Saccadic eye movements and cognition
Simon P. Liversedge and John M. Findlay

Scanning of the visual scene is an important selective process in visual perception. In this article we argue that eye-movement data provide an excellent on-line indication of the cognitive processes underlying visual search and reading. We outline some recent advances from physiological investigations of saccadic eye-movement control before focusing on eye-movement behaviour in visual search and reading studies. We consider factors that can affect the duration of fixations and the choice of saccade targets, emphasising continuities between biological and cognitive descriptions. We discuss different ways of measuring cognitive processing time from an eye-movement record and the relationship between attention and eye movements.

The visual environment is an enormously rich source of information. Any approach to understanding visual perception must recognise that only a small part of this potential information is actually used. In this article we shall be concerned with one of the principal ways in which selection of information occurs. The visual axis of the eye is directed to a series of locations in the visual field, resulting in a continually changing sequence of images falling on the fovea. This sequence is the main, although not the only, way in which visual input is selected for cognitive visual tasks. We shall mainly consider recent work in two well-controlled cognitive situations, visual search and reading, to illustrate the progress that has been made in understanding this system of visual sampling and to flag some important unanswered questions.

The fundamental nature of this sampling is neatly illustrated by a recent case report of an individual with congenital ophthalmoplegia1. This individual has no functional eye muscles and her eyes are essentially fixed in her head. Her visual impairment is surprisingly small and she lives a normal life, customarily as a university student. Examination shows that she makes scanning movements with her head which have very similar properties to the saccadic eye scanning seen in a normal individual. This shows that active saccadic scanning is a fundamental feature of vision. It is not so much dependent on the organisation of the oculomotor system as upon the organisation of the visual system. Saccades are necessitated by the rapid decline in resolution away from the fovea. It is often convenient to describe the fovea as occupying the central two degrees of the retina, flanked by the parafovea which extends out a further three degrees, beyond which the remaining area is termed the periphery2. As functional terms, however, these definitions are entirely arbitrary. Visual resolution declines steadily from a maximum in the very centre of the fovea.

Neural control of saccades
Considerable progress has been made in understanding the brain processes subserving saccade control3. The pattern of neural activity that results in a saccadic movement is shaped in the brainstem. Brainstem ‘omnipause’ cells are characterised by sustained activity except immediately before and during every saccade when the activity ceases. These cells trigger the movement but, as the name implies, they do not code the spatial characteristics. Saccade coding occurs in various ‘burst’ cells, located in neighbouring regions of the brainstem. Brainstem organisation therefore shows a separation between cells encoding the spatial characteristics of the saccadic movement (‘where’) and those concerned with triggering the movement (‘when’).

Both omnipause cells and burst cells receive signals from a higher centre intimately involved in eye-movement control, the superior colliculus (SC) of the midbrain. The SC receives visual input from several cortical regions (as well as a poorly understood direct input from the retina) and forms an important visuomotor centre, in which a retinotopically coded visual signal accesses a spatiotopic motor map that codes saccadic movements of different sizes and directions. The rostral pole region of the SC is crucially involved in fixation and saccade triggering. The readiness with which a monkey will make an orienting saccade can be increased or decreased by injection into this region of GABA agonists or antagonists respectively4. Cells in the region are active during fixation and pause just prior to and during saccadic eye movements5. Their activity is quite similar to brainstem omnipause cells and anatomical connections between the respective regions in the colliculus and the brainstem have been traced6. Across the remainder of the colliculus, two types of cell, SC build-up cells and SC burst cells, are found, whose properties code the destination of saccadic movements7. This evidence can be interpreted in terms of a further where/when separation. Saccade triggering is crucially dependent on events in the fixation centre, located in the rostral pole of the SC, whereas the choice of saccade destination is dependent on the pattern of activity throughout the build-up system, which may be likened to a salience map.
Box 1. Eye movements and attention

The sequences of eye fixations discussed in this review describe the way in which covert attention is deployed. It is well known that attention can be directed to locations in space without moving the eyes. How does this covert direction of attention interact with overt eye movements?

