

Orienting of attention: Then and now

Michael I. Posner

Department of Psychology, Institute of Neuroscience, University of Oregon, Eugene, OR, USA

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It is nearly 35 years since I gave the 7th Sir Frederick Bartlett lecture at Oxford University. This was published as a paper entitled “Orienting of attention in the quarterly journal”. The topic was then primarily in psychology, but now equally often in neuroscience. This paper summarizes the background of the reaction time methods used in the original paper and findings that emerged later on the sensory consequences of orienting, mainly in the visual system. It then discusses the brain network that is the source of the sensory amplification and other brain networks that are involved in attention. Next, it reviews studies of the development of attentional networks in early life. Finally, it indicates how the new tools available to explore the human brain can lead to further progress.

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I was delighted to be invited to give the 7th Sir Frederick Bartlett lecture at a meeting of the Experimental Psychology Society in July of 1979 (Posner, 1980). My pleasure partly reflected having met Bartlett in 1968 when I was a visitor at the Applied Psychology Lab (now Brain and Cognitive Science) of the Medical Research Council (MRC) in Cambridge, UK. Even in his 80s, Bartlett was an imposing figure and a person who had greatly influenced the development of cognitive psychology in general and me in particular. The second source of the delight was kept mainly to myself, but I felt I had something important to say. Unfortunately this is not always the case when invited to talk. My students and I had measured the time course of attention shifts without any eye movements. I felt it was an important model for the likely integration of cognitive

with neurophysiological approaches to cognition. I was right about that, and the article Orienting of Attention (O of A) resulting from the lecture has been cited more than 5000 times according to Google Scholar. A recent book with the same name summarizes much of this work in considerable detail (Wright & Ward, 2008).

In this paper I have reviewed more recent developments, some of which were directly stimulated by O of A. These include use of the method to explore orienting, findings concerning how the network of brain areas that are the source of orienting influence sensory systems, and the relation of orienting to eye movements. I also consider extensions that regarded orienting as only one of several functions of attention and based on the use of neuroimaging sought to understand the anatomy of brain networks related to attention. Understanding the

Correspondence should be addressed to Michael I. Posner, Department of Psychology, Institute of Neuroscience, University of Oregon, Eugene, OR, 97403, USA. Email: mposner@uoregon.edu

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anatomy of attention has helped foster studies of the development of attentional networks both in childhood and through training studies in adults. Finally I consider how the combined cognitive and neuroscience approach to attention may influence future findings.

METHOD

Probably the largest number of citations to my Bartlett lecture arose from the cueing method employed to observe the movement of attention to the target. I did not originate the method nor was this my first use of it. To my knowledge the method began with the effort of J. A. Leonard (1953), at the time a researcher in Cambridge, to discover the length of time needed to assimilate one bit of information. He wanted to separate the one bit of knowledge from the time to perceive the stimulus or produce the response. To do this he presented subjects with six lights; the participants were to respond as quickly as possible when one light was turned off. In some conditions, prior to extinguishing the target light he turned off three of the lights, thus reducing the possible stimulus-response (S-R) combinations by one bit (from six to three alternatives). The time required to reduce reaction time from that obtained with six alternatives to that obtained with only three was the desired time for assimilating one bit of information. This was a brilliant study, but unfortunately because the use of information theory did not solve all the problems of psychology as had been hoped it is largely forgotten. Leonard was a student of Sir Frederick Bartlett and later did research in the United States with Professor Paul M. Fitts, then at Ohio State University. Later, after Fitts had moved to the University of Michigan, I studied under him and took my PhD in 1962. This history perhaps explains my later postdoc at Cambridge with Robert Wilkinson and the close links my work has always had with the Cambridge unit.

I first applied Leonard's idea to letter matching where we (Posner, Boies, Eichelman, & Taylor, 1969) were able to measure the time necessary to

derive the name of the letter by presenting, for example, upper case (A) after a varying interval with a different case (e.g., a). When the letters were simultaneous or nearly so the cross-case match took about 80 ms longer, but eventually identical and cross-case matches produced the same reaction time. I believed this yielded the time to image the letter. In 1978 (Posner, 1978) I called this general method of using reaction time to measure entirely covert cognitive processes *encoding functions*, since they could be used to measure any internal operation free from stimulus and response factors.

In O of A I was reporting on our adaptation of this method to the study of attention in an empty visual field. The subject looked at a central stimulus, flanked on each side by a box; after an interval the box would change in luminance, and when a target asterisk appeared the subject had to respond by pressing a single key. A change in the luminance of the box was the cue for attention to move to the target, and thus the time needed to shift attention to the cued location could be measured. Various control conditions were used to eliminate alternative explanations such as forward masking or inhibiting a response to the cue. In these early experiments I also used probability to make sure that participants oriented to the cue. If the cue indicated that the target would occur at the cued location with probability .8, the target was facilitated in the first 200 milliseconds following the cue in comparison with other locations of similar eccentricity, and the facilitation remained as though attention remained at the cue. However, if the probability of the target being at the cued location was only .2, while .8 of the time it occurred at another location, one found facilitation of reaction time at the cued location for the first 200 milliseconds followed by facilitation at the most probable location. I believed that attention had been summoned to the cue exogenously, but was then voluntarily (endogenously) moved from the cued location to where the target was most likely. Within 0.5 s we seemed to have trapped a movement of attention from fixation to the cue and then from the cue to the most likely target location. It was this beautiful time-locked shifts of attention

that I thought would open the way for a detailed physiology of attention.

