A selective review of selective attention research from the past century

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Research on attention is concerned with selective processing of incoming sensory information. To some extent, our awareness of the world depends on what we choose to attend, not merely on the stimulation entering our senses. British psychologists have made substantial contributions to this topic in the past century. Celebrated examples include Donald Broadbent's filter theory of attention, which set the agenda for most subsequent work; and Anne Treisman's revisions of this account, and her later feature-integration theory. More recent contributions include Alan Allport's prescient emphasis on the relevance of neuroscience data, and John Duncan's integration of such data with psychological theory. An idiosyncratic but roughly chronological review of developments is presented, some practical and clinical implications are briefly sketched, and future directions suggested. One of the biggest changes in the field has been the increasing interplay between psychology and neuroscience, which promises much for the future. A related change has been the realization that selection attention is best thought of as a broad topic, encompassing a range of selective issues, rather than as a single explanatory process.

What we see, hear, feel and remember depends not only on the information entering our senses, but also upon which aspects of this we choose to attend. William James (1890/1950, p. 402) emphasized this in asserting that 'my experience is what I agree to attend to'. We must all have been in situations where we failed to notice something in daily life (be this a visual object, or words spoken to us) because our mind was engaged with something else. Selective attention is the generic term for those mechanisms which lead our experience to be dominated by one thing rather than another.

Selective attention has become a central topic in cognitive psychology, and more recently in cognitive neuroscience also. Discussions of the topic within the British Psychological Society date back as far as 1910 (Hicks, cited in Edgell, 1947), but here I focus mainly on work from the 1950s onwards. Given this volume's theme, I emphasize distinctive British contributions to the topic. Fortunately, these include some of the major developments in the field, so a review emphasizing these may hopefully not become too parochial (see Pashler, 1998; Yantis, 2000, for recent reviews with less of a British emphasis). Space limits preclude an exhaustive review even of British research, so I focus on research that has particularly influenced me. My account follows a roughly chronological structure. Many of the fundamental issues recur throughout the decades, although there have been many remarkable changes also.

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Early work on selective listening, and Broadbent's filter theory

Research in the 1950s concentrated primarily on hearing, and the so-called 'cocktail party' problem. Although cocktail parties regrettably may be much less common now than in those heady days, the fundamental problem they illustrate remains. In many situations (e.g. a noisy room full of people), many sounds enter our ears at once. How are we able to pick out just those sounds which are currently relevant to us (e.g. the conversation we are taking part in)? Moreover, what is the difference in processing for such attended sounds vs. unattended sounds (e.g. the other conversations taking place in the room)? Many classic experiments on this topic used the 'selective shadowing' task. In prototypical form, two different spoken messages were played at the same time (often one message to each ear over headphones, by means of the tape-recorders that were the latest technology of the time). Listeners concentrated on one message and ignored the other, which was usually enforced by requiring them to 'shadow' (repeat aloud) just one of the two messages as rapidly as they could. Nowadays we might prefer a method where the listeners did not make speech sounds themselves.

The two initial empirical questions were simple but fundamental: (1) What differences between two messages are needed for people to be good at selective shadowing (analogous to picking out a relevant conversation at a party)? and (2) What do people typically know about the message they are *not* shadowing (analogous to the currently ignored conversations that also enter the ears at a party)? The initial answers seemed straightforward: (1) for efficient shadowing, there needs to be a clear physical difference between the messages, such as their coming from different locations (or being played to different ears), or having very different voices (e.g. low-pitch male, and higher-pitch female); and (2) given such a physical difference, people appear to know surprisingly little about the non-shadowed message, at least when questioned retrospectively. They have little idea of the topic of this ignored message, and can apparently fail to notice that a single word was repeated in it many times, or even a complete change in the language spoken (Broadbent, 1958; Moray, 1959). This is true even when the ignored message is just as loud and clear at the ear as the attended message, so that its properties would have been readily noticed if it had been attended instead of the other message. The only properties which people were able to report retrospectively for the non-shadowed message appeared to be rather unsubtle, physical properties. For instance, they might notice a substantial change in the pitch of the voice (e.g. from female to male); the sudden insertion of a loud tone; or the message ending.

The pioneering experiments on selective hearing were conducted by several different people, including Cherry (1953). Perhaps the most important British contribution was Donald Broadbent's (1958) filter theory. This was presented in a landmark book that summarized the results from many experiments, integrating them into a comprehensive theoretical account. Broadbent's initial interest had been fuelled less by noisy cocktail parties than by the seemingly different (but actually related) problems of radar operators in the Second World War when trying to communicate with several different pilots at once, while their voices were all relayed over a single loudspeaker. Broadbent's (1958) book still remains an intellectual landmark, and its influence is widely felt. It was one of the first theoretical accounts to relate psychological phenomena to information-processing concepts from mathematics and computer science. The computer metaphor

for the mind, which was to become so dominant in subsequent decades, was suggested powerfully by Broadbent, with a strong analogy drawn between the attentional limits of people and limits of central processing units in many computers. His original filter theory was encapsulated in a deceptively simple flow-diagram (see Fig. 1A), which was the precursor of many subsequent 'box-models' in cognitive psychology (and later in cognitive neuropsychology).

A key insight encapsulated in Broadbent's model was that the two main empirical questions described above (i.e. what differences between inputs are needed for efficient selective attention; and what does the person then know about the unattended input?) may have yielded related answers. Recall that selective shadowing is most efficient with clear physical differences between the two concurrent messages (e.g. differences in pitch); and that people seem to notice only simple physical properties (e.g. sudden changes in pitch) for the non-shadowed message, not its meaningful content. Broadbent's (1958)
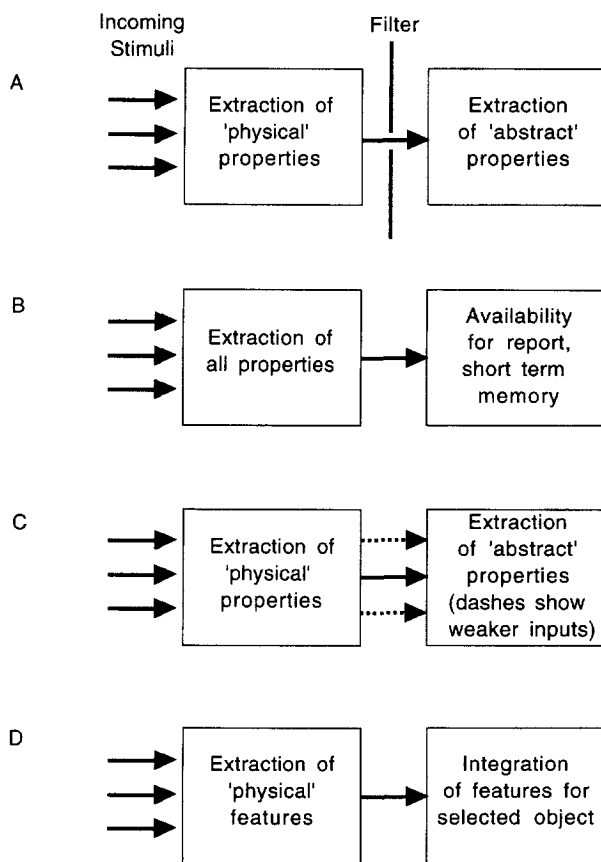

Figure 1. Schematic depiction of four influential accounts of selective attention, illustrating how they all bear a familiar resemblance to Broadbent's (1958) original filter theory. A = the early-selection filter theory; B = a rival late-selection account; C = Treisman's (1960) 'attenuation' version of Broadbent's theory; D = Treisman and Gelade's (1980) feature integration theory.

model explained all this by proposing two qualitatively different, successive stages of perceptual processing (Fig. 1A). In the first stage, 'physical' properties (such as the pitch or location of sounds) would be extracted for all incoming stimuli, in a 'parallel' manner. In the second stage, more complex psychological properties, that go beyond simple physical characteristics (e.g. the identity or meaning of spoken words), would be extracted. This second stage was held to be more limited in capacity, so that it could not deal with all the incoming information at once when there were multiple stimuli (it might therefore have to process them 'serially', rather than in parallel). A selective filter protected the second stage from overload, passing to it only those stimuli which had a particular physical property, from among those already extracted for all stimuli within the first stage.

