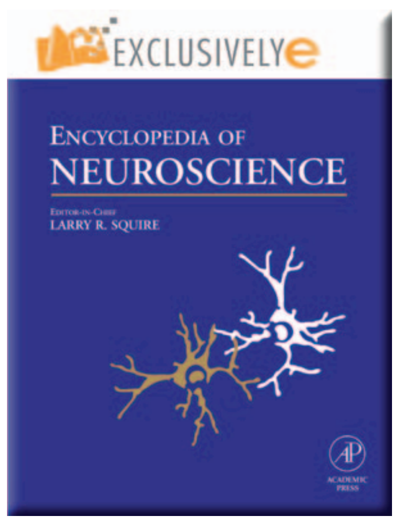

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Psychophysics of Attention

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Introduction

The amount of information available to our senses greatly exceeds the information processing capacity of our brains. How we deal with the overload is the topic of this article – attention. More specifically, this article focuses on the study of visual attention. The purpose of the article is not to summarize the neuroscience of attention, but to introduce the basic behavioral findings that have motivated interest in the concept.

Perhaps the most fundamental points about attention are that it is limited, and that it is selective. It allows an organism to select the information that is most relevant to its current goals. With attention we are not simply passive recipients of stimuli; instead, we play an active role in our interactions with the environment.

Before proceeding, it is worth making an important philosophical point. When we say something like "it allows an organism to select…" there is a real danger that we may reify the 'it.' We should remember that there is not a homunculus directing traffic in our heads; referring to attention as an active 'it' is a convenient verbal simplification. In fact, the selectivity of attention may be better thought of as an emergent property of our nervous system. In this brief overview of the field of attention we will touch on (1) evidence of limited capacity and (2) the nature of attentional selectivity.

Attention Is Limited

Enumeration

Some of the earliest experiments in psychology amounted to demonstrations of the limits of attention. For example, Jevons, a nineteenth-century researcher, picked up handfuls of beans and threw them into a box, and after glancing at them briefly, attempted to say how many there were. He found that he was essentially perfect when there were up to four beans, but beyond four made progressively more errors. Many variations of this experiment have been carried out. When reaction time is measured, the time required to respond increases only slightly from one to about four, and increases more steeply thereafter. The ability to enumerate small numbers of items quickly and accurately has been referred to as 'subitizing.' The widely, but not universally, accepted explanation is that a few items (up to about four to six, depending on the methodology) can be apprehended simultaneously; beyond that elements are presumably enumerated one at a time, or, if there is time pressure, their numerosity may be estimated.

Multiple-Item Tracking

Imagine an array of, say, ten gray disks appearing on a computer screen. They are all moving in erratic, random trajectories. One of them is marked as a target by blinking several times, but it then reverts to gray and keeps moving along with the other nine disks. Your task is to follow it for, say, 12 s. At that time the disks stop moving and a probe (a small box) appears around one of the gray disks. Your task is to indicate whether or not the probed item was the one that had been marked by flashing. Could you do it? Yes, indeed. This is a trivial task. Now imagine a trial on which not one but two of the ten disks are marked by flashing, and then after 12 s a single disk is probed and you are asked if this is one of the two that had been marked by flashing. Could you do this? Yes; this is a bit more difficult, but not much. However, as the number of marked disks increases there comes a point at which you simply cannot keep track of additional elements. That point varies across observers, but is approximately three to five disks.

Span of Immediate Memory

In a classic experiment by Sperling, when individuals were shown a 3×4 matrix of letters (four letters in three rows) briefly (say for about 0.1 s) and were asked to report as many as possible, they typically reported only four to five letters. In another condition, individuals were presented with a high-, medium-, or low-frequency tone, the tone indicating which one row (top, middle, or bottom) of the matrix they were to report. In this case they were able to report all four letters in a row when the tone came before or very shortly after the visual display. As the tone was selected randomly on each trial, this means that individuals briefly had access to all twelve letters in the display. However as the tone was delayed, performance declined, until, after as little as a 0.25 s delay, performance reached the same level as the whole report technique (i.e., about four or five letters). Thus, this research provides evidence of a high-capacity short-lived sensory memory (often referred to as iconic memory), followed by a small-capacity short-term memory store.

