Eye tracking as a tool for examining cognitive processes

Tom Beesley, Lancaster University

Daniel Pearson, UNSW Sydney

Mike Le Pelley, UNSW Sydney

NON PRINT ITEMS

Abstract

Eye-tracking tools are now commonplace in the laboratories of experimental psychologists. Recording the position of a person's gaze, often several hundred times a second, can provide rich and precise data on the mechanisms and time course of cognitive processing. This approach has transformed cognitive psychology, from the fields of language processing and reading, to categorisation, cognitive development, and many more. In this chapter we discuss briefly the history of eye-tracking research, when the technology is likely to benefit researchers, and the sorts of advantages it offers over traditional behavioural measures. We then present a selective review of areas of behavioural research in which eye-tracking has had a significant impact, before providing a more detailed discussion of its use within the field of associative learning and attention.

Keywords: eye-tracking; eye-movements; attention; experimental psychology.

CHAPTER STARTS HERE

Introduction

Our eyes are the window to the surrounding visual world and our sight is one of our most precious senses. Indeed, we experience a more intimate connection with vision than with our other senses – for example, our consciousness seems to reside behind our eyes (rather than in our ears, mouths or fingertips). We carry out visual processing seemingly without significant effort, and typically feel like we are in total control of how we choose to direct our vision from one moment to the next. Yet the complexities involved in our eye movements are largely opaque to introspection, and only truly reveal themselves through detailed measurement and analysis. Eye tracking tools are now commonplace in the laboratories of experimental psychologists. Recording the position of a person's gaze, often hundreds or thousands of times a second, can provide rich and precise data on the mechanisms and time course of cognitive processing. The analysis of eye movements in modern experimental research provides a surreptitious window into human sensitivities, desires, and biases. These tools have transformed cognitive psychology, from the fields of visual perception, language processing and reading, to cognitive development, and many more. Here we describe the basic components of eye movements, the environmental factors and internal cognitions that control these eye movements and why they occur. Through examples from empirical research, we demonstrate how the different components of eye movements can be used to make important inferences regarding cognitive function, exemplifying the benefit these methods can have for experimental psychology.

History and Measurement

The ophthalmologist Louis Émile Javal (1839-1909) is widely credited with being the first to undertake a detailed, scientific analysis of eye movements. By closely examining the eyes of people reading text, Javal noticed that their eye movements had a characteristic stop-start pattern of motion. The movement of the eyes would not sweep continually along the lines of text, but instead would flit seemingly from word to word as the text was read. This characteristic pattern of eye movements was later confirmed with the use of primitive 'eye tracking' devices, first by Edmund Huey (1870-1913), and later in the pioneering work of the Russian psychologist Alfred Yarbus (1914-1986). Yarbus and colleagues developed some of the very first methods for precisely measuring eye movements. These extremely invasive systems involved anesthetising the eye and placing a suction cup directly onto the surface. A mirror, attached to the suction cup, moved in concert with the eye, and by tracking a light reflected off the mirror, Yarbus could observe a rich display of the eye's movements across a scene. Examples of his famous demonstrations of the eye's 'scan paths' across a visual scene are shown in Figure 1, where the observer is given the same scene but with different instructions as to what information has to be gathered. Yarbus began to explore eye movements that were made when people viewed various visual stimuli (such as pictures of social scenes, or individual faces), examining the correspondence between movements elicited on repeated observations of the same image by a single observer, and the clear individual differences in eye movements between observers. Not only did Yarbus pioneer a successful technique for tracking the movement of the eyes, but he began to make the first notable connection between the patterns in these scan paths and the underlying psychological processes that gave rise to them.

[FIGURE 1 HERE] CAPTION: Scan paths in Yarbus' classic study of eye movements

Eye tracking techniques and equipment have continued to be developed and refined up to the present day. Modern systems provide rich and accurate data on eye movements with remarkable temporal resolution, and little or no discomfort to the participant (indeed, participants may not even be aware that their eyes are being tracked). These advances in technology—both in terms of the hardware used for recording gaze and the software for processing and analysing the resulting data—have led to an explosion of interest in eye tracking for both research and commercial use. Even an experience as mundane as ordering a pizza in a restaurant can now be (supposedly) enhanced with the aid of eye tracking technology, with claims that gaze patterns can be used to deduce customers' topping-preferences before customers are even consciously aware of them (Henderson, 2014).

Modern eye trackers come in a variety of forms, but typically involve illuminating the eye using infrared light and recording it with an infrared camera. Computerized image analysis is then used to provide an accurate assessment of the changes in the orientation of the eye in space, and from this, the location of gaze on (for example) a computer monitor can be extrapolated. Eye tracking products differ in terms of how they are used in practice. Some trackers need to be mounted to the head (see Figure 2 for an illustration of such a device), with cameras filming the eye from below the lower eyelid, while others have recording devices embedded into a computer monitor. The latest technology has now been miniaturized to the point that eye tracking systems can be embedded into laptop screens and even virtual reality headsets. As well as these practical differences, eye trackers vary in their technical abilities, such as how fast they sample the eye, the precision of recording measurements, and how quickly they send and receive data from a computer processing system Appendix I contains a more detailed discussion of eye tracking hardware).

[INSERT FIGURE 2 HERE] CAPTION: An illustration of a head-mounted eye-tracking and a heat-map analysis of eye-fixations.

Before we review the benefits of eye trackers for social science research, we first discuss reasons why someone might *not* want to begin an eye tracking project. Eye trackers are still relatively expensive pieces of equipment for laboratories to purchase. The average computer workstation might set a researcher back $1000. With this workstation, a researcher can accurately measure manual responses made to visual stimuli. Combined with appropriate experimental procedures, this limited hardware allows the researcher to investigate all sorts of interesting questions about the processing of those stimuli to be investigated (e.g., by looking at the relative speed of one response compared to another). Eye trackers just provide another way of studying visual processing, by measuring the location of gaze but they do so at a price; an eye tracking system suitable for research can cost anywhere from $15,000 to $100,000. In addition, using an eye tracker can require some expertise in computer programming. While many eye tracking systems will come with software that allows for the recording and analysis of eye movements 'straight out of the box', most researchers will require a greater degree of flexibility, particularly in terms of the analysis of the resulting data (e.g., the data may require recalibration to stimulus positions, see Vadillo, Street, Beesley, & Shanks, 2015). Given today's trackers can record eye movements at up to two thousand times a second, the resulting data files can be very large and often require custom analysis software to be written to parse the data. The financial cost of eye trackers may also lead to a cost in terms of time. For the price of a single eye tracker, a researcher may be able to instead buy ten or more standard workstations. The resulting trade-off is between running ten or more participants at a time on a non-eye tracking study (which may be finished in a week) or running one participant at a time on an eye tracking version of the same study (which may therefore take months to complete). These realities should be kept in mind when deciding on whether it will be useful to collect eye movement data in a particular study.

From eye tracking to cognitive science

What are the advantages of running an eye tracking study? Why is data on eye movements so important to experimental psychologists? Most psychology experiments measure behavior through recording overt intentional responses. Most commonly, these are keyboard responses made with the fingers, but could include written text or vocalisations by a participant. As an example, let us consider a *visual search task* in which participants have been given a target to search for (say, a letter 'T') that is positioned within a scene that also contains several other objects that look similar to this target (say, a number of 'L', 'F', and 'E' letters, known as distractors). In such a task, participants will be asked to press one response key if they detect the target in the search display, and another response key if the target is absent. The two critical components of the response are its *type* and its *timing*. We can use the response type to determine how accurately the participant was responding in the task, evaluating the proportion of times the 'target present' key was pressed when the target was indeed present compared to when it was absent (i.e., hits versus false alarms). The timing of the response might also tell us something important about the underlying cognitive processes. For example, imagine that we increase the number of similar looking distractor objects in the scene and we observe that the participant's response time increases. We might infer from this that perhaps more letters are being searched before the target is detected. This seems a natural conclusion, and is almost certainly right, but it cannot be inferred with certainty from the data collected. This is because response time, like response choice, represents a measurement at the terminal point of the psychological process. It comprises the accumulated time of all of the cognitive processing that precedes it, which may include (at least) the perception of the array of stimuli on the screen, the sequence of eye movements across the scene, the detection of the target, the decision about which response to make, and the execution of that response. An increase in response time might be attributed to a change in the time taken to complete any one of these steps in the chain of cognitive processes.

Due to these severe limitations in more traditional measurement of human behavior, eye movements can play a particularly important role in understanding cognitive processes. The recording of eye movements provides a continuous, real-time measure of stimulus processing throughout a series of cognitive processes. Eye tracking data provide moment-to-moment measurements of where the eyes are fixated throughout an experimental trial[i], which may provide additional insight into the dynamic pattern of cognitive processes that were engaged during that trial. Gaze data also allow us to analyze, if we wish, particular sections of the visual search performance in our task. We may have a hypothesis that the L stimuli are viewed more than the E or F stimuli during the search process. Or we may be particularly interested in where the eyes move at the start of the trial when the stimuli are initially presented, or in evaluating how many distractors are fixated before a decision is made regarding whether the target is present (examining our initial intuition above). An analysis of eye movements will allow us to begin to answer these sorts of questions through isolating the processing that occurs in different periods of the trial.

Some of these questions, about the contribution of certain psychological processes over a period of time, might be answered by other means than an analysis of eye movements. Researchers could, for example, use clever experimental designs or sophisticated statistical modelling techniques to try to tease apart the contributions of each step in the chain. However, continuous eye movement data can provide a very compelling picture, not clouded by the complexities of these other techniques. At a basic level, a 'heatmap' (see Figure 3) of where the eyes were fixated most often during a trial procedure can provide an instant picture to aid the researcher in determining the cognitive processing that took place.

[FIGURE 3 HERE] CAPTION: A heatmap showing the density of eye-fixations in space as observers view a photograph. Image courtesy of Olivier Le Meur (for details, see Le Meur, Le Callet, Barba & Thoreau, 2006).

At a more granular level, what do eye tracking data enable us to deduce about cognitive processes? When we move our eyes across a scene, thus changing the sensory information falling on our retinas, our perception of that scene seems to change smoothly and continuously. Yet this experience is, to some degree, a trick of the brain's visual processing system. As Yarbus (1967) noted, eye movements are in fact a compilation of brief pauses known as fixations, and rapid eye movements, known as *saccades* (see Appendix I for a more complete discussion of the components of eye movements). Not only do these components of eye movements differ in their observable characteristics, but they fulfil different roles in information processing. Early work by vision scientists demonstrated that during a saccade from one stimulus to another, there is a general suppression of information in the visual system, such that the detection of objects that appear as we are making a saccade is impaired, or even abolished under certain conditions (e.g., Volkmann, Schick, & Riggs, 1968; Bridgeman, Hendry, & Stark, 1975). This 'saccadic suppression' mechanism is important for maintaining a consistent visual percept. When the eyes are moved across a static scene, the location on the retina corresponding to every visual object will change. If visual input were active during this period, this would cause a flood of movement signals to inundate the visual processing system since all objects are moving from the perspective of the retina (see Figure 4 for an illustration of the anatomy of the eye). The visual system would then need to devote significant processing resources in order to establish that it is the eyes that are moving, rather than (or in addition to) objects in the world. Suppressing visual input during a saccade effectively removes the need for this processing by censoring the period in which movement signalling occurs, and thus allows the visual system to more easily maintain a stable representation of the world. Many aspects of cognitive processing may be entirely restricted to periods of fixation. For example, it has been suggested that if a cognitive process such as object identification is interrupted by the initiation of a saccade, then object identification resumes only once that saccade is complete (Sanders & Houtmans, 1985).