This brilliantly simple model could explain all the phenomena described so far (though as we shall see, it proves far too simple when faced with all the complexities of the brain). Selective attention is efficient only with clear physical differences between concurrent inputs, as the first parallel stage only extracts properties of this kind, so filtering can be based only on them. People know little about the contents of an unattended message, because the selective filter prevents this information from passing through to the second stage. They can, however, report simpler physical properties of unattended messages, as these would be extracted in the first non-selective stage.

This account is still heavily influential today. The distinction between a parallel 'preattentive' stage encoding simple physical properties vs. a serial 'attentive' stage encoding more abstract properties remains common in the current literature. Indeed, a dichotomous preattentive/attentive split is often assumed as given, perhaps too readily; likewise for the ideas that selection may arise at just one particular point in processing, and that the purpose of selection is to protect a limited-capacity system from overload. Indeed, some authors (e.g. Allport, 1980, 1987, 1992) have argued that Broadbent's ingenious ideas may if anything have been almost too influential; once exposed to them, it becomes hard to think about attentional issues in any other way!

Broadbent's account not only explained the available results at the time, but had the virtue of also making clear predictions. It quickly became a target for experiments seeking to falsify it, with some of the best-known studies being conducted by Broadbent's PhD students, including Anne Treisman. Ironically, her later proposals would replace Broadbent's as one of the main targets to shoot at later in the century, when she presented her influential feature-integration theory of visual attention.

Indirect measures of unattended processing: apparent falsifications of filter theory

Filter theory asserted that unattended information, not passed by the selective filter, would not undergo the elaborate processing (e.g. of word identity and meaning) that was envisaged to take place only in the second, serial state with its limited capacity. But several apparent demonstrations of such processing for non-shadowed messages were reported in the years following Broadbent's (1958) book.

There are many methodological problems to overcome when trying to assess the level of processing for 'unattended' stimuli. As mentioned above, the first approach used was retrospective questioning, typically given in the form of surprise questions about a non-shadowed message at the end of several minutes of selective shadowing. The problem

with this method is that people might appear to know very little by then, not because their perceptual systems had never processed the unattended information, but simply because it had been forgotten by the time of the surprise question. (This long-standing problem also applies to many recent experiments on visual attention (e.g. Mack & Rock, 1998), albeit as a finer timescale). A more immediate measure of processing for unattended information seems required. However, there clearly would be little point in asking people directly about supposedly 'unattended' information during its presentation, as they would then promptly attend to it. The solution to this thorny problem is to devise *indirect* on-line measures of processing for unattended stimuli—'indirect' in the sense that the person is never asked directly about the information they are meant to ignore. Its processing may instead be assessed in some other way, either by means of its effect on psychological responses to related attended information, or on autonomic responses (or more recently, neural responses) to the unattended information itself.

In one famous but controversial example, Corteen and Dunn (1974) conditioned people by pairing electric shock with certain words, so that when these words were heard the person would exhibit a galvanic skin response (GSR). The critical result was that after conditioning, such words apparently still produced some detectable GSR even when played among words in the non-shadowed ear, during selective shadowing of words on the other ear. Moreover, when people were instructed to make an overt response whenever they heard a conditioned word, they typically missed many critical words presented on the non-shadowed ear (perhaps suggesting that these really were unattended), yet still showed some GSR to them (though see Holender, 1986). Finally, GSRs for unattended words were claimed to generalize to synonyms of the conditioned words (Von Wright, Anderson, & Stenman, 1975), which would seem to imply some processing of their meaning—exactly the kind of processing which filter theory prohibited for unattended words.

Other indirect tests used psychological rather than physiological measures, and also produced some evidence that apparently unattended stimuli could receive a higher level of processing than that predicted by Broadbent (1958). For instance, Mackay (1973) reported that non-shadowed words could bias the interpretation of ambiguous shadowed sentences, while Lewis (1970) found that the latency to shadow relevant words on one ear could be affected if concurrent words on the other ear were related in meaning.

Early selection, early attenuation, or late selection?

Broadbent's (1958) filter theory is the classic example of 'early selection' approaches, which argue that the treatment received by attended vs. unattended information differs early in perceptual processing. It is a rather extreme example of this, as unattended information was thought to be blocked completely once a fixed bottleneck was reached, with only simple 'physical' properties being extracted prior to that. The indirect measures suggested that this was not always the case, and that unattended information could sometimes be processed more deeply. There were two different theoretical responses. One ('late selection') argued that such deep processing was the rule rather than the exception; whereas the other ('attenuation theory') argued conversely.

Late selectionists (including British researchers working in the USA, such as Deutsch and Deutsch (1963)) proposed that the limited awareness of unattended stimuli (as for the non-shadowed message in selective listening experiments) might have less to do with rejection from full perceptual processing, than with rejection from entry into memory or into the control of deliberate responses, a view that was subsequently articulated further by John Duncan (e.g. Duncan, 1980). Thus, unattended stimuli might conceivably undergo full perceptual processing, yet without the person being able to base their deliberate responses upon this, and without the formation of explicit memories. Hence, the overall architecture might in principle remain similar to that in Fig. 1A, albeit with considerable changes in what takes place within each stage (see Fig. 1B). The initial parallel, unlimited stage might now include *all* perceptual processes, with the second serial, limited-capacity stage concerning selection for awareness, response and/or memory instead. Although such a position can accommodate some of the findings on selective attention (and I once held this position myself), I would say that it has now been falsified conclusively, perhaps most clearly by recent evidence from neuroscience as described later.

Treisman (1960, 1969) proposed a less drastic revision of Broadbent's filter theory in order to accommodate the psychological evidence that apparently unattended stimuli were sometimes processed deeper than expected. On her view, such deep processing of unattended stimuli might be the exception rather than the rule. She proposed that unattended stimuli were 'attenuated' rather than completely filtered out. In terms of the simplistic two-stage models in Fig. 1, the second stage would now receive some inputs from unattended as well as attended stimuli, but these would be weaker than for attended stimuli (see Fig. 1C). Indeed, they might be so weak that they would not usually support the extraction of abstract properties like word identity and meaning. However, in exceptional cases, this weak input might be sufficient for identification. Specifically, this could apply for stimuli which currently had a very low 'threshold' for identification, such as those primed by the current context. For instance, words recently associated with electrical shock (as in the GSR experiments of Corteen & Dunn, 1974) presumably become very special words for the participants in the experimental context (!), and so might be identified on the basis of less perceptual evidence than usually required. Other words may be special over longer periods because of their personal significance. For instance, Moray (1959) observed that people often notice their own name in the non-shadowed message during shadowing (which may relate to the everyday experience of realizing that someone is now talking about you, or to you, in a conversation that you previously seemed unaware of). On Treisman's attentuation account, this could arise because we are permanently primed to detect personally significant words, such as our own name, which may therefore require less perceptual information than other words to trigger identification.

