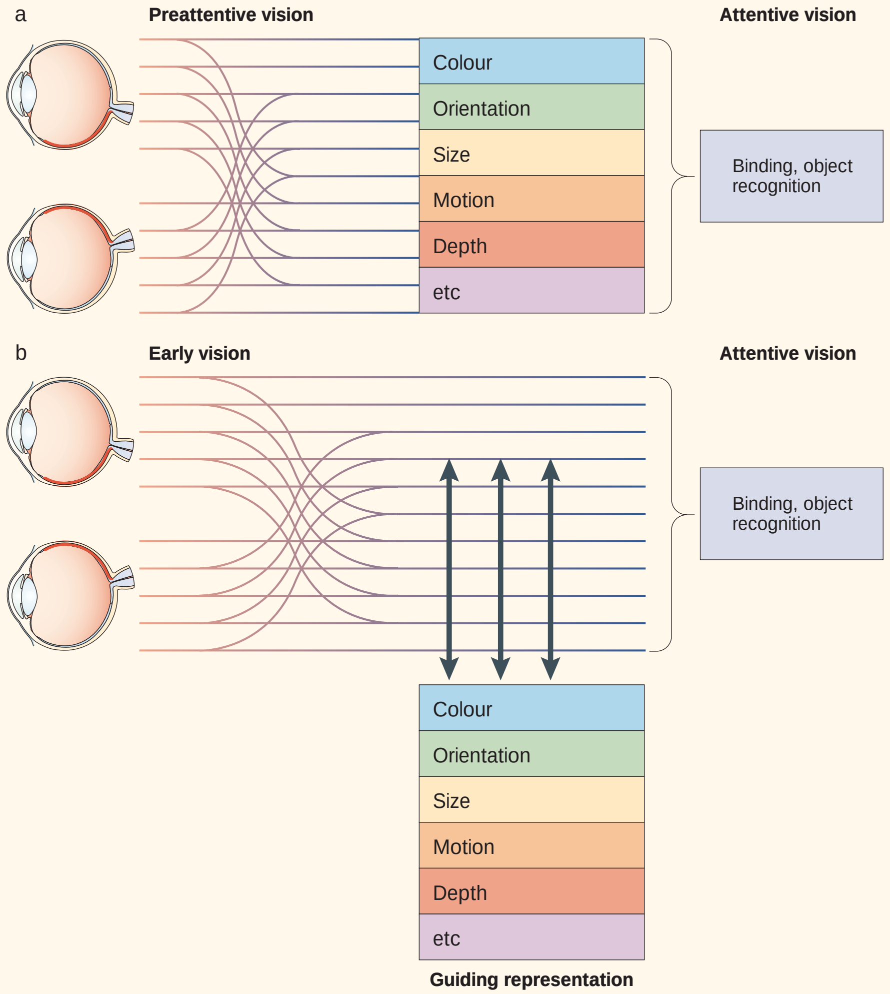

Figure 2 | **Models of visual processing. a** | A standard two-stage model with a parallel front end followed by an attentional bottleneck leading to processes such as object recognition. **b** | We suggest that it is useful to think of a 'guiding representation' that is derived from the main visual pathway and that guides access to the attentional bottleneck in the pathway but that is not, itself, part of the pathway.

First, in many cases, a texture region that possesses a unique basic feature segments 'effortlessly' from a background texture that does not[23,24]. This is illustrated in FIG. 4b for colour and orientation. This is not a perfect diagnostic because there are instances of segmentation without efficient search, and efficient search without segmentation[25]. Still, a property that produces both efficient search and effortless texture segmentation is a good candidate for guiding attribute status.

Second, for many attributes, the presence of a property is more readily detected than its absence. This leads to so-called 'search asymmetries'[26–28]. So, for example, it is easier to find a moving item among stationary distractors than vice versa[29]. This is useful only if the easy search is efficient. For example, it is easier to find a mirror-reversed letter among regular letters than vice versa, but both searches are inefficient and the mirrored target is easier to find only because the regular letter distractors can be rejected more rapidly. Rosenholtz[30] describes other important cautions about the interpretation of search asymmetries.

Third, Treisman[31] suggests that the ability to participate in 'illusory conjunctions' is evidence for feature status. For example, if red vertical and green horizontal items are briefly presented, then observers will often report seeing the occasional red horizontal or green vertical item. The interpretation of this information is complicated by existence of higher-order illusory conjunctions, for example in word formation[32].