Another aspect of the cueing method was that the peripheral cues that summoned attention to a location could be compared with central cues (arrows) that had a merely symbolic relationship to where one was to look. I called these methods exogenous and endogenous cueing. Subsequent studies have shown that the arrow heads might produce a form of orienting that is neither purely exogenous or purely endogenous (Restic & Kingstone, 2012).

At the time *O of A* was written many psychologists did not believe that attention involved internal physical mechanisms but instead viewed it as a resource or general skill (Kahneman, 1973; Neisser, 1976). However, the discoveries of Mountcastle (1978) and Wurtz, Goldberg, and Robinson (1980) of the involvement of neurons in the superior colliculus and the parietal lobe persuaded me to attempt to examine the neural basis of orienting. The cueing method survived the development of neuroimaging and has been applied to separating the neural systems used by the cue from those related to the target (Corbetta & Shulman, 2002).

As a cognitive psychologist, my goal was to understand the attention system of the human brain. Because of this goal, I was interested in the common source of attentional effects. Researchers who examined attention from the psychophysical tradition concentrated on the effects of attention on sensory systems, without worrying much about the source of these effects. Both the psychophysical and cognitive approaches have made substantial progress and fit together to describe attention and its influence on even the early stages of sensory processing.

SENSORY CONSEQUENCES OF ORIENTING

In the 25 years since *O of A*, most research has been directed to the consequences of orienting, particularly within the visual system. The exciting psychophysical results have been summarized

recently by Carrasco (2011). While our work demonstrated that orienting attention prior to a target produced faster reaction times to the target, giving it priority, work by Yeshurun and Carrasco (1998) using the cueing method I described above, coupled with sinusoidal grating targets, showed that attention actually improved visibility for high-spatial-frequency information.

In a brilliant experiment, Carrasco (2011) used a segmentation task and found that in the fovea, where spatial frequency resolution was higher than optimal for segmentation, attention actually impaired performance, while at the periphery, where spatial resolution was low, attention improved performance. Models that thought of attention as a response bias or a skill designed to improve performance could not handle these results.

Also important were results using electrical recording, which support amplitude gain models of attention to visual information by showing amplification of the P1 and N1 components of the event-related electrical potential (Hillyard, Di Russo, & Martinez, 2004). These results fit well with those of Carrasco (2011). However, in the auditory system the effects of attention occurred later in time and were found not to amplify the early event-related components but superimposed an additional negative response (Hillyard, Hink, Schwent, & Picton, 1973).

At the time of *O of A* there was a controversy about whether attention was helpful in the accuracy and speed of perceiving a target in an empty visual field. There was no doubt of the importance of attention when the field was cluttered with distractors (Engle, 1971). Knowing where to attend allowed you to go directly to the target location and save a large amount of time. It was controversial whether knowledge about where the target was to occur actually improved performance when the field was empty. We learned, using the cueing method, that the onset of a stimulus in an otherwise empty field was such a good cue for orienting, there was only a small benefit of having a cue in advance of the target. However, once engaged at a location, reorienting attention had a large effect on the time to detect a target at an uncued location. I

summarized findings on orienting in an empty field by arguing that the cost of disengaging from attending is larger than the benefits of attending. Thus when not attending there is little advantage to a cue; once orienting somewhere the cost of disengaging makes the cue quite important.

This principle can be applied more generally. Shortly before the Bartlett lecture, Richard Shiffrin (Shiffrin, McKay, & Shaffer, 1976) showed that one could attend to 49 locations as efficiently as attention to only one location. Was attention really so unlimited? Duncan (1980) showed that it mattered very little whether you knew which of several targets was going to occur, but if you detected one target your performance was greatly diminished for a second one. In other words, once attending to something there is a powerful cost of switching attention. Duncan's (1980) result was important in showing that one could monitor in parallel with relatively little or no loss, but attending in the sense of conscious detection was limited indeed. These findings became the basis for distinguishing between an orienting system involved in monitoring the sensory world and a second attention system more related to detection and conscious control.

One of the most striking demonstrations of the importance of attention in vision, called change blindness (Rensink, O'Regan, & Clark, 1997), was a further extension of this principle. This work presented participants with a complex scene. A change was produced somewhere in the scene, but without either luminance or motion cues that are normally effective in reorienting attention. They found even dramatic changes like substituting a horse's head for a human head at the dinner table went unreported. The dramatic nature of this demonstration often leads people to forget that with luminance cues or motion cues present, as happens most often, reorienting occurs, and changes can be easily detected.

THE ORIENTING NETWORK

My goal was to understand the source of the orienting effect. At the time *O of A* was written it seemed

important to me to show that attention actually moved across the visual field in a way analogous to a saccade. I felt this would contribute to making covert attention seem more concrete like an eye movement. A paper by Shulman, Remington, and McClean (1979) showed that intermediate locations between fixation and target were facilitated during the time of the shift. However, this behavioural evidence was challenged by subsequent reports (Gololmb, Marino, Chun, & Mazer, 2011). In retrospect it proved not to be crucial. At the time, the idea of an attention movement meant that we had to regard orienting as a physical event with a real time consequence in the nervous system. However, when Georgopoulos, Lurito, Petrides, Schwartz, and Massey (1989) showed how that changing set of receptive field orientations in the motor system could produce a covert analogue of mental rotation in the case of monkey arm movements, it no longer seemed necessary to have something actually moving in order to consider it as a real time event in the human brain.