The subtlety of Treisman's account is perhaps best illustrated by reference to one of her own early studies (Treisman, 1960). When shadowing a spoken message on one ear and ignoring another message on the other ear, people would occasionally switch the ear they repeated if the messages were suddenly swapped unexpectedly. For instance, the right ear might receive something like 'he put the stamp on and posted the/three possibilities'; while the left ear received 'I think we should look at these/letter with'. Under such conditions, people who had been continuously shadowing the right ear might

say aloud, 'he put the stamp on and posted the LETTER', thus swapping which ear was reported as the messages jumped. A late-selectionist would take such a result to indicate that, despite the person's apparently limited awareness of the non-shadowed message, in fact the meaning of both messages was being extracted by the brain all along. By contrast, on the attenuation account, Treisman could argue that the attenuated input from the left ear, when the right ear was initially attended, was too weak for most of the left words (i.e. 'I think we should look at these') to be identified. But the critical word 'letter' on the left would be special, being so primed by the preceding attended right-ear context (which makes 'letter' rather predictable after 'he put the stamp on and posted the...') that exactly the same attenuated level of input would suddenly become sufficient to identify the primed word.

Treisman's sophisticated position set a precedent for many ideas that were later to prove essential to cognitive psychology, and also to connectionism (e.g. McClelland & Rumelhart, 1981). In particular, Treisman's attenuation account stressed the key roles that partial information (e.g. attenuated inputs) and priming (from immediately preceding context, and also from longer-term repetition) can have on psychological processes. Anne Treisman remains a major player in attention research, and returns to centre stage later in this review.

Geoffrey Underwood (1977) added a further twist to the already sophisticated story concerning effects of priming on selective shadowing. Using two messages which did not swap ears, he showed that while it is possible to achieve some priming effects from a word presented in a non-shadowed ear (on the latency of shadowing for a related word on the task-relevant ear), there is a limit to such priming from an unattended message, as compared with that from an attended message. Priming from a preceding attended message becomes larger as one extends the related sentential context (e.g. a larger priming effect would be found upon the shadowing latency for 'letter' from the preceding phrase 'put the stamp on the envelope and post the...', than from having only one related preceding word (e.g. 'I think we should POST the...'). By contrast, if the related preceding context is played to the non-shadowed ear rather than the shadowed ear, then any priming effect on response to the critical word (here 'letter') does not seem to extend beyond that produced by a single related word (i.e. 'post'). While some researchers still argue even today about whether the meaning of single unattended words is always extracted by the brain (as on extreme late-selection positions), or is extracted only sometimes (as on attenuation theory, plus other positions that I describe below), few would challenge Underwood's (1977) conclusion that entire sentences are processed as wholes, and integrated into extended syntactic and semantic frames, only when they are attended.

Early vs. late selection in vision

Although early work in the 1950s was concerned mainly with selective attention in audition, from the 1960s onwards most work focused on vision, and gradually drifted away from the early preoccupation with language processing. Much of this work can still be considered within the agenda set by Broadbent (1958), although note that the distinction between extraction of 'physical' properties vs. more abstract 'semantic' properties (over which early and late selectionists traditionally become so exercised) is

somewhat easier to make for linguistic stimuli such as words (whose semantics are arbitrarily related to their appearance or sound) than for natural visual objects (whose 'semantics' may often relate to their visual appearance; see e.g. Shallice, 1988). Moreover, as our knowledge about perceptual processes has become increasingly sophisticated, it has become apparent that many of the apparently 'simple' physical properties attributed by Broadbent to the first stage of his model (e.g. the pitch and location of sounds, or the colour and location of visual objects) are actually not so simple at all, requiring much sophisticated computation.

Nevertheless, initial research on selective attention in vision produced many echoes of the early vs. late selection debate in audition. Early work on 'iconic memory' is often now presented outside the context of selective attention research within textbooks, but it actually provides many close analogies with Broadbent's filter theory. Sperling (1960) famously observed that when presented briefly with many letters (e.g. four rows of three) all at once, people cannot report them all, implying some form of 'limited capacity'. Yet when presented with the very same arrays, and cued to report just a specific subset (e.g. just the top row) they can do remarkably well at reporting all the relevant letters, even when eye-movements are ruled out. From the Broadbent perspective, it is tempting to think of this in terms of a selective filter passing only the relevant letters to a limited capacity stage. Further work (e.g. Von Wright, 1970) suggested that selective report in the iconic-memory paradigm may be most efficient when relevant and irrelevant letters are distinguished by apparently simple physical properties (e.g. highly distinct colours or locations), rather than by more abstract properties (e.g. letter vs. digit), suggesting a further close analogy with the Broadbent model. Again, the filter could apparently only be set to pass certain physical properties, perhaps as only these have been extracted prior to it. However, sceptics might point out that the particular physical properties used in such experiments may simply have been more discriminable than the abstract properties examined (see Bundesen, 1990; Coltheart, 1983; Duncan, 1981).

Further work in vision also produced echoes of the previous early vs. late selection debate for audition. Rock and Gutman (1981) argued that there was little processing of unattended visual information, based on poor performance in a surprise memory test at the end of the study (see also Mack & Rock, 1998), somewhat analogous to auditory observations in classic shadowing studies. They superimposed red and green outline drawings of different shapes, and asked people to concentrate on the shapes in one colour only (to rate their aesthetic appeal). A surprise recognition memory test showed good memory for attended shapes, but apparently none for unattended shapes, even though both had been equally clear on the retina. People also apparently failed to notice familiar, meaningful objects if presented in the unattended stream of shapes, when tested with retrospective questioning. Rock and Gutman argued that this poor memory reflected an absence of perceptual processing at the time of presentation (see also Mack & Rock, 1998). Of course, such an early-selection interpretation is subject to the same forgetting criticism as for the poor memory originally observed with non-shadowed auditory messages. Moreover, late selectionists might appeal not only to this retrospective point, but also to the fact that Rock and Gutman used very direct probes of the knowledge people had about ignored visual objects. On the late selectionist view that unattended information might be processed yet unavailable for conscious report, more indirect measures would be more appropriate.

In 1985, Steve Tipper produced such a measure for a situation based closely on Rock and Gutman's (1981) work. Superimposed red and green drawings of two different visual objects were presented, and the task was speeded naming of the object in one specified colour. The relationship between the ignored object on one trial and the subsequent attended object on the next trial was manipulated. Tipper found slower reaction times ('negative priming') when the previously ignored object was related to the subsequent attended object (see also Neill, 1977). He gave this a late selection interpretation, proposing that unattended visual objects may undergo full perceptual processing and object recognition, but then be actively inhibited. The notion of active inhibition during selection now seems here to stay (e.g. see the various contributions to Monsell and Driver (2000)), and there have been many subsequent studies of negative priming, including work addressing individual differences and special populations (ranging from the normal elderly to people with schizophrenia; e.g. Beech, McManus, Baylis, Tipper, & Agar, 1991; Simone & Baylis, 1997; Tipper, 1991).