[FIGURE 4 HERE] CAPTION: the anatomy of the eye.

It is perhaps unsurprising that saccadic eye movements and periods of fixation have different uses in the analysis of psychological processes. Due to the suppression of information processing during saccades, it is thought that fixations reflect the moments at which the observer is likely to be conducting meaningful information processing of a scene. Therefore, a great deal of experimental research has focussed on the analysis of fixations, disregarding the moments where saccades occurred. Saccades on the other hand can provide an important measure of the selection of information and particularly the timing at which this information (i.e., a stimulus) comes to impinge on cognitive processing.

Before we discuss some typical uses of eye tracking in cognitive psychology, it is important to note one more limitation of studying eye movements. While fixations indicate those points in time and space at which observers are likely to be conducting meaningful information processing, this might not necessarily be the case in every instance of a fixation. It is quite possible to fixate your eyes while shifting your *attention* to another part of the environment. Try it for yourself; pick a word on this page to fixate and, without moving your eyes, shift the focus of your concentration to something far away from your chosen word, across the room in which you are sitting. This potential for decoupling of attention and eye movements has been studied extensively by cognitive psychologists. In what is now known as the classic 'Posner cuing task', Posner and colleagues (e.g., Posner, 1980) asked participants to fixate on a central point, before an arrow appeared at that position, pointing either to the left or the right. After a short period, a target stimulus appeared on the screen, either in a position congruent with the direction of the arrow (e.g., to the left of a left-pointing arrow), or in an incongruent position (e.g., to the right of a left-pointing arrow). In these tasks, detection of the target is faster in congruent than incongruent positions, even though on each of these two trials, gaze was fixated on the central point of the screen. This demonstrates that we can maintain our gaze on a point of fixation, but nevertheless shift some of our processing resources towards another region of space.

Where does this leave us with respect to the measurement of eye movements? If the position of our eyes can be decoupled from the position of attentional processing, then what good is measuring eye movements? Thankfully—for the sake of research at least—the experience of decoupling one's eye-position from attentional resources tends to be the exception, rather than the rule, of visual processing. As our demonstration will have illustrated, it takes effort to perform such a decoupling and, importantly, such a decoupling requires the eyes to be stationary; once the eyes are in motion, attentional processing and eye movements are tightly coupled (Deubel & Schneider, 1996). The upshot of this in practical terms is that for many types of experimental procedures, we can be confident that an analysis of eye position will provide a meaningful and accurate measurement of overt attentional processing. Nevertheless, the possibility of a decoupling of eye movements and attention—made possible by our ability to covertly attend to stimuli in the environment—is something that researchers should bear in mind when designing experimental procedures and when analysing eye movement data.

Examples of eye tracking in cognitive science

In this section we briefly describe some of the varied uses of eye tracking within experimental cognitive science and highlight the unique contributions that eye tracking technology has made to theoretical developments. This is then followed by a more detailed discussion of the use of eye tracking within the specific research area of attentional processing in human associative learning.

Visual search

First, we return to the simple example of understanding visual search behavior. This type of activity is fundamental to our daily lives: when we search for our keys in the morning, look for the TV remote at night, or scan for friends on a beach, we have to hold in mind a representation of a target object as we search and eliminate the distracting non-target objects, often one-by-one until the target is located. Indeed, our health and safety can depend on the accuracy of visual search performance: think of radiologists searching X-rays for images of tumours, or airport security staff searching scans of suitcases for evidence of weapons or contraband. From a psychological perspective, the visual search task is certainly a non-trivial one, and there are a number of different perceptual and cognitive processes that are required for search to be efficient. For example, consider a difficult search task, such as finding one person on a beach full of hundreds of similar-looking people. In order to complete this task efficiently, we must avoid searching the same non-target objects again and again in quick succession, since repetitive sampling of the same visual information does not provide a benefit and in many searches could lead to infinitely long search times. Instead it is better to move from one object to the next, searching for novel information that has not yet been processed. Our process of visual search does not appear to be random, but instead is controlled by mechanisms that constrain the possible objects that we might search next. 'Inhibition of return' (Posner & Cohen, 1984) is one mechanism that has been proposed to operate, which simply stated is a mechanism that inhibits the further search of locations in visual space that have been recently searched, such that attention is prevented from returning to these locations in the future.

It is not straightforward to test whether inhibition of return occurs during visual search tasks (e.g., searching for a T amongst L's) if we are restricted to using standard measurements of manual responses. One could have a second display of objects appear after the primary search has been completed and ask people to detect new stimuli (probes) that appear in positions that were previously occupied by the original search objects (e.g., Klein, 1988). However, the responses issued to these probes would come sometime after the original search has finished and so this test provides only an indirect test of inhibition of return. This test would therefore capture only the final or accumulated inhibition built up in the trial, but inhibition of return is likely to be a dynamic process that evolves over the course of search. This indirect method of testing the search process once it has terminated, is therefore unlikely to give a complete picture of the underlying cognitive process.

Eye tracking provides a particularly useful measurement tool for examining this type of process, since, as we have noted, it provides a continuous real-time measurement of the search process that allows us to isolate the processing of each item in the display. As an example of this type of procedure and analysis, Gilchrist and Harvey (2000) tracked eye movements as observers searched for a target E shape within an array of 32 distractor letters. The researchers looked at the time between consecutive fixations on the same object, which allowed them to examine exactly when and how often objects were returned to in the search process. It was found that 'refixations' of an object were very uncommon within the first 400 milliseconds (approximately 2 fixations in this task) and is comparable with a typical pattern of attentional processing in other tasks that have revealed inhibition of return (e.g., Posner & Cohen, 1984). Gilchrist and Harvey's data suggest that it was extremely rare for observers to fixate an object, saccade away from it, and then immediately re-fixate the object. Instead, several additional fixations are typically made prior to any return to the object. Thus, measures of eye movements provide compelling evidence of the operation of inhibition of return during visual search, where previous evidence, provided by more indirect means, had been less compelling. Furthermore, Gilchrist and Harvey's analysis provides a very rich data set; the inhibition of return process can be evaluated for each object that is fixated during search and not just at the terminal point of the entire search process.

Reading

The field in which eye tracking has arguably had the biggest impact in the cognitive sciences is the study of reading. By applying high resolution eye tracking techniques, researchers have been able to study the subtle eye movements that contribute to what becomes a very automatic behavior for the majority of people. A review of this literature is provided by Rayner (2009), but here we highlight just a few interesting findings which demonstrate the types of data and theoretical contributions that eye tracking has provided.

Expert readers – a group that includes most adults in developed countries – can rapidly process the visual patterns on a page and process them into meaningful linguistic information. The speed at which this happens gives the impression that we can take in many words at a time. Yet eye tracking reveals that reading is actually very effective even when we are restricted to a single word at a time. In fact, a number of 'speed reading' programs claim to increase reading speeds by presenting individual words successively at a rapid rate (for an example, see http://www.readsy.co/). In the lab, eye tracking studies of reading can use real-time processing of eye movements to examine reading performance under conditions where word processing is restricted. For example, researchers can use data from the eye tracker to set a precise moving window around the point of fixation (this type of 'gaze-contingent' task is discussed in more detail later). By doing so, it is possible to manipulate the size and position of this window, and therefore examine how these variables affect the accuracy and speed of reading. It has been observed, for example, that the reading of characters is biased to the right of fixation (at least for English readers); we take in just a few characters to the left of fixation, and four or five times that on the right of fixation (e.g., McConkie & Rayner, 1976).

Analysis of the pattern of eye movements under normal conditions also reveals interesting patterns in how words are processed. For example, as fixations run across the words of a sentence, the individual words on a line do not receive equivalent processing; eye tracking reveals that many words are in fact skipped as fixations jump between non-consecutive words in a sentence. Analysis of the linguistic content of the words reveals that those words that are skipped tend to be function words, such as 'is', 'a' and 'and', which suggests that these words that contain minimal semantic value are largely superfluous to the interpretation of text (e.g., 'Larry fat cat sits mat' is largely interpretable without the addition of such function words).

Moreover, eye tracking has shown that semantic context influences the reading process. For example, Morris (1994) tracked participants' eye movements as they read sentences like those below:

1. The friend talked as the person trimmed the moustache after lunch.

2. The friend talked as the barber trimmed the moustache after lunch.

Morris found that participants' gaze duration on the word 'moustache' was significantly shorter when they read sentence 2 than when they read sentence 1. The critical difference is that, in sentence 2, 'moustache' is semantically associated with a preceding word in the sentence ('barber').

The implication is that this preceding word automatically and rapidly activates its semantic associates, reducing the resources required for processing these associates if they are encountered subsequently (as occurs in sentence 2), hence speeding reading.

Similar findings of linguistic content (semantics) interacting with processing time are observed for reading garden path sentences, wherein a grammatically correct sentence presents a level of ambiguity resulting from different plausible local interpretations of word meaning. For example, in the sentence 'The complex houses married and single soldiers and their families', the ambiguity that may initially arise is resolved by realising that 'houses', most commonly used as a noun, should here be interpreted as a verb. Analysing eye movements allows researchers to investigate the time course of the linguistic processes implicated in parsing and disambiguating such sentences. Data suggest that readers fixate longer on critical disambiguating words and return to words that precede this ambiguous element (e.g., Frazier & Rayner, 1982). By analysing the relationship between fixation durations and the syntactic structure of the material, it is possible to build more sophisticated process models of how eye movements are controlled during the process of reading (for a review, see Reichle, 2006).

One of the ultimate goals of reading and language processing research is to understand what happens when there are impairments in these skills, such as in the case of dyslexia. Eye movement data have also proved to be valuable here. It is now known that the sequenced pattern of eye movements is quite different in dyslexic and non-dyslexic readers. Dyslexic readers exhibit longer fixations and shorter saccades, resulting in an overall pattern of eye movements that contains a greater number of fixations than observed in normal reading performance (e.g., Hutzler & Wimmer, 2004). This is coupled with slower reading times overall, but whether the unusual patterns of eye movements are a cause or result of dyslexia is unsettled.

In summary, the data provided by eye tracking have led to major advances in how psycholinguists understand the process of reading. The technological power of eye tracking systems has led to a major paradigm shift in the study of reading, shedding light on the mechanisms and processes of reading in ways that arguably would not have been possible with previous experimental techniques.

