Attention, self–regulation and consciousness

M. I. Posner and M. K. Rothbart

Phil. Trans. R. Soc. Lond. B 1998 **353**, 1915-1927
doi: 10.1098/rstb.1998.0344

THE ROYAL
SOCIETY

Attention, self-regulation and consciousness

Michael I. Posner* **and Mary K. Rothbart**

Department of Psychology, University of Oregon, Eugene, OR, USA and Sackler Institute for Human Brain Development, Cornell Medical College, New York, NY 10021, USA

Consciousness has many aspects. These include awareness of the world, feelings of control over one's behaviour and mental state (volition), and the notion of a continuing self. Focal (executive) attention is used to control details of our awareness and is thus closely related to volition. Experiments suggest an integrated network of neural areas involved in executive attention. This network is associated with our voluntary ability to select among competing items, to correct error and to regulate our emotions. Recent neuroimaging studies suggest that these various functions involve separate areas of the anterior cingulate.

We have adopted a strategy of using marker tasks, shown to activate the brain area by imaging studies, as a means of tracing the development of attentional networks. Executive attention appears to develop first to regulate distress during the first year of life. During later childhood the ability to regulate conflict among competing stimuli builds upon the earlier cingulate anatomy to provide a means of cognitive control. During childhood the activation of cingulate structures relates both to the child's success on laboratory tasks involving conflict and to parental reports of self-regulation and emotional control. These studies indicate a start in understanding the anatomy, circuitry and development of executive attention networks that serve to regulate both cognition and emotion.

Keywords: anterior cingulate; attention; consciousness; marker tasks; temperament; volition

> Consider the direction of your mind at any moment you like to choose; you will find that it is occupied with what now is, but always and especially with regard to what is about to be. Attention is expectation, and there is no consciousness without a certain attention to life. The future is there; it calls up, or rather, it draws us to it. . . . All action is an encroachment on the future. To retain what no longer is, to anticipate what as yet is not—these are the primary functions of consciousness.
>
> Bergson (1920, p. 6)

1. ASPECTS OF CONSCIOUSNESS

The problem of consciousness involves many difficult and overlapping issues (Block 1995; Posner 1994). Perhaps the most frequently discussed role of consciousness involves awareness of our sensory world. Another aspect of consciousness is the fact or illusion of voluntary control. In the course of development, a central issue is the awareness of one's self, and another is the form of voluntary control involved in self-regulation. These functions develop within the dyad involving the child and the caregiver as a carrier of the culture's socialization process. It is possible, even likely, that brain mechanisms subserving these various forms of consciousness may cut across definitions in ways that defy the usual logical and philosophical distinctions.

Within neuroscience, most students have followed Crick's (1994) suggestion that sensory awareness is the aspect of consciousness most amenable to scientific analysis, placing awareness at the centre of discussions of brain mechanisms of consciousness. In this paper, however, we focus on the voluntary control of mental processes that might fit more closely with the self regulation of behaviour and thought. We believe the developmental shifts in self-regulation during the early years of life form a tractable behavioural model for studying changes in voluntary self-regulation.

In the psychology of adult cognition, systems involved in the regulation of thought, emotion and behaviour have been given the label 'supervisory' or 'executive attention'. We note that the set of functions suggested for this system appear to be implemented by a brain network that includes the midfrontal cortical areas and underlying basal ganglia.

This system is the source of attention and operates in conjunction with other structures to carry out specific cognitive and emotional computations. While we have outlined this view previously (Posner & Rothbart 1992, 1994), new data have accumulated from our studies and the work of others to provide an enlarged perspective for the theme of this paper.

In this paper, we first outline how the idea of executive control developed within cognitive psychology. Next, we review links between these functions and a specific anatomy and circuitry that have arisen from neuroimaging studies of selection, conflict and error detection. We then examine evidence on how this system begins its development in early infancy with the control of distress and assumes the control and regulation of cognition in later childhood. We conclude with consideration of new

---

*Author for correspondence (mposner@oregon.uoregon.edu).

directions for furthering our understanding of conscious control.