Early vs. late selection debates in visual research raged not only on the basis of negative priming effects, but also in relation to many other indirect, reaction-time measures of unattended processing. There are many classic demonstrations that distractors can interfere with choice reaction times to a concurrent target, if associated with a different response to that required by the target (e.g. Eriksen & Eriksen, 1974; Stroop, 1935). Late selectionists delighted in interpreting such interference effects as evidence for full processing of unattended distractors; early selectionists preferred to think of them as exceptional failures of attention, such that the distractors producing the interference effects were unwittingly attended. In apparent support of the latter view were demonstrations that distractor interference could be reduced if the distractors were made more physically distinct from targets (e.g. Francolini & Egeth, 1980), for instance, being placed further away (Eriksen & Eriksen, 1974). But apparently against a strict early-selection interpretation of this, distractors producing no interference on response to a concurrent target might nevertheless produce some negative priming on response to a subsequent target (e.g. Driver & Tipper, 1989). In much of this debate, Treisman's (1960, 1969) subtle point that such effects might be driven by only partial processing of distractor information was often overlooked, with researchers frequently adopting the dichotomous mind-set that either strict early selection, or else strict late selection, must be correct.

A reader surveying the extensive literature on the early vs. late selection debate (see Johnston & Dark, 1986; Kahneman & Treisman, 1984; Pashler, 1998, for reviews) might lose hope of any resolution, since roughly half of the evidence seems to support each opposing camp. However, Nilli Lavie recently proposed an account which may explain both halves of this seemingly contradictory evidence (see Lavie, 1995, 2000). In an extensive review of past findings, Lavie and Tsal (1994) noted that results apparently favouring late selection had typically been obtained in situations of low 'perceptual load' (e.g. with just a single target and single distractor, plus a relatively undemanding task for the target); whereas apparent support for early selection typically was obtained when perceptual load was higher (e.g. more stimuli presented, and/or a more demanding target task). Lavie (1995) then conducted further visual experiments (all measuring distractor processing via interference effects on reaction times to concurrent targets)

to test this directly. She confirmed, for several converging operational definitions of perceptual load, that distractor interference was always greater in low-load than high-load situations. She proposed an account to explain this, incorporating some aspects of both early and late selection approaches, even though these have so often been considered as mutually exclusive. As in traditional late selection (e.g. Deutsch & Deutsch, 1963), she assumes that perceptual processing is automatic, in the sense that it cannot be withheld deliberately; so we perceive whatever is within our capacity to perceive. But as in classic early selection (e.g. Broadbent, 1958), she assumes that perceptual capacity is limited. Whether or not distractor information is processed deeply will then depend on whether the perceptual task for the relevant target exceeds this limited capacity. If the target task is undemanding, spare capacity inevitably will spill over to distractors. But if the target task is higher in load, this may exhaust perceptual capacity, and so less distractor processing will take place.

Lavie (2000) reviews a substantial body of recent evidence in support of this account, including not only reaction time effects in healthy young adults, but also some paradoxical effects of ageing (whereby less capacity can actually make someone better at ignoring distractors) and recent evidence from functional imaging (discussed below). Moreover, she clarifies her conception of perceptual load, in particular pointing out that it is not simply equivalent to task difficulty. For example, tasks that are more difficult because of weaker stimuli, or because of greater memory loads, do not behave like those with higher perceptual load, defined as those which include more target stimuli and/or require more perceptual operations for the same target stimuli. Lavie's load theory seems to offer real hope of a satisfying resolution to traditional early vs. late selection debates; but here I may be even more biased than usual (she is my wife!).

It would be remiss to close this section on early vs. late selection debates in vision without acknowledging John Duncan's seminal contributions. Although I doubt he would now espouse the strong late selection position which characterized his early work (e.g. Duncan, 1980), the empirical and theoretical insights of this work remain. Indeed, as we shall see, their influence has now spread into neuroscience. Duncan (e.g. 1980, 1985) highlighted a seemingly paradoxical finding which reliably is found in many different experimental settings (e.g. Eriksen & Spencer, 1969; Ostry, Moray, & Marks, 1976; Shiffrin & Gardner, 1972). People can be surprisingly good at monitoring several different streams of information at once for a particular target. This seems to imply that they must be able to make the target/non-target distinction for several different stimuli all at once. Yet if several targets happen to occur in these streams at the same time (or close in succession, as in so-called 'attentional blink' paradigms; Raymond, Shapiro, & Arnell, 1992), people typically will detect only one target and miss the others. I will term this the 'two-target cost'. At first glance, this two-target cost seems to imply that people *cannot* make the target/non-target distinction for several stimuli at once (nor close in time), in apparent contradiction of the ability to monitor several streams for a single target. The apparent contradiction can be resolved given Duncan's insight that targets (i.e. whatever the person is currently looking for or listening for) must impose some additional demand on people, which non-targets do not. This insight turns out to be particularly important when considering the neuropsychology and neuroscience of attention.

Feature integration theory

Anne Treisman made yet another major contribution to research on selective attention, with her feature integration theory in the 1980s, developed specifically for the visual modality (e.g. Treisman, 1988; Treisman & Gelade, 1980). It is interesting to note that while revolutionary, this famous theory still shows considerable influence from the original Broadbent model (see Fig. 1D). According to the new theory, different features of visual stimuli, such as their colour and orientation, are all extracted 'preattentively' in parallel, without any need for serial scrutiny of each item in the visual field. By contrast, serial attention to the location of each item is required to integrate such different features, in order to produce appropriate multidimensional percepts of objects with particular colours, orientations, etc. all bound together.

The similarity with Broadbent's original proposals lies in the now familiar idea that simple physical features are coded in parallel preattentively, whereas more elaborate coding requires a serial attentive process. The substantial advance lies in a more exact formulation of the elaborate processing which was thought to require serial attention. Attention was proposed to be the solution to a particular computational problem (integrating separately extracted features, such as colour and orientation). Moreover, a specific mechanism was proposed to provide this solution (select particular locations in space one at a time; the features to be integrated will then be specified by their common position at their selected location). Finally, unlike Broadbent's original proposals, feature integration theory suggested some possible close contact between psychological models and those emerging in neuroscience. At the time when feature integration theory was first proposed, the idea of modular coding of different visual features (e.g. colour vs. motion) within separate areas of visual cortex was particularly prevalent in neuroscience (e.g. Zeki, 1975; see also Wade & Bruce, this issue).