Infant cognition

To see why eye tracking has also played such an important role in the study of infant cognition, consider first the difficult challenges a developmental psychologist faces when attempting to study how the mind of the infant functions and changes over time. Unlike for adult participants, it is often difficult or impossible for young children to verbalize their knowledge and beliefs about the world. It is also unreasonable to expect very young children to complete cognitive tasks suitable for adults. The sorts of tasks adults typically complete in psychology labs – whereby stimuli are presented repetitively for long periods, and manual responses are made – are clearly unsuitable for use with children; getting them to sit still for any test, let alone a boring one, is very difficult.

Eye tracking allows researchers to explore the preferences of very young children simply by assessing what they look at. It turns out quite usefully, that (other things being equal) infants show a preference for novel over familiar visual objects (Fantz, 1964). The more we present a single visual image to an infant, the less likely they are to look at that image compared to one that has not been previously seen. This simple 'habituation' procedure demonstrates that some knowledge has been acquired by the infant; it demonstrates at least that the infant retains a memory of the familiar image, and this memory is sufficiently detailed to enable the familiar image to be discriminated from the novel image.

'Preferential looking' techniques have been widely applied as a research tool in developmental psychology. Here we will consider how it might be used to study the development of categorisation; one of the basic components of mature cognitive processing in humans, and arguably in all animals. Categorisation refers to the process by which ideas and objects are recognized, grouped, differentiated, and understood. It is an essential cognitive function since it stops us from treating each and every object we encounter as entirely unfamiliar. On a basic level, it allows us to transfer our knowledge appropriately; I do not treat each new banana I buy as different from the last, but rather I mentally group all bananas together as belonging to the same category. I can hence infer that they will share similar taste, smell, longevity, etc. This type of mental processing also allows for more flexible predictions about things that are unfamiliar. I have never eaten a jackfruit, but I have a fair idea of how it might taste from looking at its skin; I have never encountered a Bedlington Terrier, but I am confident as to what it might do if I throw it a stick. Learning how to partition the vast range of sensory information is not only required for efficiency, but is critical, even for newborns, so that they can execute appropriate behaviors at the right moments (e.g., crying, sucking, smiling).

How can these categorisation processes be tested using procedures based on preferential looking? In adults, a standard way to test category knowledge is to present people with new test stimuli (probes) that contain properties we want to examine and observe how they categorize these probe stimuli (e.g., are animals with spots more likely to be categorized as leopards or as tigers?). To the extent that there is overlap in the features of the probe stimulus and the participant's stored category knowledge, the participant will be inclined to classify that probe stimulus as a member of that category. We can conduct similar tests of category knowledge in infants if we assume that looking times correlate with the degree of overlap between features of the probe stimulus and the infant's knowledge of the category that has been built through previous experience. For example, Bomba and Siqueland (1983) conducted a study in which, during an initial 'habituation phase', three and four-month old infants were presented with a series of patterns of dots, in which the dots were formed into a simple geometric shape, such as a triangle. While the arrangement of dots presented in each pattern conformed to a triangular shape, each pattern varied slightly – e.g., the triangles varied in their internal angles and side lengths – such that several unique triangular stimuli were presented over the course of the habituation phase. The question then is to what extent the infants formed a mental representation of triangles over and above the instances of the individual triangles. One theory about the nature of category knowledge is that humans form mental 'prototypes' of categories, represented by a single memory that reflects the most common or characteristic features of the category. To test this, Bomba and Siqueland examined preferential looking times for two shapes, one of which was a prototypical (equilateral) triangle, and the other a shape belonging to another category (e.g., a square). Both specific stimuli were novel – the prototypical triangle had never been shown during the habituation phase. Nevertheless, it was observed that infants were significantly less likely to look at the triangle than the other square; that is, they were less likely to look at the (novel) prototype of the familiar category. The implication is that exposure to specific examples of the category during the habituation phase led to infants abstracting general knowledge about the category of triangles, which in turn led to previously-unseen examples of this category, and especially the 'prototype' triangle, seeming somewhat familiar.

While such approaches based on eye tracking have proved very useful for examining cognitive processes in infants, they rely heavily on assumptions about what looking times mean in terms of the underlying hidden cognitive processing. Regarding Bomba and Siqueland's (1983) study of categorization, the interpretation offered above assumes that the looking preference for the novel prototype over the familiar prototype means that some category-level knowledge had previously been extracted. Alternative interpretations are possible. For example, perhaps the within-category differences between triangles are so slight as to render the prototype triangle indiscriminable, at least to an infant, from the instances encountered during the habituation phase. This account does not rely upon any learning of category-level knowledge, since differences in preferential looking times could result simply from the activation in memory of the individual training patterns that were seen earlier, rather than a unique prototype representation. Even if category-level knowledge was formed in the task, we are also far from knowing exactly what constitutes such knowledge, since all we know is that the familiar prototype is similar in some way to the other stimuli that have been experienced. While eye tracking provides a valuable source of measurement of infant preference, it does not provide a silver-bullet solution for unpicking the complexities of infant cognition (for further discussion of the pitfalls and restrictions of using preferential looking data to make inferences about the operation of psychological processes, see Aslin, 2007).

Judgment and decision-making

Eye tracking has been used widely to provide an 'incidental' measure of how people form beliefs and execute decision responses. One of the most commonly observed findings from eye tracking research is that people tend to spend most of their time looking at information that has the highest utility. This is observed in the form of high-utility information receiving a greater number of fixations, as well as overall more looking time before other information is sought (e.g., Glaholt & Reingold, 2011). When deciding between different options, people's first fixation is more likely to be on the option that they will go on to choose. Less surprisingly, they are also more likely to be looking at the to be chosen option at the time they make their choice (Krajbich & Rangel, 2011). Changes in the pattern of eye movements can hence be a consequence of decision making; we are more likely to look at options that we have decided are superior.

It has also been suggested that eye gaze may play a more active role in decision making, feeding into the decision-making system and thereby influencing the choices that are made. That is, eye movements may also be a cause of changes in decision making. For example, Shimojo, Simion, Shimojo, and Scheier (2003) had participants perform a task in which they were shown a pair of faces on each trial and had to decide which face was more attractive. In a first experiment, participants viewed the two faces freely before making their decision. Consistent with Glaholt and Reingold's (2011) findings, during the viewing period participants showed a bias in eye gaze towards the face that they subsequently chose. This result is in line with the idea that choice influences gaze. Critically, in a subsequent experiment, Shimojo et al. manipulated the length of time that participants gazed at each of the faces in the pair by showing the faces one at a time, with one appearing for longer than the other. The researchers found that this manipulation of gaze influenced the decisions that participants made; they were more likely to choose the face that they had gazed at for longer. The implication is that biases in gaze can induce biases in preference (for more on this topic, see Newell & Le Pelley, 2018; Pärnamets et al., 2015). For anyone wanting to 'nudge' our real-world preferences and decisions (politicians, advertising executives, etc) an eye tracker may be a very useful tool.

How looking preferences relate to decision making is important not only for psychologists, but also for economists and marketeers, and eye tracking has had a long history in both commercial and academic spheres as a tool for measuring and understanding consumer decisions. As far back as the work of Nixon (1924), eye movements have been used to demonstrate that the size and layout of an advertisement affects the way in which viewers process it: what they pay attention to, and what they remember. Here we briefly describe two experimental tasks that have analyzed eye movement data in interesting ways in more applied settings.

Wedel, Pieters, and Liechty (2008) examined the effects of different processing goals on how people viewed advertisements taken from magazines. They hypothesized that the pattern of eye movements might be quite different if viewers were asked to memorize the content of the advertisement versus evaluate its content, or if they were asked to focus on a specific target detail versus focus on the global properties of the advertisement as a whole. Consistent with work in scene perception, Wedel, et al. found that participants' initial viewing behavior tended to reflect a local processing state*,* with spatially dense groupings of fixations on specific details, before a transition was made to a global processing state, in which fixations were distributed more widely, thought to reflect processing of more holistic aspects of the advertisement. When asked to focus on memorising or evaluating a specific target object, participants spent a greater proportion of time in the local processing state, compared to when asked to focus on memorising or evaluating the advertisement as a whole. Interestingly, the instruction to memorize versus evaluate the advertisement or target feature also had a dramatic effect; memorising the scene led to longer times in the local processing state, while the instruction to evaluate led viewers to spend longer in a global processing state. These eye movement data therefore reveal important details about the time course of different processing styles under intentional states of the viewer and could be used to redesign advertisements to maximize their effectiveness.

Up until this point, we have discussed how eye movement data can be useful in the examination of cognitive processes. Our next example uses pupillometry, which is the measurement of the size and reactivity of the pupil, provided by many modern eye trackers. Pupil size changes in response to the available light in the environment, but it is also known that cognitively challenging and stressful tasks lead to an unconscious dilation of the pupils. Pupil dilation therefore offers a surreptitious measure of cognitive effort or stress. Wang, Spezio, and Camerer (2010), used eye tracking to provide unique insights into how people make ethical decisions that affect the financial reward that others receive. In their task, participants were paired together playing a 'sender-receiver' game. In this game, the sender transmits information about the current state of the game (states one through to five), that can either be truthful or misleading. The payoff for each player is determined by the action of the receiver, but the formulation of the payoff is different for each player. For the receiver, making an accurate prediction about the state provides the largest payoff, whereas the sender's payoff structure is such that, on some trials, the sender is inclined to mislead the receiver such that they overestimate the level of the state (i.e., guess three when the state is actually one) – this is beneficial for the sender but not for the receiver. Such tasks provide a nice experimental analogue of real world scenarios in which financial analysts seek to profit handsomely from exaggerating the value of financial products to clients. Wang et al. found that choice data unsurprisingly showed a high level of misleading advice provided by senders when it was beneficial for them to do so. Wang et al. also monitored senders' eyes to further examine the cognitive processes involved in their decision making. Most notable among their data were findings relating to the dilation of the pupil under different conditions. It is known that cognitively challenging and stressful tasks lead to a (unconscious) dilation of the pupils. Wang et al. also found this to be the case in their task; when senders were faced with a decision in which it was advantageous to lie (and in which they did in fact lie), pupils were more dilated compared to those trials in which lying was unnecessary. Moreover, the size of the lie – the difference between the communicated state and the true state – was positively correlated with pupil dilation.

In-depth example: Associative learning

Research in the field of associative learning has long considered the role that attention plays in shaping the learning process, and eye tracking has recently been used to great effect to answer specific questions on this theme.

Associative learning is the fundamental principle governing how mental representations become connected in memory and how they shape behavior. For example, in the famous case of Pavlov's (1927) studies of conditioning in dogs, a bell was rung each time food was about to be given to the dogs. Following repeat training of this kind, Pavlov noted that the ringing of the bell produced an anticipatory 'conditioned response' in the dogs; salivation. In associative learning terms, the dogs had formed an association between the mental representation of the cue stimulus (the bell) and the outcome stimulus (the food). Once this association had formed, activating the representation of the cue (by ringing the bell) was sufficient to activate and retrieve the mental representation of the food even without food being presented, such that the cue elicited the appropriate response (in this case, salivating in anticipation of food).