Psychologists have wondered whether the numerical similarity of the capacity limits (three to four items) shown in the these kinds of studies (enumeration, multiple-item tracking, and immediate-memory span) is evidence of a common limitation, or is just a coincidence. A strong case has been made for a common limit, due ultimately to the ability of attention to hold just three to four items at once. However, the issue is not yet settled. A related point is whether the limitation is properly described in terms of a fixed number of 'slots,' with one 'item' assigned to each slot. This is far from a trivial issue, as the definition of an item is by no means straightforward. For example, is the word 'attention' a single visual object, or are the nine letters composing it the proper units of analysis, or are the line segments composing those letters the proper units?

Visual Search

A popular method of studying perceptual processes is to have an individual look for a designated target item in a display that contains several distractors. Typically, the number of distractors is varied, although the number of targets has also been manipulated. Performance is assessed by measuring reaction time and/or accuracy of performance. Visual search provides a remarkably versatile tool for exploring many aspects of perception and attention with a task that has considerable ecological validity, as it is ubiquitous in everyday life.

One important characteristic of visual search is its efficiency, where by efficiency we refer to the slope relating total search time to the number of stimuli in the display. When search requires a simple discrimination, such as a circle among triangles, a 4 among Cs, or a red item among blue items, the process is highly efficient; the slope of the search function is often near zero. As adding additional items does not incur a cost in search time, such a result implies parallel processing of all elements in the display. Although a search based on a simple feature such as color or line orientation can be done in parallel, when a search target is defined as a conjunction of features (e.g., the target is a red horizontal line segment and distractors are a mixture of black horizontals and red verticals), then search time is often found to increase linearly with the number of stimuli in the display. One interpretation of such results is that efficient 'feature' searches are performed by preattentive mechanisms that can analyze the entire display at once. Searches for conjunctively defined targets, however, require sequential inspection of items, as attention is responsible for conjoining the separate features that constitute a visual object. (Although it is common to take linearly increasing reaction time functions to imply that processing is serial, it has been known for many years that this is not necessarily a safe assumption.)

The feature-integration theory of attention has been very influential. One appealing aspect of this theory is that it is based on known functions of the brain. It seems to suggest that elementary features detectable by early visual processing areas of the brain can be processed over the entire visual field at once, whereas dealing with combinations of elementary features, which presumably requires higher level cortical processing, must be done one item at a time, to avoid a 'combinatorial explosion.' However, over time, some problems with the theory have appeared. One difficulty is that several studies have demonstrated that there are feature combinations that can be processed in parallel. For example, efficient search has been found for brick-shaped objects drawn in such a way that their apparent orientation depended solely on their shading (i.e., which surface looked like it was directly illuminated). That is, a misoriented brick could be found in a background of uniformly oriented distractor bricks independent of the number of those distractors. It is possible to consider such demonstrations as either embarrassments to feature-integration theory or as discoveries of surprising new elementary features (although that claim seems inelegant and unparsimonious, as the number of such new 'features' has become substantial). Worse yet for the theory, there is clear evidence that a feature/shape conjunction can be processed in parallel. There is now even some doubt about the idea that simple features are processed preattentively; this is covered in the next section, in the discussion of the attentional blink. Finally, there are also some interesting effects of familiarity that seem inconsistent with the theory. For example, individuals have been asked to search for a single backward N among several normal Ns or a single normal N among several backward Ns. The latter search was fast and parallel, while the former search was slower and serial. The physical features of the targets and nontargets in these two searches were essentially identical; it is not obvious how the theory can account for the results. Indeed, these data suggest that familiarity itself may be serving as a feature. Could familiarity be detected by early visual areas? There is functional magnetic resonance imaging (fMRI) evidence of widespread reorganization of activity in the visual pathway after extensive training on a perceptual task. Retinotopic cortex is involved, although this is presumably activated in a top-down fashion.