The initial psychological evidence for feature integration theory came from visual search tasks, which have become one of the mainstays of attention research, and provide a laboratory version of a common real-world problem. In visual search, people have to look for a particular target among a varied number of non-targets and to determine its presence or absence as fast as possible. In cases of 'parallel' search, the target subjectively 'pops out' of the display, and objective performance shows little or no effect of the number of non-targets (e.g. detection responses may be just as fast with more non-targets as with fewer). This seems to imply that the property distinguishing the target can be extracted for all the stimuli in the display at once (though note that varying only the number of non-targets overlooks John Duncan's point about how multiple targets can impose greater constraints than a single target among multiple non-targets; see Duncan, 1985). In cases of apparently 'serial' search, performance can become substantially worse with every additional non-target, sometimes quite linearly, as if a particular process (perhaps spatial attention?) had to be repeated for every single item (though see Wolfe, 1998, for a summary of the many qualifications to be placed on such interpretation of visual search data in terms of any strict parallel/serial dichotomy).

Treisman and Gelade (1980) originally reported that search for targets defined by a unique salient colour (e.g. red among green) or orientation (e.g. vertical among horizontal) apparently could be performed in parallel. By contrast, search for specific conjunctions of the same orientations and colours (e.g. red vertical among green vertical

and red horizontal, where the target is unique neither in colour nor orientation, but only in its combination of these features) produced less efficient search, which could appear serial. This appeared to fit the prediction that individual features (colours, orientation) could be extracted 'preattentively' and in parallel, whereas feature integration required serial attention to the location of each item in turn. Treisman and colleagues (e.g. Treisman, 1986; Treisman & Schmidt, 1982) subsequently produced further evidence for their proposal. A strong point of this work, in its pioneering stages, was that such evidence came from several different paradigms (not just visual search), thus seeming to offer several independent but convergent definitions of what constituted a 'preattentive' visual feature.

As with Broadbent's original filter theory, Treisman's feature integration theory was so compelling, and its predictions sufficiently clear, that it immediately became the target for many experimental attempts to refute it. Reports of exceptions to the rule of strictly serial conjunction search soon amassed (e.g. McLeod, Driver, & Crisp, 1988; Nakayama & Silverman, 1986). The theory came under sustained attack, with several rival accounts being forwarded (e.g. Duncan & Humphreys, 1989; Prinzmetal, 1981; Wolfe, Cave, & Franzel, 1989). Space constraints preclude a full treatment of this extensive literature here (see Treisman, 1998; Wolfe, 1998, for recent overviews). I make just a few general comments.

First, visual search studies suggest that feature integration theory does not work particularly well for the integration of oriented elements which together comprise a shape (e.g. Humphreys, Quinlan, & Riddoch, 1989). Indeed, some quite sophisticated properties of shapes and surfaces can affect parallel stages of search (e.g. Davis & Driver, 1994, 1998; He & Nakayama, 1992). Secondly, one can question (see Mack & Rock, 1998) the extent to which visual search taps processing without any attention, given that typically the person is looking deliberately at a display in order to find a particular target. Thirdly, it is now clear that attention can affect the coding of single features to some extent, although it may well have larger effects upon integration of features from separate dimensions (e.g. Prinzmetal, Presti, & Posner, 1986). Fourthly, although there are now many rivals to feature integration theory (e.g. Wolfe, 1998; Wolfe *et al.*, 1989) it is striking that several of these rivals retain its fundamental insights, such as initially separate coding of different feature domains, and/or a serial selection of the most salient locations in turn during search. Fifthly, there may be some truth to the special role allocated to location in the theory (Tsal & Lavie, 1993). Indeed, several of the effects of attention upon feature integration may relate to the improved localization afforded to attended stimuli (if one knows the exact locations of particular colours and shapes, one can thereby know which colours go with which shapes; see Cohen & Ivry, 1991; Prinzmetal, 1995).

Finally, many of the experimental situations which appear to falsify a strict version of feature integration theory may have done so because, in original form, the theory did not take grouping processes sufficiently into account (Duncan & Humphreys, 1989). For instance, some of the cases of parallel search for feature conjunctions (e.g. for a moving X among moving Os and static Xs; McLeod *et al.*, 1988) may have arisen because people could effectively direct their attention to just a single perceptual group (in the example, all the moving items shift together as a group, and within them the target has a unique shape feature).

Space-based vs. object-based accounts of visual attention

The issue of perceptual grouping relates to much recent debate about whether visual attention should be thought of as space-based or object-based. This in turn can be seen as simply a new twist on the old question of how much processing takes place prior to attentional selection (cf. Broadbent, 1958). A common metaphor for visual attention is of a 'spotlight', picking out a particular region of the visual scene for more detailed processing. I suspect that the perennial appeal of this metaphor lies in the fact that visual attention in daily life often involves eye movements. Shifting the eye is akin to shifting a spotlight, as saccades direct that part of our retina which has best acuity towards regions of interest. However, there are many laboratory demonstrations that we can shift attention without moving our eyes (e.g. Grindley & Townsend, 1968; Posner, 1980), perhaps in order to solve problems which eye movements cannot. For instance, when viewing a partly occluded object, such as an animal behind a tree, it seems that we can attend to that object as a unit, without having to move the eyes effortfully towards each visible fragment of the animal in turn. Although eye movements are undoubtedly a key component of selective attention (e.g. Underwood & Everatt, 1992), and provide a dependent measure with considerable applied significance (e.g. Crundall & Underwood, 1998), space constraints preclude a lengthy consideration of their role here. I concentrate primarily on covert mechanisms of selective attention, which do not rely on receptor shifts.

The original version of feature integration theory provides one example of a 'spotlight' model of attention, as covert attention was thought to focus on successive locations in turn, as with eye movements. There are many further influential examples of the spotlight metaphor in the literature (e.g. Eriksen & Eriksen, 1974; Posner, 1980). Equally, however, there are many examples of a rival view, on which attention is not so much directed to regions of space as to segmented perceptual objects or groups (e.g. Duncan, 1984; Duncan & Humphreys, 1989; Driver & Baylis, 1989; Egly, Driver, & Rafal, 1994; Humphreys, Olson, Romani, & Riddoch, 1996; Kahneman & Henik, 1981). There is now considerable evidence to suggest that selective attention in vision is constrained not only by the location and spacing of stimuli, but also by how the visual system groups these stimuli together or apart (see Driver & Baylis, 1998, for review). For instance, Duncan (1984) showed that the two-target cost, as described earlier, can be eliminated if the two targets to be judged are both attributes of the same object, even if these attributes are no closer together than those of two separate objects which do produce the two-target cost. Driver and Baylis (1989) showed that distractors which group with a target (e.g. owing to common motion) can produce more interference than closer distractors which do not group so strongly with it. Egly *et al.* (1994) adapted the spatial cuing paradigm which has so often been used to study supposed attentional 'spotlights' (e.g. Posner, 1980), and showed that although participants perform best for targets presented at the cued location of a cued object, they do better for targets presented at the other end of the same object than for targets the same distance away in a different object. Tipper and colleagues (e.g. Tipper, Brehaut, & Driver, 1990; Tipper, Driver, & Weaver, 1991) showed that several of the effects traditionally attributed to inhibitory mechanisms of spatial attention will shift along with a particular moving object in dynamic displays.