Associative learning is thought to be the fundamental mechanism responsible for a vast array of behaviors in both human and non-human animals, underpinning much of our knowledge. For example, learning a language requires learning a set of associations between objects in the world (e.g., an apple), and the spoken and written forms of symbols (words) representing those objects. Associative learning also underpins many of our beliefs. For example, through experience we might form the belief that beer X is associated with a pleasant taste whereas beer Y is not, that sunny weather is associated with crowds at the beach, or that politicians are associated with lying. Associative learning can also give rise to preferences. For example, expectant mothers commonly develop acute dislikes for certain foods that they have eaten at the same time as experiencing morning sickness. Similar effects are frequently reported by patients undergoing unpleasant medical treatments such as chemotherapy.

Learning, blocking, and the role of attention

Researchers within the field of associative learning have questioned whether the learning process is shaped by the way in which we attend to events in the world, and this conjectured interaction between attention and learning has been investigated using eye tracking technology. For example, Beesley and Le Pelley (2011) trained participants with a task in which they learnt about the effects of drugs given to a fictitious patient. In Stage 1 of the task (see Table 1), participants learnt that treatment with chemical A led to nausea in the patient, and in Stage 2 that chemicals A and B also led to nausea. In a final test, participants are asked how likely they think it is that each of chemicals A and B – when used individually – will cause nausea. Unsurprisingly, participants report a strong belief that chemical A will cause nausea. However, participants typically do not tend to think that chemical B is likely to cause nausea, even though it has been paired with the occurrence of nausea many times (in Stage 2). This effect is known as 'blocking'; the presence of chemical A blocks learning about chemical B during Stage 2. Blocking is one of the most widely studied phenomena in the field of associative learning and has been demonstrated in a wide range of animals including rats (Kamin, 1969), pigeons (Leyland & Mackintosh, 1978), honeybees (e.g., Blaser, Couvillon, & Bitterman, 2004), goldfish (Tennant & Bitterman, 1975) and snails (Prados et al., 2013). There are many theories that predict the blocking effect, and some of the more dominant theories suggest that the effect is a result of a change in the attention paid to the stimuli (e.g., Mackintosh, 1975; Pearce & Hall, 1980). These theories suggest that during Stage 1 of the task, participants learn that chemical A is a reliable predictor of the nausea, and then bias attention to that cue over chemical B during Stage 2 (since B is not a better predictor than A – it is redundant to the prediction). As a result of this attentional bias, chemical B is effectively ignored, and very little is therefore learnt about its relationship with nausea.

Using an eye tracker to record participants' gaze as they performed the blocking task, Beesley and Le Pelley (2011) were able to examine the role of attention in blocking, by measuring whether participants were more likely to direct their gaze (their 'overt attention') towards chemical A rather than chemical B during Stage 2. This is exactly the pattern that was seen in the eye tracking data. As shown in panel A of Figure 5, participants spent less time attending to the 'blocked' cue B compared to both the 'familiar' cue (A) and 'control' cues that were novel during Stage 2 (C and D). This direct evidence from eye tracking provided a convincing demonstration that the blocking effect is, at least in part, attentional in nature (see also, Kruschke & Blair, 2000; Wills, Lavric, Croft, Hodgson, 2007).

Table 1: Design of the study by Beesley & Le Pelley (2011) – simplified		
Stage 1	**Stage 2**	**Stage 3**
A – nausea X - headache	AB – nausea CD - headache	BD - dizziness

Beesley and Le Pelley's study further examined the relationship between attention and learning in a third stage, in which cue B was paired with a control cue that had not received this 'blocking' treatment in Stage 2 (cue D). These two cues were shown to predict a new reaction of dizziness in the patient. At the end of the task, participants were presented with each cue (B and D) individually and asked to rate how likely it would be for the outcome to occur given that cue alone. It was observed that people learned more about cue D than cue B in this third stage (see also Griffiths & Le Pelley, 2009; Le Pelley, Beesley, & Griffiths, 2014; Le Pelley, Beesley, & Suret, 2007). Of critical interest here is the pattern of eye-gaze to cues B and D during Stage 3, and how that related to how much was learnt about these cues. Figure 5B shows that throughout Stage 3, participants also spent more time looking at cue D than cue B. The implication is that the bias in attention away from cue B, that was established in Stage 2, had a knock-on effect on the attention paid to this cue in Stage 3. Perhaps most importantly for attentional theories of learning (Mackintosh, 1975; Pearce and Hall, 1980), the extent of the bias away from cue B, and towards cue D, was positively correlated with the bias in learning during this stage; those participants showing the strongest attentional bias in their eye-gaze data were the ones who learnt more about cue D over cue B. This result provides a nice demonstration of how eye tracking measures can consolidate our understanding of cognitive processing when used in tandem with traditional behavioral response measures.

[FIGURE 5 HERE]: CAPTION: Eye gaze dwell times on cues during Beesley & Le Pelley's (2011) task. Blocks contained 8 trials each, where a trial consisted of the presentation of two cues (e.g., A and B), the participants issuing a response (e.g., ‘Nausea’), and the presentation of feedback (i.e., correct/incorrect).

Beesley and Le Pelley’s (2011) study gives a clear demonstration of how eye tracking can provide a valuable complementary measure in behavioral tasks that would typically just measure response choice or response time. Eye tracking provided the ability to directly test the predictions of attentional accounts of blocking. It is also worth noting the value of the continuous nature of the eye tracking measure in this task. Figure 5B shows how attention was distributed to cues B and D in Stage 3 of the task, plotted across the six training blocks of this stage. By measuring eye gaze throughout Stage 3, attentional processing can be monitored over the course of learning. One could alternatively collect response data to try to assess knowledge about cues B and D based on standard measurements. For example, we could ask participants what they believed B and D predicted (individually) after every training block, allowing us to draw a graph similar to Figure 5B based on participants’ reported knowledge. However, explicitly asking for this information may well have a considerable effect on behavior in the task. Prompting participants for their explicit judgments might alter the way in which they think about cues on the next trial (e.g., being asked what cue B predicts might prompt participants to focus more closely on learning about this cue in future, in a way that would not have happened naturally if they had not been asked). Eye tracking measures do not suffer from this type of problem, since once a calibration of the participant with the tracker is complete – typically at the very start of the task – the continuous recording and measurement of eye position can be completed in an unobtrusive manner.

The automatic capture of attention by reward

Beesley and Le Pelley’s (2011) study demonstrates that an analysis of overall dwell time – a global measure of all fixations and saccades – provides a useful, broad measure of attentional processing that can yield insights into psychological processes. Finer grained analyses of eye movements can provide a deeper understanding of the processes underlying our visual behavior. In an example of research using such an approach, Pearson et al. (2016) were interested in the effect of rewards on visual attention. If a mundane stimulus (say, a red circle) has been paired with rewards (e.g., money, food, or sex) in the past, does that stimulus become more likely to automatically grab our attention and dominate our behavior in the future? Understanding when people’s attention will be captured, and what it will be captured by, is an important question. There are times when having our attention captured may be dangerous (e.g., while driving, we must try to prevent distraction by a roadside advertisement for a restaurant associated with tasty food), or harmful to health (e.g., an addict attempting to abstain from alcohol may try to ignore the bottles in the supermarket aisle – and a failure to do so may result in relapse: see Cox, Hogan, Kristian, & Race, 2002; Marissen et al., 2006; Wiers & Stacy, 2006). At other times, attentional capture is desirable; e.g., warning indicators in a plane's cockpit should be designed to attract attention as quickly as possible.

In their study, Pearson et al. (2016) used a visual search task in which, on each trial, participants were presented with an array of six objects on the screen and their task was to find the unique diamond among five circles (see Figure 6). The task was controlled entirely with eye movements; participants simply looked at the diamond (known as the target) and once the eye tracker registered that their gaze had reached the target, the trial terminated. One additional layer of complexity was added to this otherwise simple task; on each trial, one of the circles was colored either red or green, with all other shapes (including the diamond) presented in grey. This brightly colored circle was termed the distractor, and critically the color of this distractor signalled the size of the monetary reward that participants would receive for correctly making an eye movement to the target diamond. For half of the participants, if the distractor circle was red, then this signalled that a rapid eye movement to the diamond would receive a relative large reward (ten cents), whereas if the distractor was green, a rapid eye movement to the diamond would receive only a low reward (one cent). This relationship between colors and rewards was reversed for the other half of participants – i.e., for these participants, green was the high reward color and red was the low-reward color. However, participants received their reward only for looking at the diamond target, not for looking at the colored distractor circle. In fact, the task was arranged such that if the eye tracker detected any gaze on or near the distractor circle before participants looked at the target, the reward that would otherwise have been delivered on that trial was cancelled. Looking at the distractor was therefore counterproductive to participants' goal of maximizing their payoff. The worst thing a participant could do under these conditions is to look at a distractor in the high reward color, since that resulted in loss of a larger reward. And yet that is exactly what people did. Over the course of the task, participants looked more at high reward distractors than low-reward distractors. This difference cannot have been merely a consequence of participants' preference for one color over another, since the color of the high reward distractor was different for different participants (it was red for half of them, and green for the other half). Instead the findings must reflect the influence of people's experience of the rewards paired with each color. That is, it is more likely that gaze will be directed towards stimuli that have, in the past, signalled the availability of larger rewards – even if doing so results in a loss of reward! The broader implication is that we simply cannot help but look at things that tell us something nice might be about to happen. It is little wonder then that we struggle to avoid noticing those tempting treats in the supermarket queue.

[FIGURE 6 HERE] CAPTION: The trial procedure of Pearson et al. (2016). Each square represents a part of the trial procedure. Participants were presented with a gaze-contingent fixation cross. Once gaze was registered in the centre of the screen the fixation cross was removed and then followed by the search array. Participants moved their eyes to the diamond as quickly as possible. Reward was provided for accurate performance, the value of which was determined by the color of the distractor circle (green or red).