As a result of these problems, several competing interpretations have been proposed. For example, in the 'guided search' model, attention is guided by preattentive processes to the location of likely target items. The ultimate identification of an item as the target or not requires attentive scrutiny of the item. The efficiency of a search depends on the amount of preattentive information available to guide search. This varies from the great efficiency of searching for a red patch in an array of green patches, through conjunction search, to the extremely inefficient search that occurs when the target and distractors share the same features (e.g., looking for a randomly rotated L among several randomly rotated Ts).

Doing Two Things at Once

In the preceding examples individuals may have had to deal with multiple stimuli, but the task in each case was in some sense unitary (count the objects, repeat back all of the letters, etc.) There has also been a great deal of research in which quite different tasks have been combined; what has been at issue is the extent to which tasks can be performed without mutual interference. The general expectation based on everyday experience is that it is difficult to do several things at once (e.g., pay attention to two simultaneous conversations). In contrast, multitasking is possible in some cases (e.g., driving while listening to the radio). Thus the research effort has largely been directed at finding out just which tasks are difficult to combine, and why. One part of this effort has been a search for special conditions in which tasks might be combined without loss, as such conditions might have implications for real-world scenarios, such as using a cell phone while driving.

Some early research with continuous tasks suggested that even fairly complex pairs of tasks that initially interfered with one another – such as typing visually presented text and shadowing (i.e., repeating back) a message played through earphones – could, after sufficient practice, be done as well together as separately. However, with complex continuous tasks it is often possible to interleave components of the tasks so as to minimize or even eliminate the amount of temporal overlap between components of the two tasks. (An extreme example: a centerfielder could probably read a book during the 'slack time' when he is not actively engaged in the game.) Scientists wishing to achieve a more fine-grained analysis of dual-task performance have used simplified tasks to permit a closer analysis of stimulus–response relations. Perhaps the most well-developed analyses come from the psychological refractory period paradigm. In this paradigm two stimuli are presented, S1 and S2, with a variable stimulus-onset asynchrony (SOA). Typically, study participants are instructed to respond as quickly as possible to each stimulus with the appropriate response, R1 and R2, respectively. When the two tasks are widely separated in time there should be no interference between them and we can obtain baseline reaction times (RTs). As the stimuli are presented closer together in time, the reaction time to the second stimulus (RT2) will tend to increase. Most strikingly, in some cases, as the time between stimuli becomes less than about 300 ms, RT2 increases about 1 ms for each millisecond that the SOA is decreased. It is this kind of result, suggesting a clear inability to produce R2 at the same time as R1, that led to the nomenclature of a refractory period, by analogy to the refractory period of neurons.

Another example of the difficulty of responding to two stimuli presented close together in time is known as the attentional blink (AB). In a typical AB task, a rapid series of stimuli (e.g., digits or letters) is presented at fixation, typically at a rate around 10 items per second, and either one or two targets can appear within the stream. The AB refers to a decrement in the detection or identification of the second target (T2) when it occurs soon after the presentation of the first target (T1), to which a response is required. Early models of the attentional blink assumed that T2 processing is impaired because attention is temporarily fully occupied by processing of T1.

In an instructive example, a stream of letters was presented at fixation. There were two targets. The first was a green letter; all of the other letters in the stream were black. The green letter was followed after a variable delay (the lag) by the second target, which was a ring of Gabor patches (a Gabor patch is, essentially, a small patch of parallel stripes) in the periphery surrounding one of the later letters in the stream. Participants had to name the colored letter and also indicate if all of the Gabor patches were oriented in the same direction or if one was misoriented by 90°. In a control condition, individuals could ignore the stream of letters and just indicate if the ring of Gabor patches contained an orientation oddball. Performance in the control condition was about 90% correct and did not vary with the lag between the green letter and the Gabor patches. In the experimental condition, performance was poor (about 60% correct) when the Gabor patches were simultaneous with the green target letter, and improved to nearly 90% correct when the lag between the green letter and the Gabor patches was 700 ms.