As with the debate between extreme early vs. late selection views, the confrontational disputes between proponents of space-based vs. object-based models sometimes may have generated more heat than light; but they have certainly led to informative experiments. While considerable evidence now exists to show that visual attention is modulated by grouping factors, space may still play a special role in visual attention. Indeed, it remains possible that grouping factors have their influence specifically by affecting the spatial distribution of attention (see Driver & Baylis, 1998), in which case there would be some truth to both sides of the argument. Moreover, some evidence already exists to suggest that space is indeed special for visual attention. While we can certainly attend selectively to visual stimuli as specified by their non-spatial properties (e.g. attending red while ignoring green), it appears that when doing so we end up selecting the *location* of the relevant non-spatial property (i.e. by attending to the position of the red stimulus), whereas the reverse is apparently not true (i.e. selecting locations may not have equivalent effects on non-spatial properties; see Tsal & Lavie, 1993). Moreover, many of the most common neurological deficits in attention appear to be primarily spatial in nature, as described below.

Attention and the brain

Undoubtedly the biggest change in attention research since the days of Broadbent is the increasing interaction between psychology and neuroscience, and associated efforts to produce explanations which relate not only to psychological processes, but also to neural processes. Typically, Broadbent anticipated this, and in a characteristically thoughtful manner: 'The attempt to link physiology and psychology can be disastrous when it is premature ... But it would be equally disastrous to go on forever treating the brain as an abstract and ideal construct having no biological reality' (Broadbent, 1971, p. 447). The dawn of cognitive neuroscience signifies that many researchers now believe the time has come to get to grips with biological reality, and to grapple with the brain as well as the mind in the study of attention.

Within Britain, Alan Allport and Tim Shallice were in the vanguard of this approach, long before cognitive neuroscience became a fashionable bandwagon. For many years, Allport sought to persuade psychologists studying attention that the 'brain metaphor' might be more appropriate than an overly literal 'computer metaphor' (e.g. Allport, 1980, 1987, 1992). He contrasted the serial, limited-capacity processors postulated by psychologists with the immensely parallel and powerful architecture of the brain, and brought recent findings in neuroscience to psychologists' attention. John Duncan went one step further, and actually set about collecting data from single cells in the monkey brain under different attentional conditions (e.g. Chelazzi, Miller, Duncan, & Desimone, 1993), in addition to psychophysical data from his human participants.

It would be a mistake for me to imply that British psychology had previously ignored the brain entirely, since neuropsychology had been one of its main strengths in earlier decades, with psychological theories being successfully applied to the many selective deficits observed in brain-damaged patients (e.g. Shallice, 1988). However, despite the considerable history of this approach, it has only recently been successfully applied to the study of selective attention. The success of this approach is well illustrated in Britain by the work of Glyn Humphreys and his colleagues (e.g. Humphreys *et al.*, 1996). We

can now also rejoice in having attracted Bob Rafal, one of the leaders in the field, to our shores from the USA.

Here I can only briefly sketch research relating selective attention to the brain for three different domains: deficits in brain-damaged patients; data from single-cell recording in the monkey brain; and the use of functional imaging and event-related potential methods in the normal human brain.

Relating neuropsychological deficits to the study of normal attention

Unilateral neglect is a common and disabling deficit after unilateral brain damage, especially following strokes centred on the right inferior parietal lobe. The patients behave as if half of their world no longer exists: that half towards the contralesional side of space (e.g. on the left following a right lesion). They may ignore people approaching or speaking from the left side, eat from only the right of their plate, read words from only the right page of a newspaper, and from only the right end of each line on that page (or even misread letters at the left of individual words). This brief review cannot provide an in-depth account of the various manifestations of such left neglect, nor of its anatomical basis (see Bisiach & Vallar, 1988; Driver & Vuilleumier, in press; Rafal, 1994; Robertson & Marshall, 1993). The point to be made here is simply that substantial progress in understanding the plight of such neglect patients recently has come from approaching it as an attentional deficit, armed with the theoretical ideas and experimental methods developed in the study of normal selective attention.

There are several reasons for suspecting an attentional deficit in neglect. First, although the patients can appear oblivious to sights and sounds on the affected side, they may by no means be blind or deaf on that side (i.e. primary sensory pathways may still be demonstrably intact in their brains for the neglected inputs). This seems analogous to some of the phenomena of normal selective attention. As I have described, we can all have little awareness for sights and sounds that we ignore, even though perfectly clear signals about them are projected to our brains from our eyes and ears. Secondly, drawing the patient's attention (not necessarily their eyes) towards the affected side can transiently ameliorate their deficits (e.g. Riddoch & Humphreys, 1983).

Thirdly, many parietal neglect patients also show a phenomenon called left 'extinction'. They can detect a single event (e.g. a visual flash) regardless of whether it appears towards their good (ipsilesional) or bad (contralesional) side. The preserved detection on the contralesional side indicates that the patients are not completely blind there. However, when two events are presented simultaneously (e.g. one on both sides of space), the patients will typically miss the contralesional (left) event that they could previously detect, reporting only the ipsilesional (right) event instead (which is therefore said to 'extinguish' awareness of the contralesional left event). The patient's deficit on the left thus only becomes apparent when target events there must compete for attention with concurrent target events on the right. This seems reminiscent of the two-target cost described by Duncan (1980) for neurologically healthy participants. Recall that they too may miss one target if two are presented together, yet can detect either target alone. Of course, the normal limit is only apparent with very rapid and masked displays, whereas the patients' problem is apparent for salient, suprathreshold stimuli that would present no problem to a healthy observer. Moreover, one can always predict which side

the patients will miss on double stimulation (the contralesional side; though see Robertson, 1989). Extinction may reflect a spatially specific exaggeration of the normal multiple-target limit because of attention being biased by the brain damage towards the ipsilesional (right) side.

Thus, there are several grounds for suggesting that left neglect patients may suffer from an attentional deficit, with their selective attention being biased towards the right after their lesion. But can such a proposal provide any new insights into the patients' deficit? Recent research illustrates that many of the ideas and methods developed in the study of normal attention can indeed be applied fruitfully to the patients. This has occurred recently in at least three domains: residual processing for neglected information; modulation by grouping processes; and relation to feature integration. For more extensive reviews than can be provided here, see Driver (1996, 1998, 1999); Driver, Mattingley, Rorden, and Davis (1997); and Driver and Vuilleumier (in press).

Residual processing of neglected information. If neglected information in the patients is analogous in some respects to unattended information in neurologically healthy individuals, then we should be able to address its processing with the same methods as those developed to study unattended perceptual processing. Recall that research in the early vs. late selection tradition has led to the development of numerous indirect methods, such as interference or priming measures for the effects of unattended information upon reactions times to related attended information. Recall also that such methods revealed that considerably more processing can take place for an unattended stimulus than one would ever glean simply by asking the person directly what they know about it.

A similar approach has been applied recently to neglect. Consistent with the findings in normal attention, it has now been shown that reaction times to stimuli on the non-neglected ipsilesional (right) side can be influenced by neglected stimuli on the contralesional (left) side, even when these escape the patient's awareness. Such effects can be determined by the presence (Marzi *et al.*, 1996), nature (Audet, Bub, & Lecours, 1991) and even the semantics (McGlinchey-Berroth, Milberg, Verfaiellie, Alexander, & Kilduff, 1993) of the neglected stimulus (see Driver, 1996; Fuentes & Humphreys, 1996). This in turn can be related to each patient's lesion, and to the anatomy and function of the preserved and impaired cortical pathways (Driver & Vuilleumier, in press). Such patient research was made possible only by the sophisticated indirect psychological methods developed within the traditional early vs. late selection debate. It now promises to shed new light not only on the deficit in neglect patients, but also on the neural basis of awareness. Moreover, the residual unconscious processing revealed in the patients may form the basis of new types of rehabilitation.