Pearson et al.'s (2016) finding that high reward stimuli were more likely to capture eye movements (known as oculomotor capture) suggests that the extent to which we prioritize visual information is influenced by our previous experience with that information (in this case regarding rewards; supporting data using both reaction time and eye-gaze measures is provided by Le Pelley, Pearson, Beesley & Griffiths, 2015). In subsequent analysis, Pearson et al. (2016) further explored the nature of this effect. In particular, they wanted to establish whether the effect of reward on attention reflected the operation of an automatic and involuntary process (in which the visual system prioritizes reward-related system in a 'bottom up' fashion), or a more controlled process wherein participants deliberately directed their attention towards reward-related stimuli in a 'top down' way. A hallmark of automatic influences on attention is that they are typically very rapid, whereas top-down influences are somewhat slower to take effect (Godijn & Theeuwes, 2002; Mulckhuyse, van Zoest & Theeuwes, 2008). In an analysis of the time-course of the effect of reward on attention, Pearson et al. (2016) therefore focussed on the very first saccade that participants made on each trial. In some trials, people would start moving their eyes very rapidly when the search array (the diamond and circles) appeared; that is, these trials had a short saccade latency. On other trials they would take longer to start moving their eyes, i.e., saccade latency was longer. Pearson et al. examined the direction of participants' first saccade as a function of its latency; the results of this analysis are shown in Figure 7. This figure shows that, overall, participants' first saccade was more likely to go towards a high reward distractor than a low-reward distractor – consistent with the findings described earlier. But notably, this influence of reward on oculomotor capture was most pronounced for the very fastest saccades that people made when the eyes started moving a mere 170 milliseconds after the search array was presented. This shows that reward exerts an extremely rapid influence on behavior, suggesting that it reflects an automatic, bottom-up influence that operates at an early stage of the visual processing system. Figure 7 also shows that the influence of reward on gaze was reduced at longer saccade latencies, suggesting that perhaps, given sufficient time, we might be able to prevent ourselves from having our behavior captured by reward-related stimuli – perhaps through the use of 'cognitive control' processes (Kouneiher, Charron, & Koechlin, 2009; Miller, 2000; Posner & Snyder, 1975). Taken together, these results point to an interplay between rapid and automatic processes that promote capture by reward-related stimuli, and slower, more controlled processes that prevent it. These findings, and others like them (e.g., Luque, Vadillo, Le Pelley, & Beesley, 2017), shed valuable light on when we might expect stimuli to 'take over' our behavior – which may have important implications for understanding and preventing maladaptive attentional biases, such as those associated with drug addiction (Field & Cox, 2008; Wiers & Stacy, 2006) and anxiety (Bar-Haim et al., 2007).

[FIGURE 7 HERE] CAPTION: Saccade data from Pearson et al. (2016), showing the proportion of first saccades toward the high value and low value distractors as a function of first saccade latency decile

Gaze-contingency

In this final section, we focus on the benefits of gaze-contingent eye tracking procedures for examining learning and attention. A gaze-contingent procedure is one in which eye tracking data are used to make changes to the task in real-time; events in the task procedure become contingent on the content of the gaze data. To achieve this, the gaze data are received by the computer system that is controlling stimulus presentation and then analyzed very rapidly (usually within a few milliseconds) to determine location, duration, and so on. The program then uses this information to make an adjustment to the procedure. It should be noted that gaze-contingent procedures will, somewhat inevitably, require a reasonable degree of technical expertise (see Appendix I) to write custom routines that analyze data in real time to evaluate the characteristics of the eye data and determine the appropriate next step in the procedure.

We have already discussed in several places the benefits of gaze-contingent procedures: in studies of reading they have been used to control the number of words that are viewable at any one moment; in studies of infant development to control the presentation time of the stimuli; and in Pearson et al.'s oculomotor capture task, gaze-contingency was used primarily to determine the reward that was presented.

A gaze-contingent procedure can also be useful to help ensure that participants are performing a task in the way that we (as experimenters) want them to. For example, suppose we have a task in which, on each trial, we are going to present images scattered across the screen at various positions, and participants will be required to make a response (e.g., a button press, a spoken response, or an eye movement) to one of them – much as in Pearson et al.'s (2016) study described above. Under these circumstances, we would often want to be sure that participants begin the trial with their attention in the same place (typically the centre of the screen), which makes it easier to compare performance between trials. For this reason, it is common to present a small image (often a cross) on the screen prior to the beginning of the trial, at the location where we want participants' attention to begin. Participants are asked to fix their gaze on this cross before the stimuli appear (hence this is known as the fixation period). Most participants will do this, most of the time. The question is what to do about occasions on which they do not – occasions on which their attention wanders prior to the trial, perhaps through boredom or because the participant is trying to second-guess where the stimuli will appear. Eye tracking can come to our aid here. One option is to take a passive approach. Here we record gaze during the fixation period and then, when the experiment is complete, we can analyze the gaze data offline to find those trials on which participants began the trial with their gaze on or near the fixation cross (we would include these trials in subsequent analyses), and those trials on which they did not (we would exclude these trials from subsequent analyses). This approach will work well, but the disadvantage is that if we have a particularly distractible or recalcitrant participant, we may end up discarding many trials on which the participant does not follow instructions and correctly fixate on the cross. An alternative is to use an active, gaze-contingent approach. Here we would record gaze during the fixation period and analyze the location of this gaze 'online', perhaps once every few milliseconds. We can then keep the fixation cross on-screen (and delay the start of the trial) until we register that the participant is looking at or near this cross – the trial would then begin. The advantage of this approach is that we can be sure the participant begins every trial looking where we want them to be looking. The disadvantage is that it can be frustrating for participants if tracking is not accurate – a participant may in fact be looking at the fixation cross, but the tracker may sometimes fail to register this (e.g., because it has been poorly calibrated, or because it is unable to track the participants' eyes well – see Appendix I) and the trial will therefore not begin. The study by Pearson et al. (2016) used a compromise approach; the trial began either after participants had accumulated 500 milliseconds of gaze dwell time near the fixation cross, or after 5000 milliseconds had elapsed, whichever came first.

Another good example of the value of gaze-contingent procedures is provided by Geringswald and Pollman (2015). In this experiment, the authors examined a learning effect known as contextual cuin*g.* In a typical contextual cuing experiment, participants are given a simple visual search task in which they are required to find a target 'T' shape amongst an array of distractor 'L' shapes, with some of the configurations of the search displays (the spatial arrangement of the L's and the T) repeated across trials. Participants are not told that there is anything to learn about in the task, merely that they should locate and respond to the target. However, the term contextual cuing refers to the fact that the ‘context’ of the environment (the arrangement of the L’s) cues the participant as to where the target (T) is positioned; participants are typically faster to find the target when it is presented in a repeated configuration (cued) as compared to a randomly arranged configuration (non-cued). This effect demonstrates that even in a task that does not require an intentional strategy to learn (about the arrangement of distractors), we nevertheless do store these repeating patterns in memory such that they facilitate our behavior in the future (for a recent review of theories of contextual cuing, see Beesley, Vadillo, Pearson, & Shanks, 2016). Geringswald and Pollman were particularly interested in whether the contextual cuing effect was driven primarily by *foveal* or *extrafoveal* vision. The ‘fovea’ is a small region of the retina on the back of the eye corresponding to the centre of our field of vision. The fovea is densely packed with photoreceptor cells to provide for high visual acuity – when we change our point of fixation, we are shifting the visual information that is processed by the fovea. In contrast, the extrafoveal region corresponds to the periphery of our field of vision – there are fewer photoreceptors in this extrafoveal region such that items presented in the periphery are not perceived with such acuity. To examine the role of foveal and extrafoveal vision in contextual cuing, Geringswald and Pollman used a gaze-contingent procedure in which the visual display was altered at the point of fixation. For one group, the central visual region around the participant’s fixation (~13 cm diameter) was masked, such that participants were unable to see objects falling in this central region. This provides an effective ‘scotoma’ on the foveal region (a scotoma is an area of degraded visual acuity, such as that found in conditions such as macular degeneration). In another condition, participants experienced the opposite arrangement, where objects in peripheral vision were masked, while objects in the foveated region could be seen (creating a ‘tunnel vision’ effect). Somewhat surprisingly, the researchers found that learning was significantly impaired in the case of the peripheral scotoma, such that not being able to see the peripheral objects of the scene was sufficient to abolish any learning of the scene’s content (see also Zang, Jia, Müller, & Shi, 2014). In contrast, with a central scotoma (but intact peripheral vision), learning was largely unaffected. This suggests that contextual cuing is driven in large part by extrafoveal vision.

These results provide great insights into the way in which memory processes interact with, and rely upon, the information provided to the visual system. This is a clear example of where important theoretical questions in social science research – how impaired vision affects cognitive function – simply could not be answered without the technical advances brought about by eye tracking and gaze-contingent designs.

Conclusions and future directions for eye tracking

The eye tracker has been a useful tool in modern experimental psychology from its inception, and with the wide adoption of eye tracking in psychology labs across the world, there can be no doubt that it will continue to play a prominent role in the toolkit of experimental psychologists. Beyond simply providing a complementary measure, it offers insights into cognitive processes that cannot be attained from other behavioral measures. As we have demonstrated in many of the examples of research practices, this is primarily a result of the continuous measurement provided by the tracker, which allows researchers to conduct analyses over time as a chain of cognitive processes unfolds. This has provided major breakthroughs in a number of fields and advanced psychological theories. The ease of use of eye trackers means that they are starting to play a significant role in the work of many more researchers across a variety of fields. The costs of basic eye tracking devices are now a fraction of what they once were, and built-in software allows non-expert researchers to collect gaze data and conduct basic data analyses.

What does the future hold for eye tracking research in the cognitive sciences? With eye trackers able to record at 2000 times per second and with a high degree of accuracy, it's unlikely that further improvements will have a considerable impact on the type of research that could be conducted. However, as with many computational advances, miniaturisation of eye tracking technology will benefit users in a number of ways. Recent years have seen the emergence of small, portable eye trackers, that can be attached to monitors on an ad-hoc basis, or even built into laptops, mobile phones, or specialized eyewear. These advances in technology may well change how we interact with personal computing devices. With the rise in popularity of virtual and augmented reality systems, it's also possible that eye-tracking will find new applications to refine the experiences these devices provide.

For research purposes, today's miniature eye trackers are somewhat limited in terms of the temporal and spatial resolutions they provide (see Appendix I for a discussion), but that will almost certainly change in the near future. The advent of research-quality, highly portable eye trackers, as well as continuing reductions in cost, means eye trackers will become even more widespread and will offer exciting new possibilities for science. Rather than requiring participants to come to a lab where a bulky, fixed eye tracker is located, researchers will instead be able to take the portable eye tracker to the participants. This will be a boon for researchers studying populations in which people are not easily able to access a lab (e.g., remote communities, neurological patients, prisoners), or in which many participants are located at the same off-site location away from the lab (e.g., schools, companies).

References

Aslin, R. N. (2007). What's in a look? *Developmental science*, *10*, 48-53.

Bar-Haim, Y., Lamy, D., Pergamin, L., Bakermans-Kranenburg, M. J., & Van Ijzendoorn, M. H. (2007). Threat-related attentional bias in anxious and nonanxious individuals: a meta-analytic study. *Psychological Bulletin, 133*, 1–24.

Beesley, T., & Le Pelley, M. E. (2011). The influence of blocking on overt attention and associability in human learning. *Journal of Experimental Psychology: Animal Behavior Processes*, *37*, 114.

Beesley, T., Vadillo, M. A., Pearson, D., & Shanks, D. R. (2016). Configural learning in contextual cuing of visual search. *Journal of Experimental Psychology: Human Perception and Performance, 42*, 1173–1185.

Blaser, R. E., Couvillon, P. A., & Bitterman, M. E. (2004). Backward blocking in honeybees. *Quarterly Journal of Experimental Psychology Section B*, *57*, 349-360.

Bomba, P. C., & Siqueland, E. R. (1983). The nature and structure of infant form categories. *Journal of Experimental Child Psychology*, *35*, 294-328.

Bridgeman, B., Hendry, D., & Stark, L. (1975). Failure to detect displacement of the visual world during saccadic eye movements. *Vision research*, *15*(6), 719-722.