What makes these results interesting are the implications they may have for the study of visual processing. The detection of a Gabor patch differing by 90° in orientation from an otherwise uniformly oriented set of patches should be handled preattentively according to feature-integration theory, and, indeed, the reaction time to detect a Gabor patch misoriented by 90° is independent of the number of other patches – which is precisely the diagnostic that has been taken to indicate preattentive processing in discussions of feature-integration theory. Why then should there be a large dual-task decrement? One possible answer is that it takes a really difficult competing task, such as is presumably provided by the attentional blink paradigm, to show that orientation discrimination, while easy, is not completely attention free. However, it is also possible that the deficit is not due to T1 stressing attentional capacity for feature processing; it may be that the attentional blink reflects difficulty with one or more higher level functions, such as maintaining executive control of a task set in the face of a fast-moving sequence of targets and nontargets. The attentional demands of various kinds of perceptual discriminations remain a topic of great interest and the final word has not yet been written.

Attention Is Selective

The preceding evidence points to a variety of limitations on attentional capacity. It is clear that we cannot process everything, at least not at once. What is it that determines just what it is that we do process? William James distinguished between passive and active attention. Today, the corresponding terms for passive attention are usually 'bottom-up,' 'stimulus-driven,' or 'exogenous,' while corresponding terms for active attention are 'top-down,' 'goal-directed,' or 'endogenous.' What we attend to is determined both by properties of the stimulus array (e.g., a sudden loud sound, or a movement in the periphery) and by our goals and intentions. Much research has examined the nature of the interaction between, and relative importance of, stimulus-driven and goal-directed sources of control.

The brute fact of selectivity has been demonstrated many times. In the technique known as shadowing, used in studies of dichotic listening, different messages are played to individuals over left and right earphones. Study participants are instructed to repeat back the message played to one ear. They are able to do this quite well. What is especially interesting is the analysis of what information individuals extract incidentally from the unattended message in such circumstances. They can report a change from speech to a pure tone, or a change from a male to a female voice. However very few persons notice a change from English to German or a change from normal to reversed speech when these changes were in the same voice. Most important is the near-total lack of comprehension of the message in the unattended ear. Related experiments have been performed in vision. Participants were shown two episodes on optically superimposed video screens. One was a ballgame and one was a handgame. Participants counted unpredictable events (e.g., the number of times the ball was passed from one player to another). In some conditions individuals were instructed to attend to just one of the episodes; in some conditions they were asked to attend to both. One finding concerned capacity; participants were reasonably accurate when they had to monitor one episode, but they could not deal with both simultaneously. The other finding concerned selectivity. The episodes occasionally contained distinctly odd events (e.g., a woman carrying an umbrella walking through the ballgame). After seeing the episodes, participants were asked about these odd events; they were often entirely unaware of those that occurred in the unattended episode. This kind of result has since been dubbed inattentional blindness and has been the subject of several more analytic studies.

The interaction of stimulus-driven and goal-directed attention is illustrated in a series of studies concerned with the capture of attention by featural singletons (e.g., the lone red element in a display of green elements) or by sudden onsets of a new stimulus object in a field of persisting objects. In one experiment participants searched for a target letter in an array of three or six other letters. This is a demanding search task in which reaction time increases with the number of letters in the display. Stimuli started out as placeholders (like the figure 8 of a digital clock), and at a certain point in time selected segments were deleted, revealing letters. In some conditions a new object was added to the display at the moment when the letters were being revealed (i.e., a letter was displayed in a location that had not contained a placeholder). Importantly, the location of the sudden onset was in no way predictive of the location of the target. This new object attracted attention; if it was the specified target character, reaction times were fast and independent of display numerosity, but if it was not the target, reaction times increased with display numerosity. Thus the sudden onset of a new object appears to capture attention in a stimulus-driven fashion. A follow-up experiment was conducted to determine if there is something special about sudden onsets. In this case the displays contained a single character that was unique with respect to color or brightness (e.g., a red element when other elements were green). Strikingly, reaction time was the same whether or not the display contained a singleton. In other words, unlike a sudden onset, color and brightness singletons did not automatically attract attention. This study raised at least two questions that have been the subject of further investigation: (1) Is it really the case that feature singletons do not capture attention? (2) Is the sudden onset of a new object really different from other kinds of featural singletons with respect to its ability to capture attention?