Could several covert shifts of attention occur during each eye fixation? Early estimates of the speed of covert attentional movements were as fast as 30 shifts of attention per second (Ref. 4). Such a rate would indeed allow serial movements of the supposed mental spotlight during an eye fixation (about 250 ms). As discussed in the section on visual search of this article, abstractive interpretations of the data are now common and direct estimates of the rate of deployment of covert visual attention give much lower rates (Ref. 5). Nevertheless, it appears to be possible for a peripheral cue to ‘command’ attention during an eye fixation as indexed by enhanced discrimination at the cue location. The cue may achieve this without necessarily opening the next eye movement, although such captures also occur frequently (Ref. 6).

Covert attention is induced by the phenomena that peripheral visual targets to which attention is directed covertly are better discriminated and move rapidly processed. Such processing advantages are found with visual material at the location about to receive fixation with an eye movement (Ref. 6). This may be interpreted as an indication that a covert attentional movement accompanies, and precedes, an overt eye movement. Such a close relationship between covert and overt attention is a feature of the ‘premotor theory’ of covert attention, which claims that covert attention is achieved by preparing but withholding execution of an overt eye movement (Ref. 6).

Models of eye-movement control, particularly in the area of reading, have invoked covert attentional processes. Morrison proposed that, during each fixation, covert attention shifts from the word currently being processed to select the next location for the eye (Ref. 6). The analogy of a rubber band is often made, a covert attentional shift occurring first and subsequently ‘pulling’ the eye along. Models of attention and eye movements have emphasized the capacity limitation of attention (Ref. 6). For example, arguing that when the fixated word is difficult to process, foveal attentional demands are high, we suggest that attention can be allocated to parfoveal words. This would result in shallow parafoveal processing (however, see Ref. 3 for evidence against this suggestion).

Another recent approach has been the model of the ‘E-Z reader’ of Reichle et al. (Ref. 7), which maintains the emphasis on underlying shifts of covert attention but concentrates more on elaborating the processes involved in initial access. There is no doubt that these models represent the most fully formed attempts to predict eye-movement patterns in complex cognitive tasks. However, it is clear that covert attention is not well understood at present.

References


Because much work in visual cognition relies heavily on the duration of eye fixations, the precise details of the fixation region become of great importance. Gandhi and Keller have reported cells showing ‘fixation neuron’ properties over a circular region corresponding to the central 10 degrees of visual field and Krauzlis et al. have suggested that fixation cells and build up cells form a continuum. These findings might account for the ‘remote distractor effect’ in which unattended stimuli at a remote location from the goal of a saccade delays its initiation.

Two principal descending input pathways to the SC come from the frontal eye field (FEF) region and posterior parietal cortex. Arguments have been presented that both centres can be considered as operating in terms of a salience map. These cortical areas also contain ‘fixation’ cells, whose properties are similar to those found at lower levels. Studies in these brain areas are pioneering our understanding of the way the brain is involved in the details of cognitive processes and the role of the FEF in visual search is discussed at the end of the next section.

Eye movements in visual search

Visual search has proved to be a suitable task to explore selective processes. It has been adopted by a range of workers from cognitive psychologists to neurophysiologists and has been used effectively in studies with both human participants and trained monkeys. Within cognitive psychology, visual search has been a key topic for many years but until recently active eye scanning has received relatively little consideration. This is in part a consequence of the very influential theory proposed by Treisman and Gelade who argued that, although some simple search tasks might be accomplished by pre-attentive processes, more demanding tasks required a sequential attention scanning of elements. This scanning has often been assumed to be covert, using a ‘mental spotlight’. The main supporting evidence for the theory came from the search function, showing how the time to make a target present/ target absent decision varied as the number of distractors was increased. Simple search tasks show a flatter search function whereas in demanding tasks a linear increase in search time is found in the number of items is increased.

Consideration of feature-integration theory in relation to eye scanning raises some very important questions. To what extent must a role be assigned to covert attentional processes in the choice of where the eyes move? (see Box 1). If the spotlight model is adopted, a further question becomes whether several covert attentional movements can precede an overt saccade. There has been considerable controversy over the rate at which covert attention can be redeployed but the fastest estimates (30 ms per item) would allow a number of such movements to occur in a typical fixation pause (250 ms). However the main source of such fast estimates of attentional
Eye movements while scanning scenes and pictures

The intriguing patterns of eye scanning as individuals view pictorial scenes and objects have long been a source of fascination. Space considerations preclude detailed discussion here and recent reviews of scene perception have appeared in this journal4 and elsewhere45–47. Although some gist information is acquired from a brief glance at a scene48, extended viewing of scenes or pictures inevitably results in saccadic scanning. This scanning is essential to obtain details of objects49, although a frontal mask has a somewhat less demarcating effect on an object recognition paradigm50 than on reading51.