Cox, W.M., Hogan, L.M., Kristian, M.R., & Race, J.H. (2002). Alcohol attentional bias as a predictor of alcohol abusers' treatment outcome. *Drug and Alcohol Dependence, 68*, 237-243.

Deubel, H., & Schneider, W. X. (1996). Saccade target selection and object recognition: Evidence for a common attentional mechanism. *Vision Research*, *36*, 1827-1837.

Fantz, R. L. (1964). Visual experience in infants: Decreased attention to familiar patterns relative to novel ones. *Science*, *146*, 668-670.

Field, M., & Cox, W.M. (2008). Attentional bias in addictive behaviors: A review of its development, causes, and consequences. *Drug and Alcohol Dependence, 97*, 1-20.

Frazier, L., & Rayner, K. (1982). Making and correcting errors during sentence comprehension: Eye movements in the analysis of structurally ambiguous sentences. *Cognitive Psychology*, *14*, 178-210.

Geringswald, F., & Pollmann, S. (2015). Central and peripheral vision loss differentially affects contextual cueing in visual search. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *41*, 1485.

Gilchrist, I. D., & Harvey, M. (2000). Refixation frequency and memory mechanisms in visual search. *Current Biology*, *10*, 1209-1212.

Glaholt, M. G., & Reingold, E. M. (2011). Eye movement monitoring as a process tracing methodology in decision making research. *Journal of Neuroscience, Psychology, and Economics*, *4*, 125.

Godijn, R., & Theeuwes, J. (2002). Programming of endogenous and exogenous saccades: Evidence for a competitive integration model. *Journal of Experimental Psychology: Human Perception and Performance, 28*, 1039–1054.

Griffiths, O. & Le Pelley, M. E. (2009) Attentional changes in blocking are not a consequence of lateral inhibition. *Learning & Behavior, 37*, 27-41.

Henderson, J. M. (2014). *Eyetracking technology knows your subconscious pizza desires . . . or not*. Retrieved from https://theconversation.com/eyetracking-technology-knows-your-subconscious-pizza-desires-or-not-35132

Hutzler, F., & Wimmer, H. (2004). Eye movements of dyslexic children when reading in a regular orthography. *Brain and language*, *89*, 235-242.

Kamin, L. J. (1969) Predictability, surprise, attention and conditioning. In B. A. Campbell & R. M. Church (Eds.), *Punishment and aversive behavior*. New York: Appleton-Century-Crofts.

Klein, R. (1988). Inhibitory tagging system facilitates visual search. *Nature*, *334*, 430-431.

Kouneiher, F., Charron, S., & Koechlin, E. (2009). Motivation and cognitive control in the human prefrontal cortex. *Nature neuroscience*, *12*, 939-945.

Krajbich, I., & Rangel, A. (2011). Multialternative drift-diffusion model predicts the relationship between visual fixations and choice in value-based decisions. *Proceedings of the National Academy of Sciences*, *108*, 13852-13857.

Kruschke, J. K., & Blair, N. J. (2000). Blocking and backward blocking involve learned inattention. *Psychonomic Bulletin & Review, 7*, 636-645.

Le Pelley, M. E., Beesley, T., & Suret, M. B. (2007). Blocking of human causal learning involves learned changes in stimulus processing. *Quarterly Journal of Experimental Psychology, 60*, 1468–1476.

Le Pelley, M. E., Beesley, T., & Griffiths, O. (2014). Relative salience versus relative validity: Cue salience influences blocking in human associative learning. *Journal of Experimental Psychology: Animal Learning and Cognition, 40*, 116

Le Pelley, M. E., Pearson, D., Griffiths, O., & Beesley, T. (2015). When goals conflict with values: Counterproductive attentional and oculomotor capture by reward-related stimuli. *Journal of Experimental Psychology: General*, *144*, 158.

Luque, D., Vadillo, M. A., Le Pelley, M. E., & Beesley, T. (2017). Prediction and uncertainty: Examining controlled and automatic components of learned attentional biases. *The Quarterly Journal of Experimental Psychology, 70*, 1485–1503.

Mackintosh, N. J. (1975). A theory of attention: Variations in the associability of stimuli with reinforcement. *Psychological Review*, *82*, 276.

Marissen, M.A.E., Franken, I.H.A., Waters, A.J., Blanken, P., van den Brink, W., & Hendriks, V.M. (2006). Attentional bias predicts heroin relapse following treatment. *Addiction, 101*, 1306-1312.

McConkie, G. W., & Rayner, K. (1976). Asymmetry of the perceptual span in reading. *Bulletin of the Psychonomic Society*, *8*(5), 365-368.

Miller, E. K. (2000). The prefontral cortex and cognitive control. *Nature Reviews Neuroscience*, *1*, 59-65.

Morris RK. (1994). Lexical and message-level sentence context effects on fixation times in reading. *Journal of Experimental Psychology: Learning, Memory, & Cognition, 20*, 92–103.

Mulckhuyse, M., van Zoest, W., & Theeuwes, J. (2008). Capture of the eyes by relevant and irrelevant onsets. *Experimental Brain Research, 186*, 225–235.

Newell, B. R., & Le Pelley, M. E. (2018). Perceptual but not complex moral judgments can be biased by exploiting the dynamics of eye-gaze. *Journal of Experimental Psychology: General, 147*, 409-417.

Nixon, H. K. (1924). Attention and interest in advertising. *Archives of Psychology, 72*, 5–67

Pärnamets, P., Johansson, P., Hall, L., Balkenius, C., Spivey, M. J., & Richardson, D. C. (2015). Biasing moral decisions by exploiting the dynamics of eye gaze. *Proceedings of the National Academy of Sciences of the United States of America, 112,* 4170–4175.

Pavlov, I. P. (1927). *Conditioned Reflexes* (translated by G. V. Anrep). London: Oxford University Press.

Pearce, J. M., & Hall, G. (1980). A model for Pavlovian learning: variations in the effectiveness of conditioned but not of unconditioned stimuli. *Psychological Review*, *87*(6), 532.

Pearson, D., Osborn, R., Whitford, T. J., Failing, M., Theeuwes, J., & Le Pelley, M. E. (2016). Value-modulated oculomotor capture by task-irrelevant stimuli is a consequence of early competition on the saccade map. *Attention, Perception, & Psychophysics*, *78*, 2226-2240.

Posner, M. I. (1980). Orienting of attention. *Quarterly Journal of Experimental Psychology*, *32*, 3-25.

Posner, M. I., & Cohen, Y. (1984). Components of visual orienting. *Attention and performance X: Control of language processes*, *32*, 531-556.

Posner MI, Snyder CRR (1975. Attention and cognitive control. In: Solso RL, editor. *Information Processing and Cognition: The Loyola Symposium*. Lawrence Erlbaum

Prados, J., Alvarez, B., Acebes, F., Loy, I., Sansa, J., & Moreno-Fernández, M. M. (2013). Blocking in rats, humans and snails using a within-subjects design. *Behavioral processes*, *100*, 23-31.

Rayner, K. (2009). Eye movements and attention in reading, scene perception, and visual search. *The Quarterly Journal of Experimental Psychology*, *62*, 1457-1506.

Reichle, E. D. (Ed.). (2006). Models of eye movement control in reading [special issue]. Cognitive Systems Research, 7, 1–96.

Sanders, A. F., & Houtmans, M. J. M. (1985). There is no central stimulus encoding during saccadic eye shifts: A case against general parallel processing notions. *Acta Psychologica*, *60*, 323-338.

Shimojo, S., Simion, C., Shimojo, E., & Scheier, C. (2003). Gaze bias both reflects and influences preference. *Nature neuroscience*, *6*(12), 1317-1322.

Tennant, W. A., & Bitterman, M. E. (1975). Blocking and overshadowing in two species of fish. *Journal of Experimental Psychology: Animal Behavior Processes*, *1*(1), 22.

Vadillo, M. A., Street, C. N. H., Beesley, T., & Shanks, D. R. (2015). A simple algorithm for the offline recalibration of eye tracking data through best-fitting linear transformation. *Behavior Research Methods, 47*, 1365-76.

Volkmann, F. C., Schick, A. M., & Riggs, L. A. (1968). Time course of visual inhibition during voluntary saccades. *Journal of the Optical Society of America*, *58*, 562-569.

Wang, J. T., Spezio, M., & Camerer, C. F. (2010). Pinocchio's Pupil: Using Eyetracking and Pupil Dilation to Understand Truth Telling and Deception in Sender-Receiver Games. *American Economic Review, 100*, 984-1007.

Wedel, M., Pieters, R., and Liechty, J. (2008). Temporal dynamics of scene perception: Goals influence switching between attention states. *Journal of Experimental Psychology: Applied, 14*, 129–138

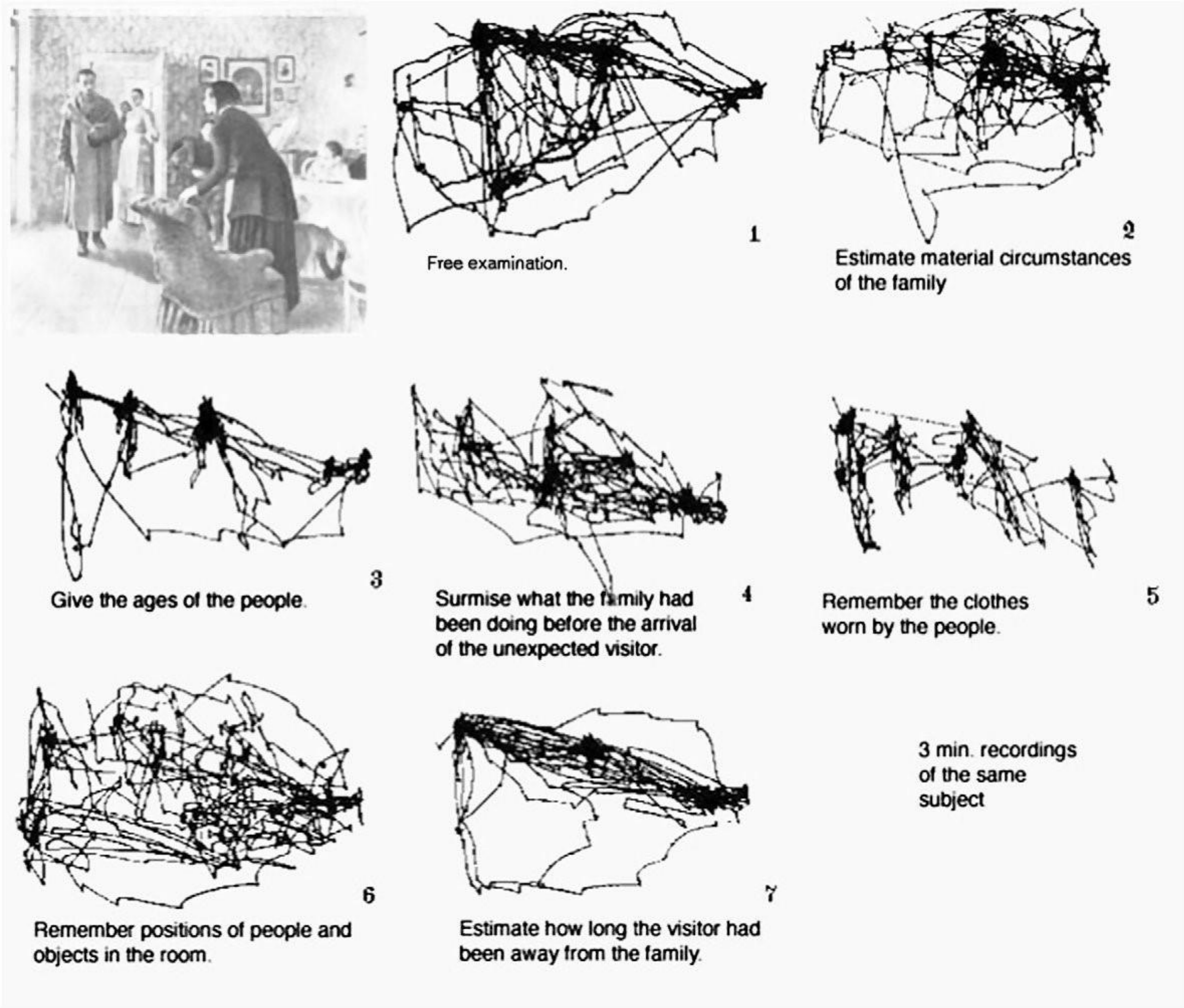
Wiers, R.W., & Stacy, A.W. (2006). Implicit cognition and addiction. *Current Directions in Psychological Science, 15*, 292-296.