A more persistent issue has been the relation between covert shifts of attention and eye movements. This issue was fundamental to me because I hoped to use orienting of attention as a model for probing areas of attention that were not at all close to sensory systems (e.g., attending to the meaning of a word). If orienting was the same as preparing a saccade, knowledge of its properties would be less useful as a model for types of attention that had nothing to do with sensory systems, but involved emotions, memories, or thoughts. To capture this idea, I now distinguish between the site at which attention can operate and the sources of that influence in the orienting and executive attention networks (Petersen & Posner, 2012).

In *O of A* I did establish that orienting of attention could take place without an eye movement. I also presented evidence in the same paper (Posner, 1980, Figure 11, p. 18) that attention shifts could occur in one direction while preparing to move the eyes in a different direction, a result that I thought fatal to various efference theories based on the preparation of saccades that were not executed. I was certainly wrong about that.

Rizzolatti, Riggio, Dascola, and Umiltà (1987) argued that premotor cortex, especially the frontal eye fields, was the source of the orienting effects that involved programming, though not always making an eye movement. Moreover, some behavioural results did not show the independence between eye movements and attention shifts that were reported in O of A, but favoured Rizzolatti's argument. Somewhat later there was also a clear imaging result (Corbetta, 1998) showing a very strong overlap, approaching identity, between brain areas involved in generation of saccades and those involved in covert orienting of attention.

For this reason, I began to think that orienting of attention was not a good model for a separate attention system, but was instead very closely related to saccadic eye movements. However, studies using cellular recording in the frontal eye fields, which was a part of the overlapping networks for both saccades and attention shifts, showed that there were separate populations of cells that were active either before saccades or before covert eye movements, but not both (Thompson, Biscoe, & Sato, 2005). Some recent reviewers of the behavioural work also concluded that covert attention was not as dependent upon eye movement programming as required by the premotor theory (Smith & Schenk, 2012). Important to the relationship between covert and overt attention is the idea that maybe transient shifts of attention are more dependent on saccade preparation than is the maintenance of attention once a shift has occurred (Belopolsky & Theeuwes, 2009).

One place where dependence between covert attention and eye movements is strongest is when stimuli lie between the fovea and a peripheral target so that the perception of the target is diminished (Bouma, 1970). This phenomenon is often called crowding. When people are asked to make an eye movement toward the target the crowding effect is reduced, even before the eyes begin to move. An instruction to attend covertly to the target has no similar effect (Harrison, Mattingley, & Remington, 2013). This finding shows that making an eye movement can amplify attention effects and produce results not obtained by a covert attention shift. Moore, Burrows,

Armstrong, Schafer, and Chang (2012) argue that the populations of sensory and movement cells in the frontal eye fields are not distinct, and most cells have both motor and sensory functions. These authors also indicate that covert shifts and saccadic preparation interact and that in some circumstances, the attention shifts appear to control saccadic trajectories, and in other situations, the reverse.

Although the premotor theory was certainly correct that both attention and eye movements are influenced by the same prefrontal structure, it appears that there is an important separation and interaction between the two at both the cellular and the behavioural levels. Although even now this issue is not settled, it is a very good example of the importance of considering all levels of analysis when attempting to develop a strong theoretical account. For the time being, I still think that O of A, which illustrates the various theories of the relation between saccades and eye movements, may be about right in proposing an intermediate level of dependence that may reflect early experience leading to their close coordination. It has been observed that infants often make multiple saccades when attempting to foveate targets (Aslin & Salapatek, 1975), thus providing an opportunity to learn to coordinate attention and eye movements.

The cueing method and the distinction between exogenous and endogenous cueing had a further significance when neuroimaging began to be used to study orienting of attention (Corbetta & Shulman, 2002). I had often used an arrow at fixation to direct attention to locations in the visual field. Since the cueing method allows separation of the influence of the cue from that of the target, it is possible to examine the parts of the brain activated by the cue separate from those activated by targets. In a very influential series of experiments (summarized in Corbetta & Shulman, 2002) it was found that the arrow cue influenced a dorsal network of brain areas including the superior parietal lobe and frontal eye fields that seemed most important for voluntary orienting of attention. Following an invalid target, a more ventral set of brain areas that included the temporal-parietal junction were activated.

At the time of *O of A* I did not imagine that neuroimaging would provide evidence clearly suggesting a ventral brain network involved in more automatic processes and a dorsal network in more voluntary top-down control (Corbetta & Shulman, 2002). The finding that the brain systems of orienting separate voluntary from automatic control into distinct but interacting brain networks is, to me, one of the best openings for the study of the physical basis for volition or what some call “will” that I know about.