There has been considerable study of statistical patterns of eye movements during scene viewing and how these change during the viewing period. There have also been demonstrations that fixation durations are affected both by low-level visual factors such as contrast52 and high-level semantic properties of the fixated object53. The processes that determine the choice of individual saccade destinations, on the other hand, are still very poorly understood. An early report suggested that the eyes would be attracted rapidly to an out of context object (e.g. an octopus in a farmyard). However, several attempts to replicate this finding have now proved unsuccessful36,54.

Eye-movement research into reading

In this section we will argue that eye movements provide an excellent, on-line behavioural measure of the cognitive processes underlying reading. We provide a description of some general characteristics of eye movements during reading before summarising the contribution that this research has made to the psycholinguistic literature.

There has been a substantial amount of eye-movement research related to reading (see Rayner39 for a review). Within this field, two distinct research groups have developed each of which uses eye-movement methodology to slightly different ends. The first group aims to understand the mechanics of how the eyes move. This group is primarily interested in the effects of relatively low level visual and linguistic factors on eye-movement control. The second group aims to make inferences about higher order psycholinguistic processes underlying written language comprehension. Factors affecting word identification, computation of structural relationships between words of a sentence (syntactic processing) and understanding the meaning of a sentence or short text as a whole (semantic processing) have all been investigated. To such psycholinguistic researchers the mechanics of eye-movement behaviour is not of principal interest. Instead, they are concerned with how linguistic differences between sentences cause differences in reading behaviour.

Before embarking on a discussion of eye movements and reading it may be useful to consider a typical record of a subject’s eye movements as a sentence is read (see also Box 2). A normal eye-movement record comprises a series of fixations and saccades. During each fixation the subject extracts the visual information that they process after which they make a saccade to relocate the point of fixation elsewhere in the text.

General characteristics of eye movements during reading

When people read sentences their fixations are typically between 60 and 300 ms long, being about 250 ms on average. When reading English text, readers move their eyes from left to right in a saccade that ends51. The first group aims to understand the mechanics of how the eyes move. This group is primarily interested in the effects of relatively low level visual and linguistic factors on eye-movement control. The second group aims to make inferences about higher order psycholinguistic processes underlying written language comprehension. Factors affecting word identification, computation of structural relationships between words of a sentence (syntactic processing) and understanding the meaning of a sentence or short text as a whole (semantic processing) have all been investigated. To such psycholinguistic researchers the mechanics of eye-movement behaviour is not of principal interest. Instead, they are concerned with how linguistic differences between sentences cause differences in reading behaviour.

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Relative to a given element in a display is the most direct spatial measure. The spatial and temporal features of this command can be measured, and are both of considerable interest. Which aspects are used depends on the objective, and level of detail sought, by the investigator (see below). Importantly, the use of static visual displays (of search elements of text) in this kind of research obviates the need to consider pursuit eye movements, which simplifies the analysis of the eye-movement record considerably.

Although absolute spatial measures of eye movements, such as saccade length, are sometimes of interest, it is generally more useful to relate the spatial aspect of the measurement to the material being viewed. Thus, saccade landing position relative to a given element in a display is the more direct spatial measure. Fixation duration is another measure, which relates to the temporal aspect of saccade programming. In this review, we consider situations in which eye sampling is related to visual displays of discrete elements, either abstract elements in visual search (Fig. I), or linguistic elements such as the individual words or phrases of sentences in reading research. Measures of eye-movement behaviour and the psychological processes underlying reading and visual processing will be obtained. As we develop more detailed measures of eye-movement behaviour, a greater degree of specificity regarding the relationship between patterns of eye-movement behaviour and the psychological processes underlying reading and visual processing will be obtained.