2. EXECUTIVE CONTROL

All normal people have a strong subjective feeling of intentional or voluntary control of their behaviour. These subjective feelings can be freely verbalized. Indeed, asking people about their goals or intentions is probably the single most predictive indicator of their behaviour during problem solving (Newell & Simon 1972). The importance of intention and goals is illustrated in observations of patients with frontal lesions (Duncan 1994) or mental disorders (Frith 1992) who show disruption in either their central control over behaviour or their subjective feelings of control. Despite these indices of central control, it has not been easy to specify exactly the functions or mechanisms of central control. Norman & Shallice (1986) argued that a supervisory system would be necessary for situations in which routine or automatic processes are inadequate. These functions include selection among competing inputs, resolution of conflict among responses, and monitoring and correcting errors.

The idea of executive control was made more concrete in cognitive studies of the 1970s and 1980s (see Posner (1978) for a review). In this research, it was possible to separate conscious control of mental events from automatic activation of the same events. The research approach involved semantic priming of a target word by a related (prime) word. If the prime was masked so that subjects were unaware of its identity, priming could still take place. However, the effects of priming were somewhat different from trials in which the prime had been carefully attended. When masked, ambiguous primes (e.g. palm referring to tree or hand) improved performance on targets related to both of its meanings (e.g. tree and hand). However, when presented in context and unmasked, only the relevant meaning was primed (Marcel 1983).

If a word from one category (e.g. animal) was presented as a prime and subjects were instructed they should associate animal primes with the category 'building', target words in the associated category (e.g. window) were faster in comparison with those in a category unrelated to the instructed category (e.g. tin). The subject had voluntarily activated the instructed category. If an animal target (e.g. dog) was presented before subjects could switch from the prime category 'animal' to the instructed category 'building', fast reaction times were shown to the word 'dog', but if dog was delayed until after subjects had a chance to execute the switch to the instructed category, the target 'dog' would have a slow reaction time since subjects were now attending to the wrong category (Neeley 1977).

These findings gave a concrete reality to the difference between the voluntary control of mental events and the same event when driven by input. Priming could be produced by an automatic activation of a pathway without attention, facilitating reaction times for primed items. Imaging studies have shown that automatic priming of this sort is produced by a reduction of blood flow within the brain area related to the form of priming. For semantic priming, this reduction would be within areas of the brain related to the meaning of the word (Demb *et al.* 1995). A second form of priming could be produced by attention. Within one second, subjects could voluntarily choose an associated category and the consequence of that selection was faster processing of related targets and retarded processing of unrelated targets. When a category was attended, items within the category were facilitated in reaction time, but items in other categories were retarded over what they would be if unprimed. Imaging studies have suggested that attention to a computation increases blood flow within the attended area. Thus, priming may be produced by different brain mechanisms and have quite different consequences for performance.

3. BRAIN MECHANISMS

When studies were begun using neuroimaging with PET, it was possible to discover brain areas that might reflect the various functions of attention (Posner & Petersen 1990). These include orienting to sensory stimuli and maintenance of the alert state as well as higher level executive attention. The executive network was found to be active in tasks involving selection, conflict and error detection, the very functions outlined in the earlier cognitive models (Shallice & Burgess 1996). In all of these cases, there was evidence of activity within the frontal midline, most often within the anterior cingulate gyrus.

(a) *Selection*

One task that has been analysed in great detail involves reading individual words. In a typical task, subjects are shown a series of 40 simple nouns (e.g. hammer). In the experimental condition they indicate the use of each noun (for example, hammer→pound). In the control condition, they read the word aloud. The difference in activation between the two tasks illustrates what happens in the brain when subjects are required to develop a very simple thought, in this case how to use a hammer. Brain activity obtained during reading words aloud is then subtracted from the activity found in the generate condition. Results illustrate the surprising fact that the anatomy of this high-level cognitive activity is similar enough among individuals to produce focal average activations that are both statistically significant and reproducible.

There are four focal but well separated areas of increases in brain activity during the simple thought needed to find the use of the word. The first is activity in the midline of the frontal lobe in the anterior cingulate gyrus. This area is involved in higher level aspects of attention, regardless of whether the task involves language, spatial location or object processing. We believe it relates to what we called above executive attention (Posner & DiGirolamo 1998). Two additional activations are in the left lateral frontal and posterior cortex in areas involved with processing the meaning of words or sentences. Finally, there is activation in the right cerebellum, which is closely connected to the left frontal areas.