Finally, detection of a target that is defined by a candidate feature should be able to tolerate some distractor heterogeneity (FIG. 4c,d). On the basis of FIG. 4c, one might be tempted to conclude that junction type (T versus L) or perhaps even letter identity has featural status. However, what should be irrelevant variation

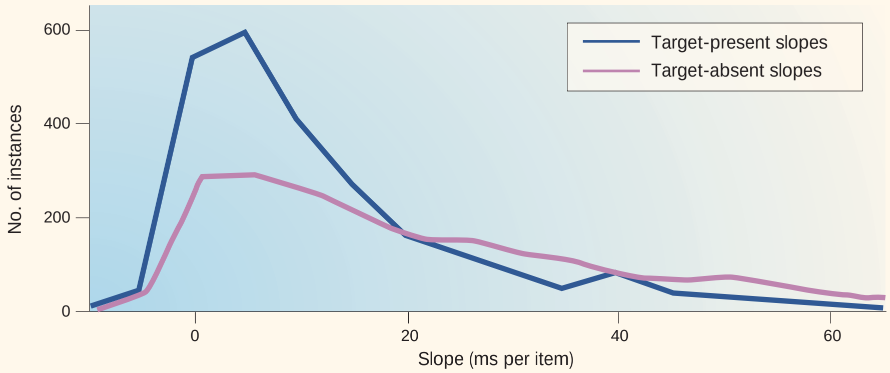

Figure 3 | **Distribution of slopes from individual sessions in a wide range of search tasks.** Sessions are generally 300–400 trials. The distribution is clearly not biomodal. Modified, with permission, from REF. 19 © (1998) American Psychological Society.

in orientation destroys the efficiency of that search (FIG. 4d). On the other hand, efficient colour search for the red L survives orientation variation with ease. Disruption by distractor heterogeneity can indicate that the wrong feature has been identified as the source of guidance. In FIG. 4c, the T might be found by the orientation of the triangle that would enclose it (its convex hull). This would be disrupted by orientation variation, whereas the identity of a T-junction would not be. This test is most important for 'higher order' features, where it is often possible that other simpler, more basic features are driving the efficient search.

To summarize, no single diagnostic assures the presence of a guiding feature. Converging evidence from several of the tests described here makes it possible to identify guiding attributes with some assurance.

Signal and noise in feature search. When a unique feature defines a target in visual search, efficient visual search is not guaranteed. The difference between the target and the distractors can be considered to be a signal that must be found amidst the noise of the surrounding distractors. The qualitative nature of this signal detection problem is neatly captured by Duncan and Humphreys'[33] formulation of their 'attentional engagement theory'. Search efficiency increases as a function of target–distractor (TD) difference (signal) and decreases as a function of distractor–distractor (DD) difference (noise). More formal signal detection approaches (generally involving relatively simple stimuli) can be found elsewhere[34–36].

Research on visual search for colour illustrates these ideas and reveals certain limitations. FIGURE 5a–d shows a set of stimuli with varying TD differences. FIGURE 5e shows, schematically, the data that might be expected from such an experiment[37]. For a range of relatively large TD differences (as in FIG. 5c,d), RTs will be fast, slopes of the RT × set size function will be near zero, and error rates, even for briefly presented displays, will be low. Once the TD difference drops below some critical value, RTs, slopes and/or errors will begin to increase. The first important point is that any type of search for a target defined by a unique basic feature can be made arbitrarily difficult if the TD difference can be made arbitrarily small, whereas search for targets not defined by a unique basic feature cannot be made arbitrarily easy by increasing the TD difference.

The second important point is that the bend in the function in FIG. 5e is not located at the resolution limit for that feature. Staying with the example of colour, for a given point in colour space, one can define an elliptical set of other points that represent 'just noticeable differences' in colour known as a MacAdam ellipse[38]. To have an efficient search for one colour among homogeneous distractors, the difference needs to be much greater than the just noticeable difference. Moreover, the shape of the efficient search contour around a specific location in colour space does not look like a scaled version of a MacAdam ellipse[37]. The metrics of colour difference for foveal colour discrimination are quite unlike those that govern deployment of attention in visual search.

FIGURE 5f–h illustrates the effects of DD differences. It is easy to find the orange target among red or yellow homogeneous distractors (FIG. 5f or h). However, when the distractors are heterogeneous, the task becomes more difficult. The nature of the heterogeneity is important. Specifically, search is inefficient if distractors flank the target in the feature space. If a line can be drawn in a two-dimensional colour space, with the target colour on one side and the distractors on another, then search will be easy. Assuming that the TD differences are large enough, these targets and distractors are 'linearly separable'[39,40]. If such a line cannot be drawn, search will be inefficient.