OTHER ATTENTION NETWORKS

At the time I was writing *O of A*, I did not think about there being separate brain networks for different functions of attention. In fact almost nothing was known about the neural system underlying orienting, much less other networks of attention. However, within a decade the advent of neuroimaging had made a dramatic change (Posner & Petersen, 1990). In our earliest neuroimaging studies of language (Petersen, Fox, Posner, Mintun, & Raichle, 1989) we had shown that making a simple word association, in comparison to merely reading a word aloud, activated an area of the frontal midline called the anterior cingulate. Jose Pardo (Pardo, Pardo, Janer, & Raichle, 1990), who had worked with us on these studies, asked me to say what task he could use to see whether the cingulate activation was due to attention. I said try the Stroop effect; he did, and his study became the first of many revealing that Stroop and other conflict-related tasks activate the dorsal anterior cingulate (Bush, Luu, & Posner, 2000).

These studies led me to update three functions of attention that I had earlier postulated (Posner, 1978) by arguing for three different brain networks supporting the functions of orienting, alerting, and executive control (Petersen & Posner, 2012; Posner & Petersen, 1990). Each of these networks involved multiple brain areas and their connections. Imaging data support the argument for separable brain networks (Fan, McCandliss, Fossella, Flombaum, & Posner, 2005). At first, imaging

was very restricted in the ability to deal with individual brains because of limits to the amount of radiation one could use, but with the advent of magnetic resonance imaging (MRI) that restriction was reduced, and it became possible to consider individual differences as resulting from the efficiency of brain networks that were common to everyone. I believe that the ideas concerning brain networks that arose with imaging studies provides a very good way of relating common psychological functions, studied by cognitive psychologists, with individual differences as they have been studied by researchers in development and personality.

There are individual differences in the efficiency of each of the three attention networks. The Attention Network Test (ANT) was devised as a means of measuring these differences (Fan, McCandliss, Sommer, Raz, & Posner, 2002). The task requires the person to press one key if a central arrow points to the left and another if it points to the right. Conflict is introduced by having surrounding flanker arrows point in either the same (congruent) or the opposite (incongruent) direction. Cues presented prior to the target provide information on where or when the target will occur. Three scores are computed, which relate to the performance of each individual in alerting, orienting, and executive control. In our work we have used the ANT to examine the efficiency of brain networks underlying attention (Fan et al., 2002). A children’s version of this test is very similar to the adult test, but replaces the arrows with fish (Rueda et al., 2004).

Studies have shown moderate reliability of conflict scores, but much lower reliability for the orienting and alerting scores (MacLeod et al., 2010), and recent revisions of the ANT provide better measures of orienting and alerting, which may improve these results, but usually at the cost of additional trials (Fan et al., 2009). The attentional networks involve different cortical brain areas (Fan et al., 2005), and scores on the ANT are related to distinct white matter pathways (Niogi & McCandliss, 2009) and structural differences in cortical thickness (grey matter; Westlye, Grydland, Walhovde, & Fjell, 2011). Although there is considerable independence between the

networks, revisions of the ANT show significant interaction between networks (Callejas, Lupianez, & Tudela, 2004; Fan et al., 2009). It is clear that the networks communicate and work together in many situations, even though their anatomy is mostly distinct.

The network view arising from imaging of attention seems to me to bring together the cognitive approach with its emphasis on functions common to most or all of the people studied with the individual differences approach. Attention networks are common to everyone, but their efficiency differs. These differences may in part reflect genetic variation between people and in part reflect life experiences.

DEVELOPMENT

An important consequence of imaging brain networks is to raise the issue of how attention networks become organized in early life. We have been examining issues of how genes and experience shape the three attention networks (Posner, Rothbart, Sheese, & Voelker, 2012, 2014). We conducted a longitudinal study on the development of the executive attention network, which is closely related to self-regulation. The testing began when the infants were 7 months old. We had thought that this was enough for us to observe the earliest part of the development of the executive network. However, even at 7 months infants detect errors by activating the anterior cingulate just as adults do (Berger, Tzur, & Posner, 2006).

Because infants are not able to carry out voluntary attention tasks, we used a visual task in which a series of attractive stimuli are put on the screen in a repetitive sequence (Clohessy, Posner, & Rothbart, 2001; Haith, Hazan, & Goodman, 1988). Infants orient to them by moving their eyes (and head) to the location. On some trials infants showed that they anticipated what was coming by orienting prior to the stimulus. We found (Sheese, Rothbart, Posner, White, & Fraundorf, 2008) that infants who made the most anticipatory eye movements also exhibited a pattern of cautious reaching toward novel objects

that predicts effortful control in older children (Rothbart, 2011). In addition, infants with more anticipatory looks showed more spontaneous attempts at regulation of emotional distress when presented with somewhat frightening objects.

We had originally thought that the relation of anticipatory eye movements to self-regulation was evidence of early control by the executive network. However, this was a longitudinal study so at age 4 we were able to run the same infants in the ANT, and that indicated that anticipatory eye movements in infancy were more related to the orienting scores at age 4.

These findings led us to the view that the orienting network provides the primary regulatory function during infancy. The orienting network continues to serve as a control system, but starting in childhood the executive attention appears to dominate in regulating emotions and thoughts (Isaacowitz, 2012; Posner et al., 2012, 2014; Rothbart, Sheese, Rueda, & Posner, 2011). The executive network is present in infancy but it is not yet connected in a way that produces control over behaviour. For example, even though infants at 7 months detect errors, we observed the ability to slow down behaviour following an error to develop between 3 and 4 years (Jones, Rothbart & Posner, 2003).