Fig. I. A hypothetical scan path during a visual search task. A typical eye-movement record of a subject carrying out a visual search task. The subject first fixates the central point on an otherwise blank screen and when the display is presented the task is to search with the eyes for a red cross. In this case, the eye-movement record has been superimposed on the visual array, it must be decided (in a relatively arbitrary way) which fixations should be summed in order that a processing difficulty be detected. Most measures of disruption sum spatially contiguous fixations (fixations occurring within roughly the same location). While such measures provide valuable information regarding processing difficulty, Liversedge et al. argue that considering these alone may result in a failure to detect exactly when readers experience processing difficulty. For example, if a reader makes a series of saccades to re-read different portions of a sentence, each successive fixation might occur in a different position in the sentence (e.g. the fixations of 190 and 270 ms in Fig. II) but these fixations may well reflect the same recovery process. For each pattern of eye movements, a measure that sums temporally contiguous fixations may also be required to detect this disruption (e.g. regression path duration; Ref. c).

References

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to right approximately 85% of the time and from right to left 15% of the time. Saccades are on average 7–9 characters in size (that is, they typically jump from one character to another, 7–9 characters downstream). However, they vary in length, some being the length of only one character, while others may be almost as long as the sentence itself (e.g. a return sweep saccade from right to left in order to initiate a new line of text). Readers tend to fixate content words, which are usually quite long, but skip function words, which tend to be quite short. Fixations usually land between the beginning and the centre of a word (preferred viewing location) but there is some evidence suggesting that readers fixate informative portions of words (the optimal viewing position). The number of characters in a saccade varies on any fixation is termed the visual span and the number of characters that a reader processes at least partially during a fixation is termed the perceptual span. The perceptual span is asymmetrical about the point of fixation, being extended towards the direction in which the reader progresses through the text. For English readers the perceptual span is about four characters to the left and 15 characters to the right of fixation. For Hebrew readers, who read text from right to left, the perceptual span is offset in the opposite direction. The perceptual span is under cognitive control with English-Hebrew bilinguals switching their span offset to the right when reading English and to the left when reading Hebrew. Readers not only process text that they are fixating, but also process text in the distraction that they are reading. Readers make more fixations and fixate for longer when they experience processing difficulty. Additionally, when readers misanalyse sentences they make regressive saccades to re-read the appropriate analysis. These decisions about where in the text to fixate, and when to move the eyes following a fixation, reflect the ‘where’ and ‘when’ aspects of eye-movement control discussed in the previous section.

‘Lower level’ linguistic influences on eye movements

There has been a substantial amount of eye-movement research investigating lexical processing (word identification). The duration of a fixation on a word is affected by its basic lexical properties such as frequency and length. Lower frequency words are fixated for longer than higher frequency words, and the longer a word is, the more likely a reader is to refixate it, producing increased gaze durations. Fixation times on lexically ambiguous words (e.g. bank) vary depending upon the word’s meanings and the within-sentence context. When ambiguous words with two equally likely meanings (balanced ambiguous words) are embedded in a semantically neutral sentential frame, then reading times are slower than for control words matched for length and frequency. In contrast, when an ambiguous word has a dominant meaning (biased words), readers fixate it for no longer than they do an unambiguous word, provided the context permits the more frequent meaning of the word. However, when sentential context favours the less frequent meaning of a biased ambiguous word, fixation durations on the word increase relative to those for a control word. These findings show that eye-movement behaviour is affected not only by the characteristics of the words being fixated, but also by the relationship between the fixated word and preceding text.

Recent work has also shown that the number of orthographic neighbours that a word has (words that differ by just one letter) affects eye movements. When a word has many neighbours, the duration of the fixation immediately after leaving the word is longer than when a word has few neighbours. This effect probably reflects competition between candidate words during the identification process (though it is not clear why this effect does not occur on the word itself).

Given that readers pre-process text to the right of the word they are fixating, the question arises of what kind of information is being extracted. A contingent-change boundary technique has been used in a number of studies to obtain an indication of the information a reader extracts from non-foveal locations. In such a study by Rayner, Kambe and Duffy has shown that when readers are fixating a word, they make a longer saccade from the word when it is the last word in the clause than when it is not. This suggests that the process of ‘wrapping up’ a linguistic constituent to determine its meaning affects the subsequent saccade into a new linguistic constituent. This result is striking as it indicates that higher-level as well as lower-level linguistic factors impact upon eye guidance during reading.