Grouping and extinction. I argue above that extinction phenomena in the patients may be a pathological exaggeration of the normal attentional 'two-target cost', as characterized by Duncan (1980) and others. Recall that, as discussed in the earlier section on space-based vs. object-based models of visual attention, Duncan (1984) had shown that the normal two-target cost disappears if the targets in question are both attributes of the same object. When grouped together, two targets seem to become allies rather than

competitors in the bid to attract attention. If extinction really does relate to the normal two-target cost, then we can predict that it too should be modulated by grouping. Specifically, if two concurrent targets, one on the left and one on the right, could somehow be grouped together into a single object, then extinction should disappear, and the patient should become aware of both targets for the first time.

This prediction has now been spectacularly confirmed by several independent British studies (e.g. Gilchrist, Humphreys, & Riddoch, 1996; Mattingley, Davis, & Driver, 1997; Ward, Goodrich, & Driver, 1994). Extinction can be greatly reduced by appropriate grouping of the displays, bringing left events that the patients would otherwise miss back into their awareness. As with the results in the previous section, this again reveals some residual processes in the patients (now, effective grouping operations) which can again be related to their lesions and to those brain structures which remain intact (Driver & Vuilleumier, in press), and which might be exploited in future rehabilitation. Similar conclusions follow from the recent literature on so-called 'object-based' aspects of visual neglect (e.g. Behrmann & Tipper, 1999; Driver, 1999).

Feature integration in parietal patients. A few studies have examined whether integration of different visual features may be more disrupted than extraction of individual features in parietal patients (e.g. Riddoch & Humphreys, 1987). Neglect and extinction patients exhibit losses of awareness even for single features (e.g. the colour, shape, and even the presence of stimuli on the affected side), contrary to the simplest prediction one might derive from Treisman's feature integration theory, at least in its original form (Treisman & Gelade, 1980). Nevertheless, there is some evidence that the patients' deficit can be even greater in feature conjunction tasks than in feature detection tasks, provided performance is sufficiently above floor to allow a meaningful comparison. For instance, Friedman-Hill, Robertson, and Treisman (1995) reported the case of a patient with bilateral parietal damage. When presented with displays of two coloured shapes, he could report the colours and the shapes quite accurately, but his reports showed an exceptionally high rate of miscombinations concerning which shape was in which colour, a result recently confirmed and extended by Glyn Humphreys and colleagues (Humphreys, Cinel, Wolfe, Olson, & Klempen, 2000).

Attentional effects on neural activity in animals

As mentioned earlier, Broadbent's filter theory was a landmark in cognitive psychology, not least because it provided a mechanistic approach to a concept (namely, attention) that had previously been purely mentalistic. Nevertheless, attention still remained too mentalistic a notion for most reductionist neuroscientists in the immediately following years. Physiologists recording from single cells in cats and monkeys made enormous strides, which began to make it possible to study perception at the cellular level (e.g. Hubel & Wiesel, 1968). However, this work was done initially with anaesthetized animals, so attention presumably had little relevance to the results.

All this was to change dramatically when physiologists later began to record from single-cells in awake, behaving animals. It soon became clear that sensory responses to external stimuli presented to the eye or ear could be modulated by the animal's

attentional state (e.g. Moran & Desimone, 1985; Wurtz, Goldberg, & Robinson, 1982). At first, some of these effects were relatively small, or were only obtained in brain areas traditionally associated with selective attention (e.g. in the parietal lobe; Wurtz *et al.*, 1982). However, as the research developed and the methods for directing the animal's attention to one stimulus or another became more sophisticated (and more closely related to those used in psychological research with humans), it became clear that very substantial effects of selective attention on sensory neural responses could be obtained at many, many sites in the brain—for instance, virtually throughout the complex hierarchy of cortical visual areas (Desimone & Duncan, 1995). Thus, a visual stimulus which strongly drives a neuron when covertly attended (e.g. when the animal has to make some judgment about that stimulus) may produce little or no response when the animal attends covertly to a different stimulus instead (Chelazzi *et al.*, 1993; Moran & Desimone, 1985; Treue & Maunsell, 1997).

The general principles for such attentional modulation of sensory neural responses are only starting to be established. Several firm conclusions can nevertheless already be drawn in relation to traditional issues in the study of selective attention. First, the cellular data appear deeply problematic for any strict version of late selection, since they show clearly that selective attention can modulate perceptual coding from quite early levels of processing. Secondly, it may nonetheless still be possible to reconcile the existing cellular data with late selectionists' favourite psychological results: the evidence that unattended processing can sometimes be considerable in people, certainly deeper than one would have thought simply by asking the person directly what they know. Most of the cellular evidence shows attenuation, rather than total elimination of sensory responses to unattended stimuli, especially for more posterior areas of visual cortex. Just as Treisman (1960) first supposed, an attenuated representation of ignored stimuli might thus still percolate through the system to quite high levels. Finally, it is clear that much more detailed computational models will be required to handle the neuroscience data than those provided in the traditional psychological literature (cf. the very simplistic box-models in Fig. 1), although such models are now starting to emerge (e.g. Braun & Koch, in press).

Desimone and Duncan (1995; see also Duncan, 1996) have provided an initial attempt to summarize the cellular data on selective attention in vision, and to relate it to the effects of lesions, and also to the psychology of normal human attention. They propose that many neurons in extrastriate visual cortex, which respond preferentially to different stimuli, are mutually inhibitory. Apparent 'capacity limits' thus emerge because not all of the stimuli in a visual scene can drive all of the neurons at once. The mutual inhibition means that the different stimuli in any scene compete to drive the neurons, which will tend to produce a 'winner-takes-all' outcome. In addition to the bottom-up influences produced by the stimuli (favouring stronger stimuli in the competition), this competition can also be biased in a top-down manner by signals representing, say, the stimulus currently to be looked for or attended. Excitatory top-down signals of this kind can bias the competition within the mutually inhibitory network to favour the currently relevant stimulus. Hence an 'attended' (i.e. currently relevant) stimulus can produce a stronger neural response than an 'unattended' (irrelevant) stimulus. Note that this might go some way to explaining the psychological observation that multiple target stimuli can impose greater capacity limits than multiple non-targets (Duncan, 1980); targets are more likely

to dominate the competition than non-targets of equivalent bottom-up salience, because of top-down support for the former only. Finally, competitive phenomena after lesions, such as extinction, can be explained readily by supposing that the lesion biases the competition in favour of certain stimuli (e.g. towards right stimuli in patients with left neglect after right-parietal injury). As Driver and Vuilleumier (in press) note, the particularly important role that parietal regions appear to play in spatially selective attention might be because of a particularly extreme form of winner-takes-all function within these brain areas.