Wills, A. J., Lavric, A., Croft, G. S., & Hodgson, T. L. (2007). Predictive learning, prediction errors, and attention: Evidence from event-related potentials and eye tracking. *Journal of Cognitive Neuroscience, 19*, 843-854.

Yarbus A L. *Eye Movements and Vision*. New York: Plenum Press; 1967

Zang, X., Jia, L., Müller, H. J., & Shi, Z. (2015). Invariant spatial context is learned but not retrieved in gaze-contingent tunnel-view search. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *41*, 807.

Figure 1



1
Free examination.
2
Estimate material circumstances of the family
3
Give the ages of the people.
4
Surmise what the family had been doing before the arrival of the unexpected visitor.
5
Remember the clothes worn by the people.
6
Remember positions of people and objects in the room.
7
Estimate how long the visitor had been away from the family.
3 min. recordings of the same subject

Figure 2

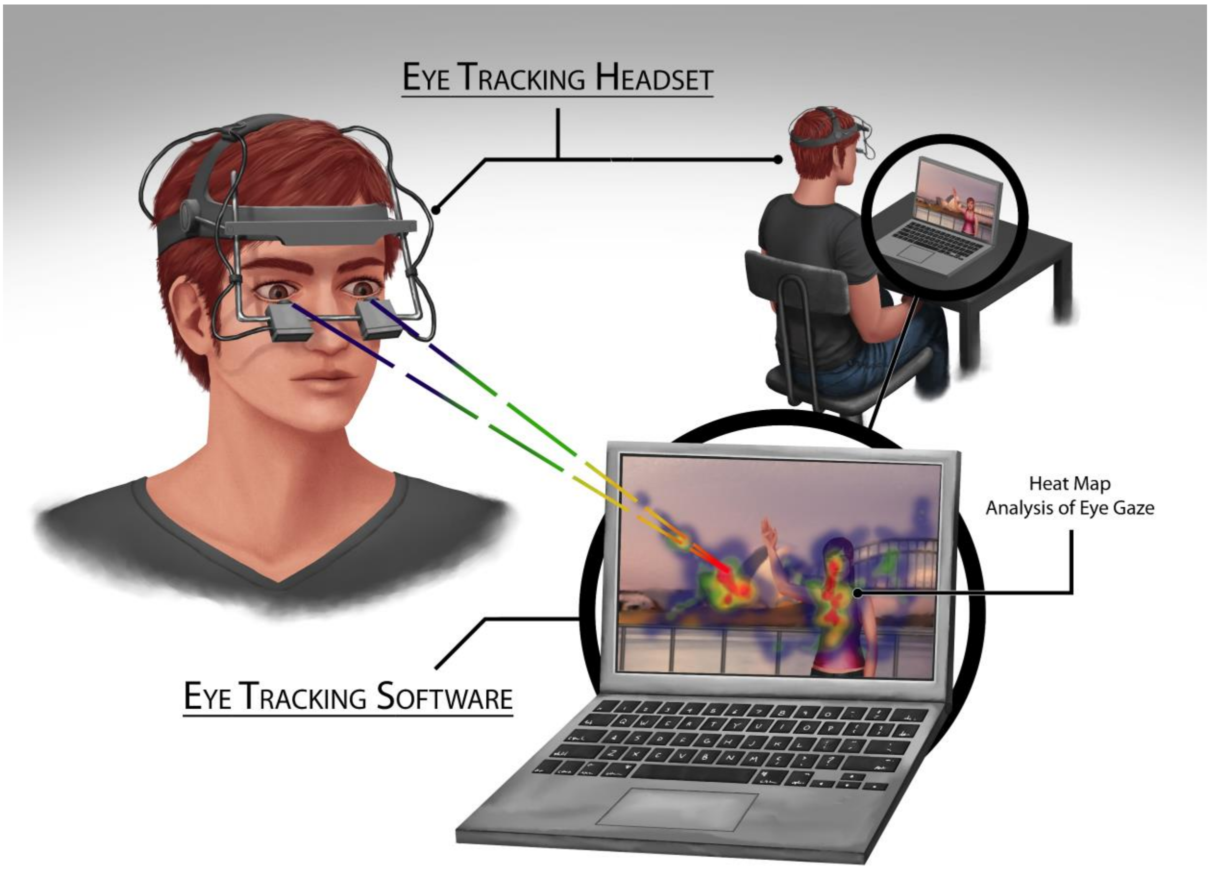

EYE TRACKING HEADSET
Heat Map
Analysis of Eye Gaze
EYE TRACKING SOFTWARE

Figure 3

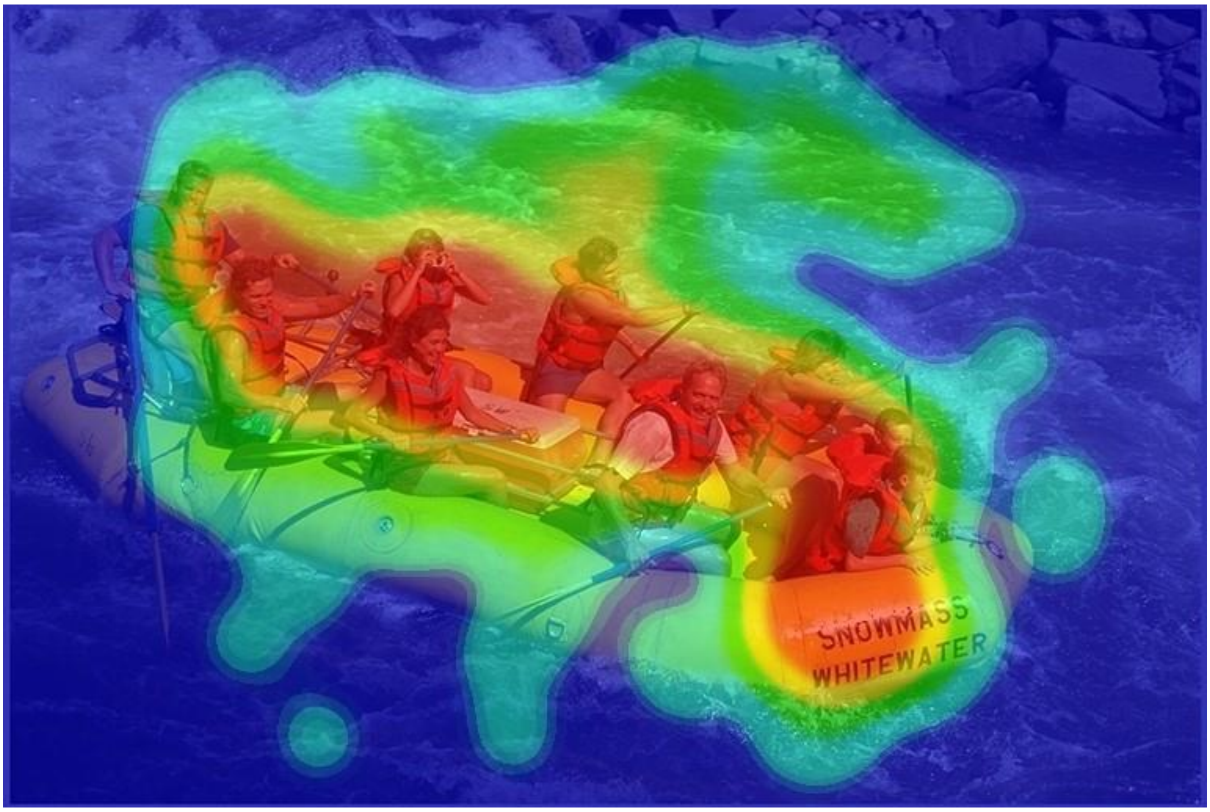
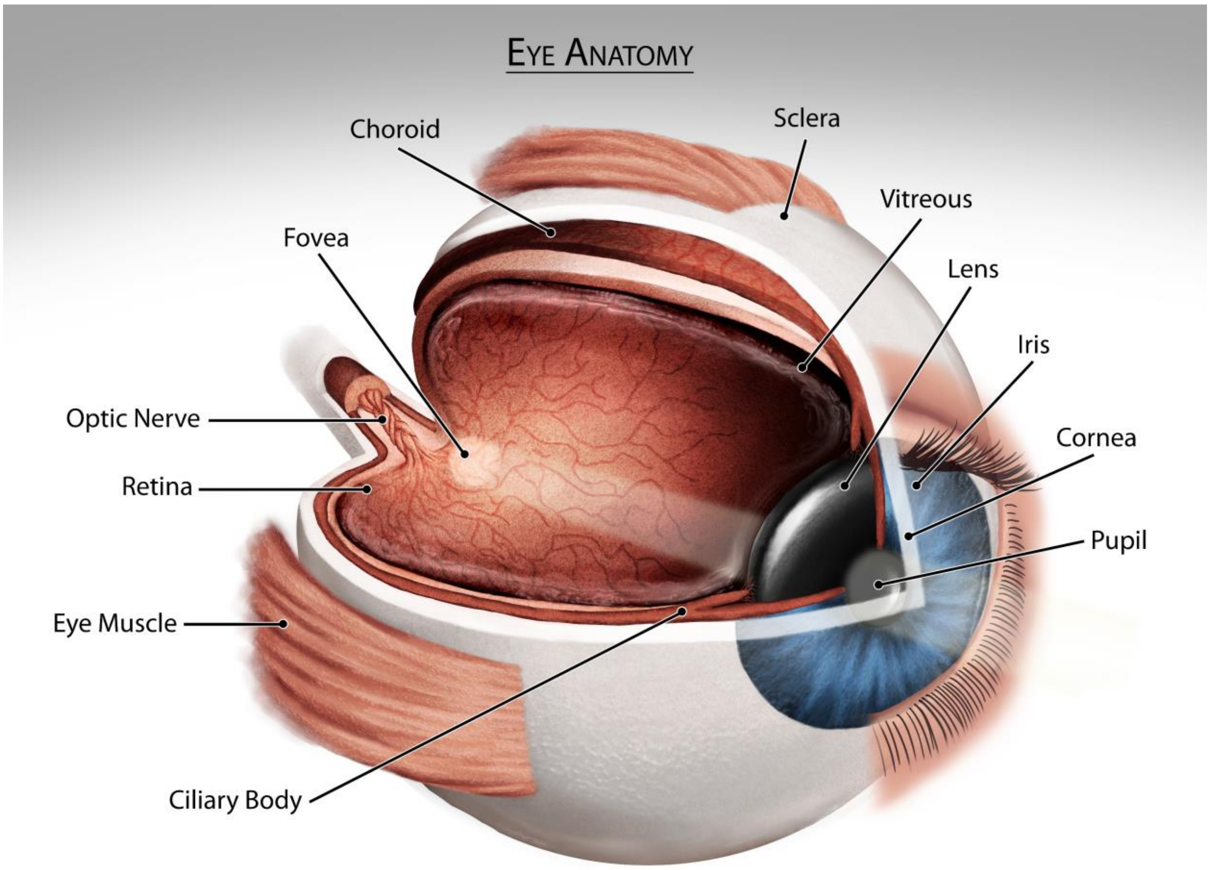