These are general principles — not curiosities of colour processing. In the search for oriented targets, large TD differences in orientation will support efficient search[9]. Smaller differences will not[41]. Foster's data show that the critical TD difference for efficient orientation search is much larger (~15°) than the minimum difference needed

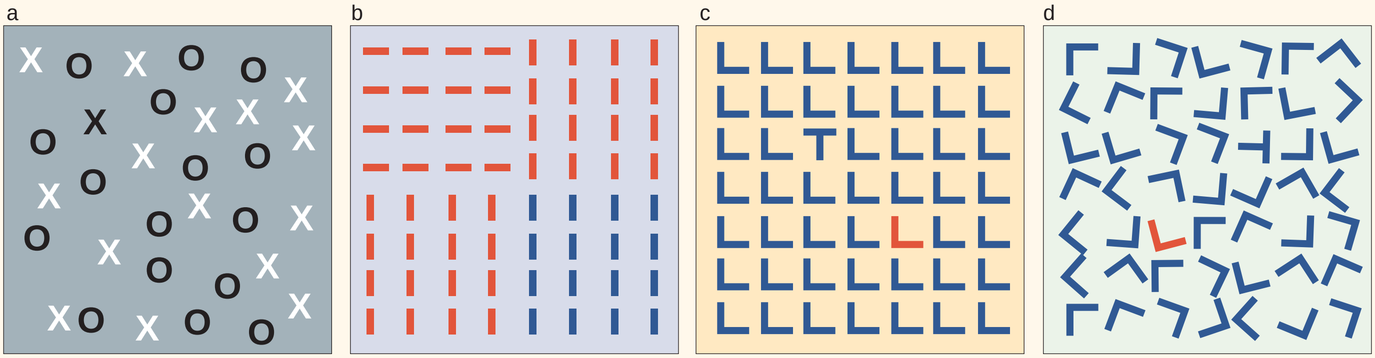

Figure 4 | **Clues to guidance. a** | Some conjunctions are very easy to find. In this case, the target is the black X — a shape–luminance polarity conjunction[21]. **b** | Segmentation of texture regions on the basis of the colour or orientation of their local elements. **c** | Both the 'T' and the red 'L' appear to 'pop out', but pop-out of the T does not survive irrelevant variation in orientation (**d**). This indicates that the distinction between T- and L-junctions is not a guiding feature.

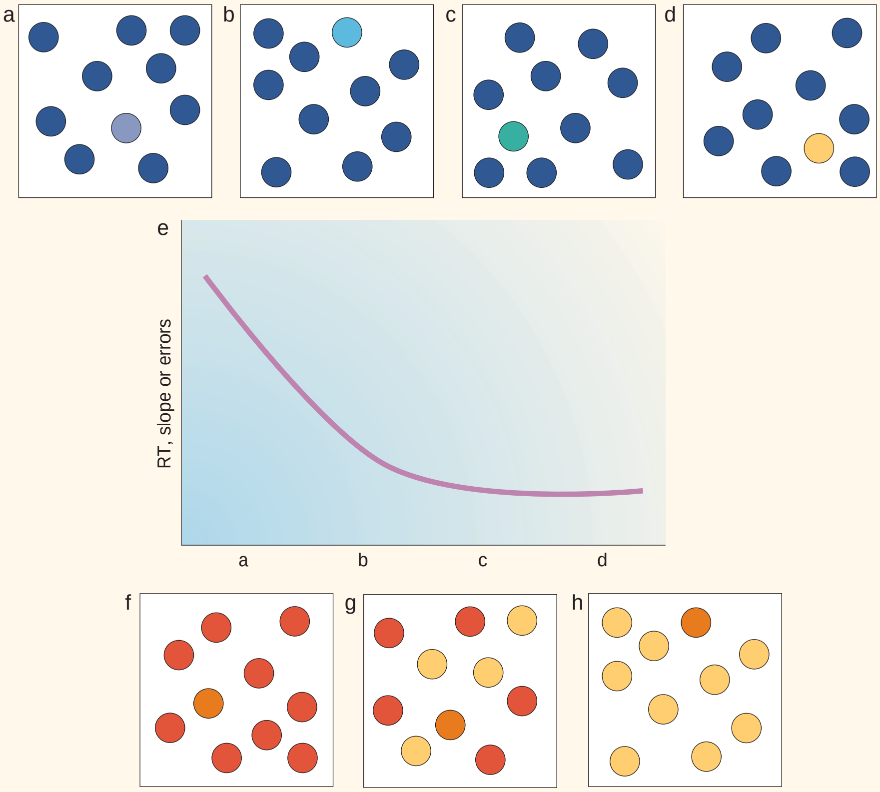

Figure 5 | **Target–distractor and distractor–distractor differences. a–d** | Search is easier when the target–distractor (TD) difference is larger. A simple feature search can produce steep slopes and/or long reaction times (RTs) if the TD difference is small (**e**). **f–h** | Distractor heterogeneity makes search harder (compare **g** with f or **h**). Part **e** modified, with permission, from REF. 37 © (1990) Optical Society of America.