We have been able to find the scalp signatures of three of these activations in our high density electrical recording studies and to trace the time-course of this activation (Abdullaev & Posner 1997, 1998; Snyder *et al.* 1995). When subjects obtain the use of a noun, there is an area of positive electrical activity over frontal electrodes starting about 150 ms after the word appears. This early electrical activity is most likely to be generated by the large area of activation in the anterior cingulate shown by the PET studies.

Two other areas active during generating word meanings occur in the left frontal and left posterior cortex. The left frontal area (anterior to and overlapping classical Broca's area) begins to show activity about 220 ms after the word occurs. During this interval, both the cingulate and the left frontal semantic area are active. We assume that the left frontal activation is related to the meaning of the individual word presented on that trial. The time-course of the left frontal area during processing the meaning of words is further supported by results obtained from cellular recording in patients with depth electrodes implanted for neurosurgery (Abdullaev & Bechtereva 1993). This area is active early enough to influence motor and eye movement responses, typically occurring by 200–300 ms, that can be influenced by the meaning of a word.

On the other hand, the left posterior brain area found to be more active during the processing of the meaning of visual words does not show up in the electrical maps until about 600 ms after input. This activity is near the classical Wernicke's area and lesions of this area are known to produce a loss of understanding of meaningful speech. We think this area is important in the storage and integration of words into larger meaningful units. Damage to this area makes it difficult to understand speech or written material. These results demonstrate how one can approach both the anatomy and circuitry of higher mental processes. By observing the brain areas activated in PET studies and relating them to scalp electrical activity, we have a picture of the temporal dynamics in creating a simple thought.

Recent fMRI studies have confirmed the presence of the semantic areas shown by PET and have provided more information on individual differences. For example, an fMRI study has shown that within the anterior and posterior semantic areas, different portions are active when processing different semantic categories (Spitzer *et al.* 1996). In Spitzer's data, the exact organization of individual categories within the general anterior and posterior semantic brain areas appears to differ from one subject to another. Nevertheless, the presence of category specific semantic areas indicates that the brain uses the same general mapping strategy to handle semantic relations as it does to handle sensory processing.

This form of semantic mapping by word category helps explain the automatic effect of semantic priming described above. If a category is activated by input, it simply makes more available words related to the same category. Automatic priming in the brain seems to be produced by a reduction in blood flow by neurons in the primed area (Demb *et al.* 1995; Raichle *et al.* 1994). However, priming can also occur as the result of attending to items. Attention appears to involve the midline frontal activity described above, and has the effect of boosting activity within the attended area. Cognitive studies argue that attended activation produces both an improvement in the processing of related items and also a reduction in the efficiency of processing unrelated items. It is as though the increase in neuronal activity in one area induced by attending to that area actually inhibits other items far outside of the attended category. By bringing together methods for examining anatomy and circuitry of brain activity with analysis of the cognitive consequences it is now possible to see much of what is involved when carrying out the conscious or voluntary act of selecting a thought.

(b) *Conflict*

The next step was to test whether these midfrontal activations were generally involved when elements of the task were in conflict, requiring executive control to perform the selected function. The most frequently studied conflict task is the Stroop effect in which subjects are instructed to name the colour of ink of a word which may be either the same as the ink colour (congruent), a different colour word (incongruent), or a non-colour word (neutral) (Pardo *et al.* 1990).

Figure 1 shows the results of six studies using variants of this task. All of them have activation in the frontal midline, but at a variety of locations. Although the colour word task is effective for eliciting conflict, it is by no means required. Conflict between word and location (e.g. the word right on the left of the screen), or between the number of items present and their names (e.g. reporting that there are four items present when the items are the word two), are other examples of conflict. A recent fMRI study of word–number conflict, for example, found strong activation of the anterior cingulate and also some motor areas (Bush *et al.* 1998).

The studies summarized in figure 1 show quite a spread over areas of the cingulate. Since the studies shown in figure 1 differ in subjects, methods and experimental procedure, this is not surprising. However, somewhat more disturbing, some studies showed the same degree of activation in the cingulate whether the trials were congruent or incongruent, although both differed from neutral trails. Since these trials give very different reaction times, and quite different subjective impressions of conflict, it appeared as though the frontal midline activation might not relate to conflict after all.