‘Higher level’ linguistic influences on eye movements

The preceding discussion has described research investigating the effect of relatively low level linguistic and visual factors on eye-movement behaviour. This research usually involves taking very fine-grained measurements from the eye-movement record. However, work that investigates higher order processes involved in reading tends to involve the use of more coarse measures (see Box 2). Researchers investigating syntactic processing have typically compared eye-movement records for syntactically ambiguous sentences with records for unambiguous counterpart sentences. Such comparisons...

[Box 2 content is not visible in the image]
one way rather than another.86,88,89,91,92. Other studies have readers prefer to process structurally ambiguous sentences in potential and discourse context can modulate this preference93–98 convincingly demonstrated that linguistic factors such as sen-
downstream from the critical word91. A number of recent studies have been taken to support constraint-satisfaction sources of linguistic and statistical information act as con-
progressions in order to re-read the sentence. However, there is they are said to have been ‘garden-pathed’90. Usually, when subjects do initially misanalyse a sentence syntactically, they often show differences in eye-movement patterns that reflect a syntactic misanalysis of the ambiguous portion of a sentence. When subjects do initially misanalyse a sentence, they are said to have been ‘garden-pathed’90. Usually, when readers are garden-pathed the time spent on the disambiguating word will be quite long and readers will often make re-
manipulated the distance (in words) between the category and the instance and found that distance and typicality had
A number of eye-movement studies have shown that readers prefer to process structurally ambiguous sentences in one way rather than another.86,88,89,91,92. Other studies have convincingly demonstrated that linguistic factors such as sen-
tential and discourse context can modulate this preference86,88,89,91,92 and that readers are often able to use a contextual cue to guide their initial interpretation of a sentence. Results from such studies have been taken to support constraint-satisfaction models of sentence processing86,88,89,91,92. According to such models, sources of linguistic and statistical information act as con-
straints on the particular analysis that the sentence processor favours at any point in the sentence. Thus, different analyses compete with each other for activation and the competition between the different alternatives can be the cause of observed disruption86,88,89,91,92, though other studies have provided evidence against this suggestion86,88,89,91,92. Eye-movement data have also been used to investigate aspects of semantic processing. In order for readers to develop a full understanding of a sentence, they must determine ante-
cedents of referential expressions and make inferences in order in that the sentence is coherent with preceding discourse. Each of these processes has been shown to affect eye movements. For example, Garrod, Franklin and Boyle recorded sub-
jects’ eye movements as they read sentences containing a pronoun that could refer to either of two entities mentioned in a preceding passage.86,88,89,91,92 Garrod and colleagues manipulated whether the potential antecedents were in or out of linguistic focus, and also whether the verb associated with the pronoun was congruous with one or the other of the antecedents. They showed that both variables influenced first pass reading times indicating that higher-order semantic processes such as the formation of co-referential relationships influence how we read.

### Box 3. Eye movements and auditory language processing

Although eye-movement recordings are frequently used to examine reading, a number of recent studies by Tanenhaus and his col-
leagues, have used eye-movement recordings to investigate spoken language comprehension (Refs a–c), using methodology that was originally described by Cooper (Ref. f). In these studies the ex-
perticipants processed particular objects in a visual array while carefully manipulating the spoken instructions that the subjects receive. Through the use of a head-mounted eye-tracking sys-
tem, subjects’ eye movements are recorded as they carry out the instructions. For example, one experiment investigated how listeners process complex noun phrases such as “the starred yellow square” (Ref. b). During this experiment subjects were sat in front of a table on which were positioned a series of blocks that differed in shape and colour, and whether or not they were marked with a star. Simultaneously, the verbal instructions to the subject uniquely ident-
ified the object to be touched at different points during the utterance. For example, one set of instructions might have been: “Touch the plus red square. Now touch the neutral yellow square. Now touch the plus blue square. Now touch it again.” If there were two differently coloured squares in the array marked with a star, then the instruction “touch the starred yellow square” would only be referentially unambiguous when the subject heard the word yellow. The results of this experiment showed that subjects delayed making an eye movement until after the offset of a disambiguating word when that word came early in the noun phrase. However, when the disambiguating word came late in the noun phrase, at a point when there was only one entity to which it could refer, subjects made an eye movement prior to the offset of that word. These findings indicate that eye movements are time-locked to spoken input and that readers make immediate use of the linguistic information to reduce incrementally the candidates set to which the utterance refers. Thus, it seems that spoken language comprehension proceeds on a word-by-word basis, and auditory and visual information are rapidly integrated. Clearly, eye-movement recordings can provide important information about both written and spoken language comprehension. Indeed, in further experiments this methodology has been used to investigate a number of other aspects of speech comprehension, including effects of constraint stress, and the influence of a visual referential context on initial syntactic-processing preferences (Refs c–e).