to discriminate oriented lines (~1–2°). His data also show that variation in these critical values is not the same as the variation in discriminability with orientation. Search is inefficient when distractor orientations flank target orientations. So, it is easy to find a vertical target among homogeneous distractors tilted 20° to the left or 20° to the right. It is quite difficult to find the same vertical target among heterogeneous distractors tilted 20° left and right[42]. The effects of distractor heterogeneity again reinforce the differences between determinants of search performance and determinants of discriminability. In search, the categorical status of the target is important. So, search is more efficient if the target is uniquely steep, shallow, or tilted left or right[42].

What attributes guide visual search?

One goal of this review is to provide the best current list of the attributes that guide the deployment of attention. Most of the candidates for this list have not been put through all the tests described above. Nevertheless, TABLE 1 is an effort to make such a list. Note that the references are representative, not exhaustive. They are intended to provide the interested reader with pointers to the main evidence for and, in some cases, against the featural status of various attributes. Further discussion can be found in various review chapters[43–45].

The list is organized into five groups of candidate sources of guidance. The first category of 'undoubted' attributes are those for which there is so much evidence that it is almost beyond question that these are dimensions whose features can guide search. This certainty fades as we go along the categories until we reach the final category of proposed attributes where the best evidence indicates that these are not guiding attributes. In the remainder of this paper, we briefly consider some of the issues raised by this list.

The undoubted guiding attributes. Colour, motion, orientation and size are all supported as guiding attributes by large amounts of convincing data. However, in the case of size, it is possible that properties such as size and spatial frequency might be disentangled into two or more separate dimensions[46].

Probable guiding attributes. These are attributes where more data would help to clear up ambiguities. For example, in the case of luminance onset, under some circumstances, luminance offsets might also work[47]. The only reason to question luminance polarity as a guiding attribute is that it might be a subset of colour (that is, it might be the black–white or luminance axis of a three-dimensional colour space). Motion might be a single dimension, or speed and direction might be separate dimensions[48].

Vernier offset — a small lateral break in a line — is a less than assured guiding property, because it might be reducible to a form of an orientation cue[49]. In the case of stereopsis, there might be a broader dimension of something like three-dimensional layout that would capture various depth cues including stereopsis, the various pictorial depth cues, and shading. The cues would merely serve to create three-dimensional surfaces in the way that wavelength (not a guiding dimension) creates colour.

Shape is, perhaps, the most vexed of the guiding attributes, and several other attributes on this list have the same problems. It is clear that some aspects of shape are available to guide attention. It is not clear exactly what those aspects are. Evidence can be mustered for closure (for example, O versus C) or the topological property of having a 'hole', but closure could also be the state of not having clear line terminators. The various claims for the featural status of letters (see below) are endlessly complicated by our inability to settle on a set of shape features. For the present, it is clear that a feature such as line termination can distinguish between 'O' and 'Q', but it is not clear that such features can account for all of the search effects that are seen with letter stimuli.

Observers are sensitive to the direction of curvature (for example, left versus right)[27]. If the curves are part of the bounding contour of an object, this becomes concavity and convexity, with a possible preference for concavities[50]. So, concavity and convexity could be features of a curvature dimension. Taken into three dimensions, the concavity and convexity of surfaces might be the 'real' features in studies that argue for shading as a feature.

Possible guiding attributes. Shading or lighting direction is also an interesting case for other reasons. Early evidence such as Ramachandran's 'eggs' study[51] looked persuasive, but recent work (Ostrovsky, Y., Cavanagh, P. & Sinha, P., unpublished observations) suggests that we are not very sensitive to the actual properties of shadows. It might be that shading information is available in early vision. Like other depth cues, it might merely create other guiding attributes (such as surface orientation, convexity and concavity) while not guiding attention itself.