Changes in connectivity in infancy and early childhood have been supported by resting state MRI studies (Fair et al., 2009) and by MRI during conflict tasks (Fjell et al., 2012). Also this parallel use of the two networks fits with the findings of Dosenbach et al. (2007) that in adults the frontal-parietal network (orienting) controls task behaviour at short time intervals whereas the cingulo-opercular (executive) network exercises strategic control over long intervals.

There are very important consequences for the developing child in these internal changes. The executive network is involved in resolving competing actions in tasks where there is conflict. This is done both by enhancing activity in networks related to our goals and inhibiting activity in conflicting networks; these controls are effected by long connections between the nodes of the executive network and cognitive and emotional areas of

the frontal and posterior brain. In this way the executive network is important for voluntary control and self-regulation (Bush, Luu, & Posner, 2000; Sheth et al., 2012). Effortful control is a higher order temperament factor assessing self-regulation that is obtained from parent report questionnaires (Rothbart, 2011). In childhood, performance on conflict-related cognitive tasks is positively related to measures of children's effortful control (Rothbart, 2011). During childhood and in adulthood effortful control is correlated with school performance and with indices of life success, including health, income, and successful human relationships (Checa & Rueda, 2011; Moffitt et al., 2011).

The changes in connectivity reported by Fair et al. (2009) during development using resting state MRI studies involve functional connectivity based upon correlations between blood-oxygen-level-dependent (BOLD) activity in separated brain areas. During development there are large physical changes in connections between brain areas. The number of axons connecting brain areas increases, followed by an increase in the myelin sheath that surrounds the axon and provides insulation. Together these changes result in more efficient connections (Lebel et al., 2012). Fractional anisotropy (FA) is the main index for measuring the integrity of white matter fibres when using diffusion tensor imaging (DTI).

In our work we studied FA in college students before and after a form of mindfulness meditation called integrated body mind training (IBMT) in comparison to a control group given the same amount of relaxation training. Using the ANT we found clear improvement in executive attention after only five days of training (Tang et al., 2007). After two to four weeks of training we found significantly greater change in FA following meditation training than following the relaxation training control in all areas of connectivity of the anterior cingulate, but not in other brain areas (Tang et al., 2010).

These alterations in FA could originate from several factors such as changes in myelination, or factors related to axon density. Several DTI studies have examined axial diffusivity (AD) and

radial diffusivity (RD), the most important indices associated with FA, to understand the mechanisms of FA change (Bennett, Madden, Vaidya, Howard, & Howard, 2010; Burzynska et al., 2010). Changes in AD are associated with axon morphological changes, with lower AD value indicating higher axonal density. In contrast, RD implicates the character of the myelin. Decreases in RD imply increased myelination, while increases represents demyelination.

In our study (Tang, Lu, Fan, Yang, & Posner, 2012), we investigated AD and RD where FA indicated that integrity of white matter fibres was enhanced in the IBMT group more than in the control group. We found that after two weeks there were changes in axonal density but not in myelination. In some areas these changes in axonal density were correlated with improved mood and affect as measured by self-report. After 4 weeks of training we found evidence of myelination changes. Since the developmental changes in childhood first involve changes in axonal density and only later myelination, our training may provide changes that are somewhat similar to those found in development. If so, it might be possible to use training to study how physical changes in connectivity alter aspects of control including reaction time, control of affect, stress reduction, and other changes found with meditation training. In fact at the time of changes from the orienting to the executive network, children are undergoing changes in behaviour that are consonant with the development of self-control.

Environmental factors help to shape development of the brain network related to attention. Several lines of research converge to argue that training can influence these networks. In childhood, exposing the infant to novel objects may help develop the executive network (Posner et al., 2012; Shulman et al., 2009). In addition, specific training at age 4–6 appears to produce changes in the executive network that make it more adult-like in response to conflict-related challenges (Diamond & Lee, 2011; Rueda, Checa, & Combata, 2012; Rueda, Rothbart, McCandliss, Saccamanno, & Posner, 2005). Even adults can show change in white matter pathways due to

training as discussed above. Thus the general environment together with genes provide important means for shaping the efficiency of executive attention all through life.

THE FUTURE

The Bartlett lecture was one of the most memorable events of my career in psychology. O of A was a purely behavioural paper. At the time I could not have imagined writing the paragraphs above, in which changes in control pass from the orienting network, involving one set of brain areas, to the executive network due to changes in connectivity that can be mapped in the developing human brain. The advent of neuroimaging made this possible.

Further changes in the technology for studies of the brain may be expected. For example, current studies of rodents and primates (Diester et al., 2011) are using light (optogenetics) methods to manipulate cells of particular types within brain networks. This method could help to solve the problem of relating large-scale neural networks more directly to specific neural activity. The connectome project may allow tracing of a large number of white matter pathways in the human brain at varying ages to provide a detailed pattern of development (Sporns, 2012).

The pace of technological advance in mapping brain systems is likely to increase over the coming years. It may be daunting for psychologists to understand and keep up with these advances. However, it does seem to me that the lesson of O of A is that psychological studies at the behavioural level will continue to be needed in order to be able to relate the myriad of brain changes to their significance for human thought and action. Even at this current moment, we have a rough picture of how brain activation, functional connectivity, and white matter efficiency change with age, but only the most primitive ideas of how these changes actually work to produce the dramatic differences between infancy and childhood.