Do Feature Singletons Automatically Capture Attention?

In some studies, performance on displays containing an irrelevant singleton is compared to performance when displays contain no irrelevant singleton. For example, in one study participants were presented with displays consisting of colored circles or diamonds arranged around an imaginary circle. A line segment of a variable orientation appeared inside each shape; the task was to determine the orientation of the line segment within a target item. The target item was defined as the unique green diamond among green circles. Search was parallel – that is, independent of display size – but was significantly slower when one of the circles was red than when all elements were green. When the color singleton was made less salient than the shape singleton by changing the colors in the display, the color singleton no longer slowed search for the shape singleton; indeed when the roles of the original color and shape dimensions were reversed (color target and shape distractor), the more salient shape singleton now slowed search for the color target. Note that the color singleton provided no information about the target. This study was interpreted as showing that attention is captured automatically by the most salient element in the display.

An alternative to this analysis is that what an individual first attends to depends not just on the salience of stimuli, but also on the individual's task set. It has been suggested, for example, that salient stimuli may only attract attention when individuals adopt the strategy of searching for a feature discontinuity (singleton-detection mode). When individuals adopt the strategy of searching for a specific, known-to-be-relevant, feature (feature-search mode), bottom-up capture can be overridden. In tasks where both strategies are available to the individual (e.g., where the target is a specific feature and also a singleton, such as a green circle among green triangles), both search strategies are available. Therefore, an irrelevant singleton may or may not cause interference, depending on which strategy the individual adopts. In support of this claim it has been shown that when singleton-detection mode is discouraged, and individuals are forced to resort to feature-search mode, a salient distractor no longer interferes with search.

There has been an ongoing debate about the extent to which the most salient item captures attention automatically, as opposed to capturing attention only when an appropriate strategy has been selected. Be that as it may, the consideration of search strategies has led to new findings. For example, circumstances can be arranged to force individuals to search in time rather than in space. Individuals viewed a central rapid serial visual presentation stream (just as in the attentional blink paradigm) in which a target letter was defined by being a particular color (e.g., red). On critical trials, an irrelevant color stimulus could appear in the periphery during one frame of the stream. Interestingly, the irrelevant stimulus reduced the probability of an individual identifying the target letter, when that irrelevant stimulus preceded the target by 200 ms. That is, even though the peripheral stimulus was irrelevant and did not have to be responded to, it had the same effect as a first target in the attentional blink paradigm. That sounds like automatic capture by the irrelevant stimulus, but there is a critical additional finding: the existence of this interference effect was dependent on whether the individual was in singleton-detection mode or feature-search mode. In one experiment, to induce singleton-detection mode, the letters were all gray except for one that was red. (In fact, half the individuals were tested with red, half with green.) Note that when there is just one colored character in a stream of otherwise all gray characters, either feature search or singleton detection could have been applied. In this experiment, regardless of whether an individual was in the search-for-red or search-for-green group, both red and green peripheral distractors produced substantial, and equal, interference with target detection. In a second experiment, multiple colors were used in constructing the letter stream. Again the target was either red or green (different groups of individuals), but now the individuals had to look for a particular color, whereas in the first experiment they could have searched for 'anything chromatic.' Now, individuals who searched for a red target only suffered interference when the distractor was red, and individuals who searched for a green target only suffered interference when the distractor was green. Follow-up experiments established that the interference was due to a spatial capture of attention.

Are Sudden Onsets Special?