Table1 | Attributes that might guide the deployment of attention

Undoubted attributes*	Probable attributes‡	Possible attributes§	Doubtful cases‖	Probable non-attributes¶
-Colour[26,27,37,39,40] -Motion[30,56,57] -Orientation[41,42,58–61] -Size (including length and spatial frequency)[27,62,63]	-Luminance onset (flicker)[64,65] -Luminance polarity[21,66] -Vernier offset[67] -Stereoscopic depth and tilt[68–70] -Pictorial depth cues[71–73] -Shape[27,58,74–80] -Line termination[22,81,82] -Closure[26,77,83–85] -Topological status[77,86,87] -Curvature[27,67,88]	-Lighting direction (shading)[51,89] -Glossiness (luster)[52] -Expansion[90,91] -Number[27,81] -Aspect ratio[27]	-Novelty[28,53,92] -Letter identity (over-learned sets, in general)[93–95] -Alphanumeric category[96–99]	-Intersection[8,58] -Optic flow[29,91] -Colour change[64] -Three-dimensional volumes (such as geons)[100,101] -Faces (familiar, upright, angry and so on)[102–108] -Your name[109] -Semantic category (for example, ‘animal’,‘scary’)[10]

Attributes are grouped by the likelihood that they are, in fact, sources of guidance of attention. References are representative but not exhaustive. *‘Undoubted’ meaning that they are supported by many studies with converging methods. ‡Less confidence owing to limited data, dissenting opinions or the possiblity of alternative explanations. §Still less confidence. ‖Unconvincing, but still possible. ¶Suggested guiding features where the balance of evidence argues against inclusion on the list.

The evidence for shininess or gloss as a guiding attribute comes from a single experiment on binocular luster[52]. Current work in our laboratory casts doubt on the generality of the finding.

Expansion is problematic because of limited data and because it could be a version of a depth cue, a size cue, a motion cue or some combination of these. Its independent status has not been verified. Candidate dimensions such as number (is this clump made of one item or two?) and aspect ratio (for example, ovals among circles) could be on the list, but the evidence is scant and these should be revisited.

Doubtful cases. The central issue in the case of novelty is whether a novelty feature can survive any degree of distractor heterogeneity. For example, a mirror-reversed ‘N’ will pop-out among Ns and a mirror-reversed ‘Z’ will pop-out among Zs[53], but it is unclear whether novel mirror Ns and Zs will pop-out from a mixture of boring Ns and Zs. They should, if ‘novel letter’ had the status of a guiding feature.

Nobody believes that nature has equipped us with parallel processors for the Roman alphabet. The crucial question in letter search (and some related tasks) is whether over-learned sets acquire the ability to guide attention[54,55]. In the case of alphanumeric stimuli, it is exceedingly difficult to sort out possible visual confounds. It is worth noting that letter search tasks (like novelty tasks, above) seem to be vulnerable to distractor heterogeneity. The alphanumeric category refers to the specific claim that a letter might pop-out among numbers and vice versa. These effects (such as the ‘zero–oh’ effect) have been difficult to replicate.

Probably not guiding attributes. Intersection, once a plausible guiding attribute, has fallen off the list of guiding attributes[8]. Earlier experiments used stimuli that confounded intersection with other features such as line termination. Optic flow, colour change and three-dimensional volume are reasonable candidates that might have guided the deployment of attention. However, the data indicate that they do not. Faces are also natural candidates for guiding features. However, the preponderance of evidence indicates that, although faces are ‘special’ stimuli, they are processed one at a time. Evidence for guidance by faces tends to be followed by a study that shows that another visual feature is at work. This point is debatable and, certainly, there are others who would place faces higher on this list. The substantial and growing literature on search for semantically or affectively meaningful stimuli has a similar feel to it. An ability to find threatening snakes and spiders efficiently seems to have more to do with their visual status as distinctive shapes than their affective status as scary objects.

Conclusion

Some properties of visual stimuli can be used to control the deployment of attention. These are not simply the properties of early stages of visual processing. Instead, they seem to be a specific abstraction from the visual input. We can call this abstraction the guiding representation. On the basis of several decades of research, a list of guiding attributes can be proposed. Some dimensions, such as colour, size and orientation, are assured places on that list. Others, such as line termination, are probably guiding attributes, whereas others, such as threat, are probably not. For each of these dimensions, the specific rules of guidance must be worked out by experimentation. It is useful to think of the guiding representation as a control device that sits to one side of the pathway from early vision to object recognition. Whether this psychophysical structure has a neuroanatomical manifestation remains to be seen.

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Competing interests statement

The authors declare that they have no competing financial interests.

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