It is certainly true that not all of the ideas described in this paper came directly from O of A. However, at least eight years before imaging

was to usher in the era of cognitive neuroscience, I was already convinced that we had opened a small but important window on how cognition and neuroscience could work together to solve the many issues of brain research. Over 30 years later I realize how far we have come and how distant the goal remains, but am still pleased to have had this small role in its history.

REFERENCES

- Aslin, R. N., & Salapatek, P. (1975). Saccadic localization of visual targets by the very young human infant. *Perception and Psychophysics*, 17(3), 293–302.
- Belopolsky, A. V., & Theeuwes, J. (2009). When are attention and saccade preparation dissociated?. *Psychological Science*, 20(11), 1340–1347.
- Bennett, I. J., Madden, D. J., Vaidya, C. J., Howard, D. V., Howard, J. H.Jr. (2010). Age-related differences in multiple measures of white matter integrity: A diffusion tensor imaging study of healthy aging. *Human Brain Mapping*, 31, 378–390.
- Berger, A., Tzur, G., & Posner, M. I. (2006). Infant babies detect arithmetic error. *Proceeding of the National Academy of Science USA*, 103, 12649–12653.
- Bouma, H. (1970). Interaction effects in parafoveal letter recognition. *Nature*, 226, 177–178.
- Burzynska, A. Z., Preuschhof, C., Bäckman, L., Nyberg, L., Li, S.-C., Lindenberger, U., & Heekeren, H. R. (2010). Age-related differences in white matter microstructure: Region-specific patterns of diffusivity. *Neuroimage*, 49, 2104–2112.
- Bush, G., Luu, P., & Posner, M. I. (2000). Cognitive and emotional influences in the anterior cingulate cortex. *Trends in Cognitive Science*, 4(6), 215–222.
- Callejas, A., Lupianez, J. & Tudela, P (2004). The three attentional networks: On their independence and interactions. *Brain and Cognition*, 54(3), 225–227.
- Carrasco, M. (2011). Visual attention: The past 25 years. *Vision Research*, 51, 1484–1525.
- Checa, P., & Rueda, M. R. (2011). Behavior and brain measures of executive attention and school competence in late childhood. *Developmental Neuropsychology*, 36(8), 1018–1032. doi:10.1080/87565641.2011.591857.
- Clohesy, A. B., Posner, M. I., & Rothbart, M. K. (2001). Development of the functional visual field. *Acta Psychologica*, 106, 51–68.