An influential account of how performance in search tasks might be affected by nominally irrelevant singletons is that participants in search experiments always adopt one or another sort of attentional control setting that determines what will be selected. (We have already come across this notion; singleton detection and feature search can be considered specific examples of attentional control settings.) To test this idea, participants searched for a target character that could be either a color or an onset singleton across blocks. Immediately preceding each search display another display appeared that contained a cue that was itself either a color or an onset singleton in one of the (four) potential target locations. It was explained to the participants that the location of the cue was independent of the location of the target. The chief result was that target reaction times were strongly dependent on the cue location, but only when the cue matched the target dimension. For example, if the task was to identify a color singleton, then reaction time was faster when the target was in the same location that the cue had occupied than when it was in another location. However, when participants had to identify a color singleton, the location of an onset cue had no effect on reaction time. This finding is contrary to the notion that the sudden onset of a new object is unique in that it captures attention automatically (i.e., in a stimulus-driven fashion). The possibly special status of sudden onsets is controversial and remains a topic of lively current interest.

Conclusion

The study of attention has been of keen interest to psychologists for over a century. A great deal of progress has been made in understanding the limitations of our perceptual and cognitive processes, and the selectivity these limitations force on us. Most of this research has used psychophysical methods solidly within the behavioral tradition. However over the past 20–30 years the conceptual and methodological armamentarium available to study attention has been expanded in scope by the growth of the neurosciences.

See also: Attention: Models; Attentional Networks; Attentional Networks in the Parietal Cortex; Attentional Functions in Learning and Memory; Human Methods: Psychophysics; Short Term and Working Memory; Visual Attention.

Further Reading

Burnham BR (in press) Displaywide visual features associated with a search display's appearance can mediate attentional capture. *Psychonomic Bulletin & Review.*

Cowan N (2001) The magical number 4 in short-term memory: A reconsideration of mental storage capacity. *Behavioral and Brain Sciences* 24: 87–185.

Enns JT and Rensink RA (1990) Sensitivity to three-dimensional orientation in visual search. *Psychological Science* 1: 323–326.

Folk CL, Remington RW, and Johnston JC (1992) Involuntary covert orienting is contingent on attentional control settings. *Journal of Experimental Psychology: Human Perception & Performance* 18: 1030–1044.

Jonides J and Yantis S (1988) Uniqueness of abrupt visual onset in capturing attention. *Perception and Psychophysics* 43: 346–354.

Joseph JS, Chun MM, and Nakayama K (1997) Attentional requirements in a 'preattentive' feature search task. *Nature* 379: 805–807.

Leber AB and Egeth HE (2006) It's under control: Top down search strategies can override attentional capture. *Psychonomic Bulletin & Review* 13: 132–138.

Lien M-C, Ruthruff E, and Johnston JC (2006) Attentional limitations in doing two tasks at once: The search for exceptions. *Current Directions in Psychological Science* 15: 89–93.

Mandler G and Shebo BJ (1982) Subitizing: An analysis of its component processes. *Journal of Experimental Psychology: General* 11: 1–22.

Neisser U and Becklen R (1975) Selective looking: Attending to visually specified events. *Cognitive Psychology* 7: 480–494.

Olivers CNL, Stigchel S van der, and Hulleman J (2005) Spreading the sparing: Against a limited-capacity account of the attentional blink. *Psychological Research* 8: 1–14.

Pashler H (1998) *The Psychology of Attention.* Cambridge, MA: MIT Press.

Pylyshyn ZW and Storm RW (1988) Tracking multiple independent targets: Evidence for a parallel tracking mechanism. *Spatial Vision* 3: 179–197.

Sperling G (1960) The information available in brief visual presentations. *Psychological Monographs* 74(no. 11): 1–30.

Theeuwes J (2004) Top-down search strategies cannot override attentional capture. *Psychonomic Bulletin & Review* 11: 65–70.

Treisman A and Gormican S (1988) Feature analysis in early vision: Evidence from search asymmetries. *Psychological Review* 95: 15–48.

Wang Q, Cavanagh P, and Green M (1994) Familiarity and pop-out in visual search. *Perception & Psychophysics* 56: 495–500.

Wolfe JM (2003) Moving towards solutions to some enduring controversies in visual search. *Trends in Cognitive Sciences* 7: 70–76.