However, the PET method provides little evidence on how the frontal activation relates to the overall task. Because trials of a given type have to be blocked together, it is hard to know for all congruent trials whether subjects are responding based on reading the name or whether they really inhibit the name to respond based on the ink colour, since the output would be the same in both cases. To discover exactly what the internal processing is like, it is important to ask when conflict is occurring and for what range of trials.

We have recently completed two studies using high-density electrical study to address these issues (DiGirolamo *et al.* 1998). Both experiments demonstrated similar temporal and spatial patterns of data for the congruent (e.g. the word 'BLUE' in blue ink) and incongruent (e.g. the word 'RED' in blue ink) Stroop conditions. These two conditions first diverged from a neutral condition (a non-colour word; e.g. 'KNIFE' in blue ink) at 268 ms over midline and lateral posterior electrode sites (see figure 2).

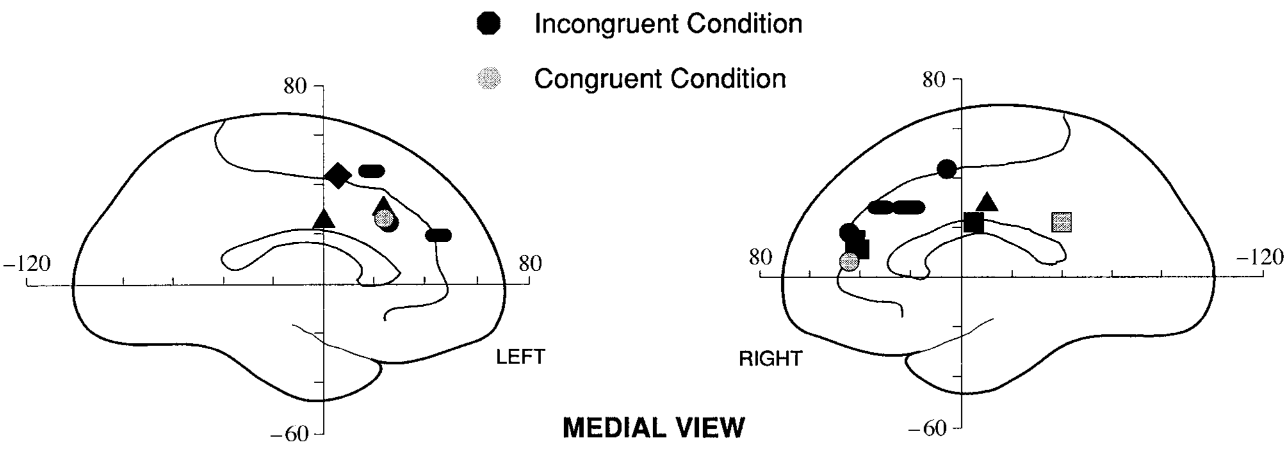

Figure 1. Activations in various Stroop and Stroop-like experiments in areas of the frontal midline. Activations in congruent and incongruent blocks are plotted as dark and light figures. The data are from the following studies: circle, Carter *et al.* (1995); diamond, Taylor *et al.* (1994); triangle, George *et al.* (1994); oval, Bench *et al.* (1990).