Some of Broadbent's themes—such as limited capacity, and the selection of relevant stimuli—remain clear in Desimone and Duncan's more biological formulation and in related proposals (e.g. Allport, 1987). But it is apparent that much has changed also. Attention is no longer cast as a specific device (a filter) acting at a specific point to protect a system of limited capacity from overload. Instead, one can begin to see the various phenomena of attention as the emergent properties of competitive processes within many different brain areas. Moreover, it is overload which produces the selectivity, in effect now acting as the causal solution rather than the problem to be avoided (see also Lavie, 1995, 2000). Finally, since attention evidently can modulate perceptual processing even at the very earliest cortical stages of sensory processing, it is clear that purely feed-forward accounts, as in the box models of Fig. 1, are inadequate. Attentional modulation of sensory processing clearly depends also on back-projections that allow top-down influences from current goals.

Attention and neural activity in the human brain

One can now study neural activity not only at the level of single-cells in animals, but also in the intact human brain, either by event-related potentials (ERPs) recorded as voltage fluctuations on the scalp, or by functional imaging. The ERP method has been around for some time. Indeed, pioneers such as Steven Hillyard and colleagues actually conducted revealing attentional experiments with it several decades ago (e.g. Van Voorhis & Hillyard, 1977). Such work has more recently reached the wider audience it deserves. Many studies have now shown that sensory ERPs can be modulated by the current attentional state at quite early points in time during the sensory response (e.g. within around 100 ms after the onset of a visual stimulus, at occipital electrodes, in components thought to reflect extrastriate activity). The same visual stimulus typically shows a larger amplitude ERP component in this time range, at occipital sites, when attended than when unattended. This is consistent with attenuation of ignored information (à la Treisman, 1960), and/or amplification of attended information (e.g. Mangun, Hillyard, & Luck, 1993).

Such results have now been supplemented by functional imaging methods such as PET and fMRI, which can provide much better localization information than ERPs, but with poorer (though improving) temporal resolution. This is a rapidly moving international field, though British researchers have again made important contributions, with the Functional Imaging Lab in London being particularly prominent to date. PET and fMRI have demonstrated that blood flow (and presumed neural activity) in sensory areas of the brain can be modulated by the attentional task required of the participant. For instance, in one early study, judgments of colour increased blood flow in colour-related areas of

visual cortex, whereas judgments of movement for the same stimuli increased blood flow in motion-related areas instead (Corbetta, Meizin, Dobmeyer, Shulman, & Petersen, 1990). With the blocked designs required by PET methodology, it remained unclear whether such effects reflected modulation of stimulus-driven activity, or instead concerned the decisions made or the task set. More sophisticated studies with fMRI (which has better temporal resolution that now allows intermingling of trial types) have suggested subsequently that all these influences can be found, and can be distinguished (Chawla, Rees, & Friston, 1999). Thus, attentional state can modulate stimulus-driven phasic responses in visual cortex, but there may also be tonic changes in activity as a person prepares to attend to a particular stimulus or dimension, perhaps consistent with the top-down biasing signals envisaged by Desimone and Duncan (1995).

Several recent British studies have used the new fMRI methods to address theoretical questions arising from traditional psychological attention research. For instance, Rees, Russell, Frith, and Driver (1999) used fMRI to assess whether word identification always proceeds automatically for unattended visual words (as strong late selection would traditionally claim), or whether this can be prevented when ignoring the words and attending to other visual stimuli for a suitably demanding task. Their results suggest that, provided the task performed for the other stimuli is high in perceptual load (cf. Lavie, 2000), the brain may show absolutely no differential response to unattended words (as compared with random letter strings)—even when a person looks directly at these ignored words. In another study, Rees, Frith, and Lavie (1997) directly manipulated the load of a central visual task, while measuring the brain response to visual motion in a surrounding display, in order to test Lavie's (1995, 2000) perceptual load theory. When the central task was low in perceptual load, area V5 (known to respond to visual motion) was activated by motion of the irrelevant background. Remarkably, however, when the central task was high in perceptual load, no differential brain response to a moving vs. stationary background was found in V5. Such studies illustrate the potential of the new methods to address some of the oldest questions in attention research, and in particular to determine the fate of unattended information.

Future attention research

I hope that this rather idiosyncratic review has illustrated the tremendous progress made in selective attention research in the second half of the 20th century, and also the substantial contribution from British psychology. We have come a long way from Broadbent's filter model to contemporary cognitive neuroscience approaches, learning much *en route*. It seems clear that attention, once regarded suspiciously as a nebulous concept, is here to stay as a central topic in psychology and neuroscience. Moreover, it is a topic of considerable applied importance also. Broadbent (1958, 1971) always stressed the implications for human factors (see also Crundall & Underwood, 1998, for a more recent example), but there are clinical implications also. Space constraints mean I could sketch these only briefly for effects of brain damage in patients with the particular neurological disorder of left neglect (see Robertson & Marshall, 1993). Robertson (1999) has stressed recently the importance of attention in neurological rehabilitation more generally. There is also a vigorous literature on the role of attentional biases in various psychiatric clinical conditions, including depression, anxiety and schizophrenia (e.g.

Wells & Matthews, 1994). As William James (1890/1950) originally noted, the way people experience the world is indeed very much determined by attentional factors, not only in health but also in neurological and psychiatric illness.

While attention is here to stay as a topic, it has become increasingly clear that it is just that: a general topic, not a single psychological process. 'Attention' now refers to a whole set of phenomena to be explained rather than to a single process which explains those phenomena (see Allport, 1992). The various issues which psychologists address under the general heading of 'attention' still do have something in common though. They are all concerned with selectivity in mental life, and these days in neural activity also.

In keeping with this realization that many different selective issues and processes may be subsumed under the general heading of 'attention', one way the field is heading is for increasingly specific questions to be asked about increasingly specific processes. We no longer ask 'can attentional state affect perception?' as we now know the basic answer (i.e. 'Yes, in all sorts of ways; it also affects availability for response, and memory'). Instead, we can now ask whether a particular kind of attentional manipulation affects a particular type of perceptual judgment (as many psychophysicists are starting to do; e.g. Morgan, Ward, & Castet, 1998).

A further new line of questioning concerns relations between different kinds of attention (e.g. whether auditory spatial attention affects visual spatial attention; see Driver & Spence, 1998; Eimer & Schröger, 1998). Yet another development concerns the realization that issues of selective attention arise for motor processes, as well as for perceptual processes. Much traditional research has cast people simply as perceivers of the world, exerting some will over which inputs dominate their perception, but little in the way of willed action. However, there has been an increasing realization (e.g. Allport, 1987; Rizzolatti & Camarda, 1987) that one of the main pressures for selective processing may be the need to pick out particular stimuli to control particular actions (as even the biggest brain can only direct the eyes, or a hand, towards one object as a time). Steve Tipper and colleagues (e.g. Tipper, Lortie, & Baylis, 1992) have conducted some pioneering studies on attention in the context of selective reaching, and much research is now addressing interactions between motor preparation and perceptual selectivity (e.g. Rizzolatti & Carmada, 1987; Rorden & Driver, 1999).

A particularly clear future trend is the increasing integration of psychology and neuroscience, plus the development of ever more sophisticated functional imaging methods. Crystal-gazing is difficult here. To most of us, it would have seemed unimaginable only a few years ago that we could ever study selective attention in the human brain, and the fate of unattended information, in the way that fMRI now allows. Given the potential profusion of new questions and new methods, we will have to strive to maintain focus on the 'big picture' that Broadbent always sought to portray.

Acknowledgements

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