Figure 4



EYE ANATOMY
Choroid
Sclera
Vitreous
Fovea
Lens
Iris
Optic Nerve
Cornea
Retina
Pupil
Eye Muscle
Ciliary Body

Figure 5

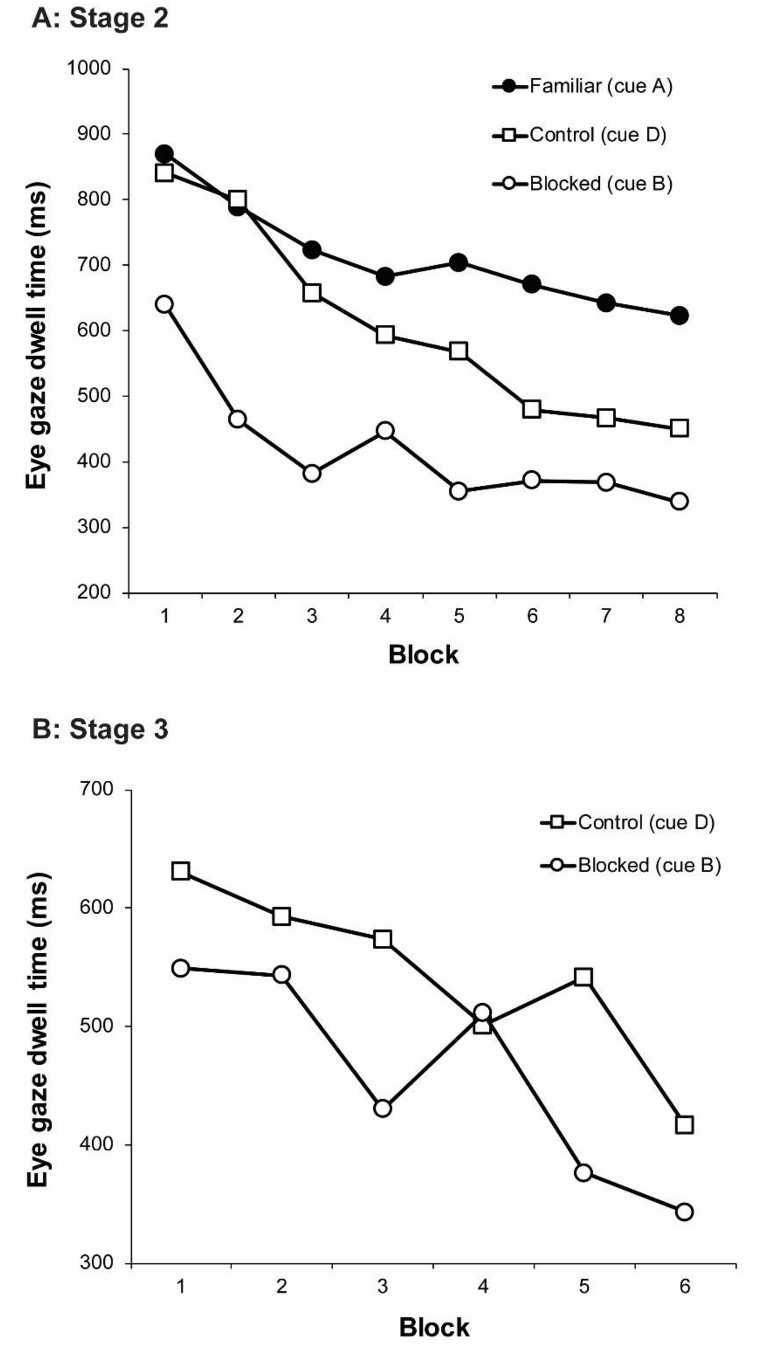
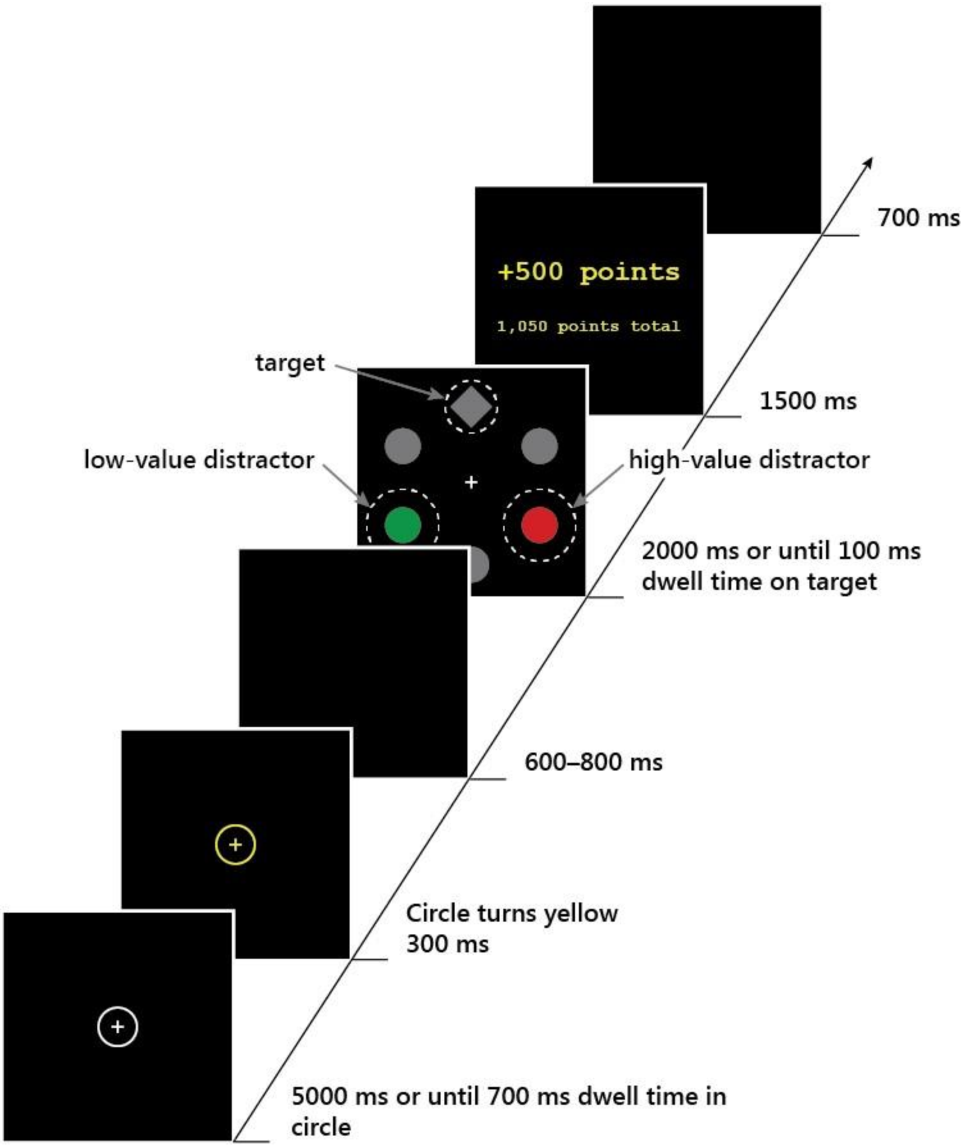
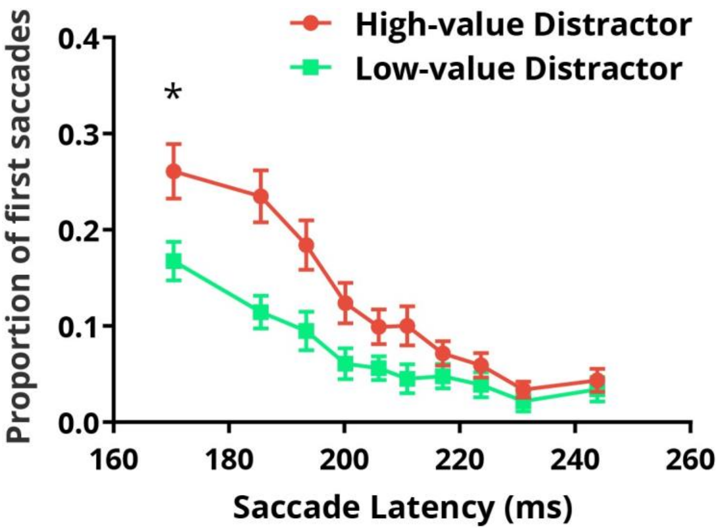

A: Stage 2
1000
900
800
700
600
500
400
300
200
Eye gaze dwell time (ms)
Familiar (cue A)
Control (cue D)
Blocked (cue B)
1
2
3
4
5
6
7
8
Block
B: Stage 3
700
600
500
400
300
Eye gaze dwell time (ms)
Control (cue D)
Blocked (cue B)
1
2
3
4
5
6
Block

Figure 6



+500 points
1,050 points total
target
low-value distractor
high-value distractor
700 ms
1500 ms
2000 ms or until 100 ms dwell time on target
600–800 ms
Circle turns yellow 300 ms
5000 ms or until 700 ms dwell time in circle

Figure 7


High-value Distractor
Low-value Distractor
*
Proportion of first saccades
0.4
0.3
0.2
0.1
0.0
160
180
200
220
240
260
Saccade Latency (ms)

Endnotes

[i] [i] The term 'trial' here is intended to reflect the presentation of stimuli and the recording of a behavioural response. In typical experimental tasks, of the sort described here, many such trials will be used to minimize the effects of measurement error. Data from a set of trials are often grouped and analyzed in 'blocks'.