- Corbetta, M. (1998). Frontoparietal cortical networks for directing attention and the eyes to visual locations: Identical, independent, or overlapping neural systems?. *Proceedings of the National Academy of Science*, 95, 831–838.
- Corbetta, M., & Shulman, G. L. (2002). Control of goal-directed and stimulus-driven attention in the brain. *Nature Neuroscience Reviews*, 3, 201–215.
- Diamond, A., & Lee, K. (2011). Interventions shown to aid executive function development in children 4 to 12 years old. *Science*, 333, 959–964.
- Diester, I., Kaufman, M. T., Mogri, M., Pashaie, R., Goo, W., Yizhar, O., ... Shenoy, K. V. (2011). An optogenetic toolkit designed for primates. *Nature Neuroscience*, 14/3, 387–397. doi:10.1038/nn.2749.
- Dosenbach, N. U. F., Fair, D. A., Miezin, F. M., Cohen, A. L., Wenger, K. K. R., Dosenbach, A. T., ... Petersen, S. E. (2007). Distinct brain networks for adaptive and stable task control in humans. *Proceedings of the National Academy of Sciences of the USA*, 104, 1073–1078.
- Duncan, J. (1980). The locus of interference in the perception of simultaneous stimuli. *Psychological Review*, 87, 272–300.
- Engle, F. L. (1971). Visual conspicuity, directed attention and retinal locus. *Vision Research*, 11, 563–575.
- Fair, D. A., Cohen, A. L., Power, J. D., Dosenbach, N. U. F., Church, J. A., Miezin, F. M., ... Petersen, S. E. (2009). Functional brain networks develop from a “local to distributed” organization. *PLoS Computational Biology*, 5, e1000381. doi:10.1371/journal.pcbi.1000381.
- Fan, J., Gu, X., Guise, K. G., Liu, X., Fossella, J., Wang, H., & Posner, M. I. (2009). Testing the behavior interaction and integration of attentional networks. *Brain and Cog*, 70, 209–220.
- Fan, J., McCandliss, B. D., Fossella, J., Flombaum, J. I., & Posner, M. I. (2005). The activation of attentional networks. *Neuroimage*, 26, 471–479.
- Fan, J., McCandliss, B. D., Sommer, T., Raz, M., & Posner, M. I. (2002). Testing the efficiency and independence of attentional networks. *Journal of Cognitive Neuroscience*, 3(14), 340–347.
- Fjell, A. M., Walhovd, K. B., Brown, T. T., Kuperman, J. M., Chung, Y., Hagler, D. J., Jr., ... Dale, A. M. (2012). Multimodal imaging of the self-regulating developing brain. *Proceedings of the National Academy of Sciences of the United States of America*, 109(48), 19620–19625.
- Georgopoulos, A. P., Lurito, J. T., Petrides, M., Schwartz, A. B., & Massey, J. T. (1989). Mental rotation of the neuronal population vector. *Science*, 243, 234–236.
- Gololomb, J. D., Marino, A. C., Chun, M. M., & Mazer, J. A. (2011). Attention doesn't slide: Spatiotypic updating after eyemovement instatiates a new, discrete attention locus. *Attention, Perception and Psychophysics*, 73(1), 7–14. doi:10.3758/s13414-010-0016-3.
- Haith, M. M., Hazan, C., & Goodman, G. S. (1988). Expectations and anticipations of dynamic visual events by 3.5 month old babies. *Child Development*, 59, 467–469.
- Harrison, W. J., Mattingley, J. B., & Remington, R. W. (2013). *Journal of Neuroscience*, 33(7), 2927–2933.
- Hillyard, S. A., Di Russo, F., & Martinez, A. (2004). The imaging of visual attention. In N. Kanwisher & J. Duncan (Eds.), *Functional neuroimaging of visual cognition attention and performance XX* (pp. 381–390). Oxford: Oxford University Press.
- Hillyard, S. A., Hink, R. F., Scwent, V. L., & Picton, T. W. (1973). Electrical signs of selective attention in the human brain. *Science*, 182, 177–180.
- Isaacowitz, D. M. (2012). Mood regulation in real time: Age differences in the role of looking. *Current Direction in Psychological Science*, 21(4), 237–242.
- Jones, L., Rothbart, M. K., & Posner, M. I. (2003). Development of inhibitory control in preschool children. *Developmental Science*, 6, 498–504.
- Kahneman, D. (1973). *Attention and effort*. New York: Prentice Hall.
- Lebel, C., Gee, M., Camicioli, R., Wielere, M., Martin, W., & Beaulieu, C. (2012). Difusion tensor imaging of white matter tract evolution over the lifespan. *Neuroimage*, 60, 240–352.
- Leonard, J. A. (1953). Partial advance information in a choice reaction time task British. *Journal of Psychology*, 49(2), 89–96.
- MacLeod, J. W., Lawrence, M. A., McConnell, M. M., Eskes, G. A., Klein, R. M., & Shore, D. I. (2010). Appraising the ANT: Psychometric and theoretical considerations of the attention network test. *Neuropsychology*, 24(5), 637–651. doi:10.1037/a0019803.
- Moffitt, T. E., Arseneault, L., Belsky, D., Dickson, N., Hancox, R. J., Harrington, H. L., ... Caspi, A. (2011). A gradient of childhood self control predicts health, wealth and public safety. *Proceedings of the National Academy of Science USA*, 108(72), 693–98.
- Moore, T., Burrows, B., Armstrong, K. M., Schafer, R. J., & Chang, M. H. (2012). Neural circuits controlling visual attention. In M. I. Posner (Ed.),