**References**

some findings (e.g. the gap effect) show that the detailed timing of eye movements during reading can have a profound impact on the processing of visual information.

What factors affect when and where we make a regressive saccade during reading?

Some properties, such as color, are very effective in guiding eye movements in an interactive way. These pathways made?

pictorial material.

What factors influence eye-movement behaviour when people process interactive displays such as animated sites on the World Wide Web?


Outstanding questions

• What factors influence eye-movement behaviour when and where we make a regressive saccade during reading?

• What factors influence eye-movement behaviour when and where we make a regressive saccade during reading?

• What is the precise relationship between eye movements and psychological recovery processes after an initial misanalysis during reading?

• Why do some linguistic factors have a delayed influence on eye-movement behaviour relative to other linguistic factors?

• Some findings (e.g. the gap effect) show that the detailed timing of eye scanning is automatically affected by physical aspects of the visual stimulation. To what extent can cognitive processes such as lexical access exert their effects in a similar automatic way?

• What factors influence eye-movement behaviour when people process interactive displays such as animated sites on the World Wide Web?

Conclusions

In this review we have argued that eye movements reflect a large number of psychological processes underlying various cognitive tasks. In particular, we have focused upon visual search and reading, two areas in which eye-movement studies have made a tremendous contribution to our understanding. We have argued that deciding where and when to move the point of fixation are key aspects of eye-movement control and that understanding the relationship between the two is necessary to understand fully the cognitive processes reflected by eye movements. We also noted that investigators examining low-level aspects of eye-movement control and researchers investigating reading have independently found the conclusion that the ‘when’ and ‘where’ components of eye-movement control are separable, both psychologically and physiologically.

We have seen how different algorithms for summing fixations can be useful in making claims about qualitatively different psychological processes. We have described recent studies showing that eye-movement recording can be used to study aspects of human behaviour that we do not intuitively associate with visual processing (e.g., auditory language processing, see Box 3). It can be hoped that future eye-movement research will reveal more of the cognitive processes that are hidden behind eye-movement patterns.

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References


Philosophical conceptions of the self: implications for cognitive science

Shaun Gallagher

Several recently developed philosophical approaches to the self promise to enhance the exchange of ideas between the philosophy of the mind and the other cognitive sciences. This review examines two important concepts of self: the ‘minimal self’, a self devoid of temporal extension, and the ‘narrative self’, which involves personal identity and continuity across time. The notion of a minimal self is first clarified by drawing a distinction between the sense of self-agency and the sense of self-ownership for actions. This distinction is then explored through the neurological domain with specific reference to schizophrenia, in which the sense of self-agency may be disrupted. The convergence between the philosophical debate and empirical study is extended in a discussion of more primitive aspects of self and how these relate to neonatal experience and robotics. The second concept of self, the narrative self, is discussed in the light of Gazzaniga’s left-hemisphere ‘interpreter’ and episodic memory. Extensions of the idea of a narrative self that are consistent with neurological models are then considered. The review illustrates how the philosophical approach can inform cognitive science and suggests that a two-way collaboration may lead to a more fully developed account of the self.

References


Ever since William James categorized different senses of the self at the end of the 19th century, philosophers and psychologists have refined and expanded the possible variations of this concept. James’ inventory of physical self, mental self, spiritual self, and the ego has been variously supplemented. Noë, for example, suggested important distinctions between ecological, interpersonal, extended, private and conceptual aspects of self. More recently, when reviewing a contentious collection of essays from various disciplines, Strawson found an overabundance of delineations between cognitive, embodied, fictional and narrative selves, among others. It would be impossible to review all of these diverse notions of self in this short review. Instead, I have focused on several recently developed approaches that promise the best exchange of ideas between philosophy of mind and the other cognitive sciences and that convey the breadth of philosophical analysis on this topic. These approaches can be divided into two groups that are focused, respectively, on two important aspects of self – the ‘minimal’ self and the ‘narrative’ self (see Glossary).