- Cognitive Neuroscience of Attention* (2nd ed., pp. 257–276). New York: Guilford.
- Mountcastle, V. M. (1978). The world around us: Neural command functions for selective attention. *Neuroscience Research Progress Bulletin*, 14(Suppl), 1–47.
- Neisser, U. (1976). *Cognition and reality: Principles and implications of cognitive psychology*. New York: WH Freeman.
- Niogi, S., & McCandliss, B. D. (2009). Individual differences in distinct components of attention are linked to anatomical variations in distinct white matter tracts. *Frontiers in Neuroanatomy*, 3, 21.
- Pardo, J. V., Pardo, P. J., Janer, K. W., & Raichle, M. E. (1990). The anterior cingulate cortex mediates processing selection in the stroop attentional conflict paradigm. *Proceedings of the National Academy of Science USA*, 87(1), 256–259.
- Petersen, S. E., Fox, P. T., Posner, M. I., Mintun, M., & Raichle, M. E. (1989). Positron emission tomographic studies of the processing of single words. *Journal of Cognitive Neuroscience*, 1, 153–170.
- Petersen, S. E., & Posner, M. I. (2012). The attention system of the human brain: 20 years after. *Annual Review of Neuroscience*, 35, 73–89.
- Posner, M. I. (1978). *Chronometric explorations of mind*. Hillsdale, NJ: Lawrence Erlbaum Associates.
- Posner, M. I. (1980). Orienting of attention. The 7th Sir F. C. Bartlett Lecture. *Quarterly Journal of Experimental Psychology*, 32, 3–25.
- Posner, M. I., Boies, S. W., Eichelman, W., & Taylor, R. (1969). Retention of visual and name codes of single letters. *Journal of Experimental Psychology Monographs*, 79, 1–16.
- Posner, M. I., & Petersen, S. E. (1990). The attention system of the human brain. *Annual Review of Neuroscience*, 13, 25–42.
- Posner, M. I., Rothbart, M. K., Sheese, B. E., & Voelker, P. (2012). Control networks and neuro-modulators of early development. *Developmental Psychology*, 48(3), 827–835. doi:10.1037/a0025530.
- Posner, M. I., Rothbart, M. K., Sheese, B. E., & Voelker, P. (2014). Developing attention: Behavioral and brain mechanisms. *Advances in Neuroscience*, Article ID 405094. doi:10.1155/2014/405094.
- Rensink, R. A., O'Regan, J. K., & Clark, J. J. (1997). To see or not to see: The need for attention to perceive changes in scenes. *Psychological Science*, 8, 368–373.
- Restic, J., & Kingstone, A. (2012). A new form of human spatial attention: Automated symbolic orienting. *Visual Cognition*, 20(3), 244–264.
- Rizzolatti, G., Riggio, L., Dascola, I., & Umiltà, C. (1987). Reorienting attention across the horizontal and vertical meridians: Evidence in favor of the premotor theory of attention. *Neuropsychologia*, 25, 31–40.
- Rothbart, M. K. (2011). *Becoming who we are: Temperament, personality and development*. New York: Guilford Press.
- Rothbart, M. K., Sheese, B. E., Rueda, M. R., & Posner, M. I. (2011). Developing mechanisms of self-regulation in early life. *Emotion Review*, 3(2), 207–213.
- Rueda, M. R., Checa, P., & Combata, L. M. (2012). Enhanced efficiency of the executive attention network after training in preschool children: Immediate and after two month effects. *Developmental Cognitive Neuroscience*, 2(Suppl 1), 192–204. doi:10.1016/j.dcn.2011.09.004.
- Rueda, M. R., Fan, J., Halparin, J., Gruber, D., Lercari, L. P., McCandliss, B. D., & Posner, M. I. (2004). Development of attention during childhood. *Neuropsychologia*, 42, 1029–1040.
- Rueda, M. R., Rothbart, M. K., McCandliss, B. D., Saccamanno, L., & Posner, M. I. (2005). Training, maturation and genetic influences on the development of executive attention. *Proceedings of the National Academy of Sciences of the USA*, 102, 14931–14936.
- Sheese, B. E., Rothbart, M. K., Posner, M. I., White, L. K., & Fraundorf, S. H. (2008). Executive attention and self regulation in infancy. *Infant Behavior and Development*, 31, 501–510.
- Sheth, S. A., Mian, M. K., Patel, S. R., Asaad, W. F., Williams, Z. M., Dougherty, D. D., ... Eskander, E. N. (2012). Human dorsal anterior cingulate cortex neurons mediate ongoing behavioural adaptation. *Nature*, 488, 218–221. doi:10.1038/nature11239.
- Shiffrin, R. M., McKay, D. P., & Shaffer, W. O. (1976). Monitoring 49 spatial positions at once. *Journal of Experimental Psychology-Human Perception And Performance*, 2(1), 14–22. doi:10.1037//0096-1523.2.1.14.
- Shulman, G. L., Astafiev, S. V., Franke, D., Pope, D. L. W., Snyder, A. Z., McAvoy, M. P., & Corbetta, M. (2009). Interaction of stimulus-driven reorienting and expectation in ventral and dorsal frontoparietal and basal ganglia-cortical networks. *Journal of Neuroscience*, 29, 4392–4407. doi:10.1523/JNEUROSCI.5609-08.2009.
- Shulman, G. L., Remington, R. W., & McClean, J. P. (1979). Moving attention through space. *Journal of Experimental Psychology: Human Perception and Performance*, 5, 522–526.

- Smith, D. T., & Schenk, T. (2012). The premotor theory of attention: Time to move on. *Neuropsychologia*, 50 (6), 1104–1114.
- Sporns, O. (2012). From simple graphs to the connectome: Networks in neuroimaging. *Neuroimage*, 62(2), 881–886. doi:10.1016/j.neuroimage.2011.08.085.
- Tang, Y. Y., Lu, Q., Fan, M., Yang, Y., & Posner, M. I. (2012). Mechanisms of white matter changes induced by meditation. *Proceedings of the National Academy of Sciences of the United States of America*, 109: 10570–10574.
- Tang, Y., Lu, Q., Geng, X., Stein, E. A., Yang, Y., & Posner, M. I. (2010). Short term mental training induces white-matter changes in the anterior cingulate. *Proceedings of the National Academy of Sciences of the United States of America*, 107, 16649–16654.
- Tang, Y. Y., Ma, Y., Wang, J., Fan, Y., Feng, S., Lu, Q., ... Posner, M. I. (2007). Short term meditation training improves attention and self Regulation. *Proceedings of the National Academy of Sciences of the United States of America*, 104, 17152–17156.
- Thompson, K. G., Biscoe, K. L. & Sato, T. R. (2005). Neuronal basis of covert spatial attention in the frontal eye fields. *Journal of Neuroscience*, 25, 9479–9487.
- Westlye, L. T., Grydeland, H., Walhovd, K. B., & Fjell, A. M. (2011). Associations between regional cortical thickness and attentional networks as measured by the attention network test. *Cerebral Cortex*, 21(2), 345–356. doi:10.1093/cercor/bhq101.
- Wright, R. D., & Ward, L. M. (2008). *Orienting of attention*. New York: Oxford Univ. Press.
- Wurtz, R. H., Goldberg, E., & Robinson, D. L. (1980). Behavioral modulation of visual responses in monkey: Stimulus selection for attention and movement. *Progress in Psychobiology and Physiological Psychology*, 9, 43–83.
- Yeshurun, Y., & Carrasco, M. (1998). Attention improves or impairs visual performance by enhancing spatial resolution. *Nature*, 396, 72–75.