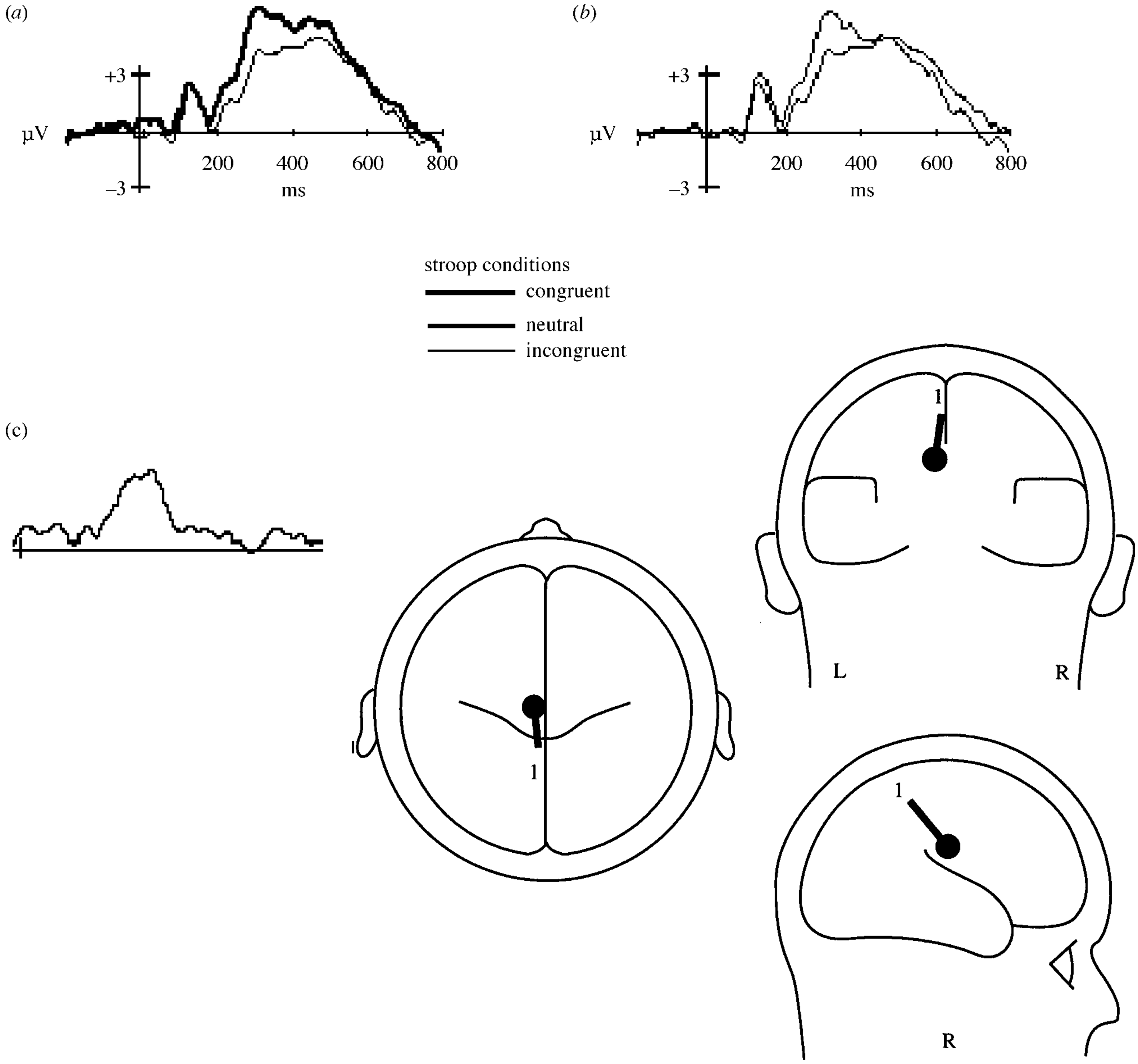

Figure 2. Scalp electrical activity from a study of the Stroop effect. Event-related potentials for congruent trials (*a*), and incongruent trials (*b*). Each is compared to neutral trials. Data are from midline electrodes. Best fitting single dipole solutions to 64 channel difference waves between incongruent–neutral trials (*c*) (DiGirolamo *et al.* 1998).

Dipole models of the congruent and incongruent conditions produced matching neural solutions accordant with a cingulate gyrus generator, suggesting the activity of an anterior attentional system during both conditions. These results support an analysis of the Stroop effect postulating comparable selective attentional processes to resolve conflict in both the congruent and incongruent conditions. These occur at multiple levels of processing, from stimulus selection through response choice. The data help to resolve some of the controversies in this literature.

The instruction to select by ink colour is implemented by amplifying computations in prestriate colour areas when there is simultaneous activity in colour name areas, as occurs on both congruent and incongruent trials. It appears that at the time of selection, the subject does not know if the activation in the colour name area matches or mismatches the ink colour. Thus the same cingulate activity is found on both trial types. Presumably both the ink colour and the colour name activate response tendencies. The congruent trials activate only the correct response, while incongruent trials activate conflicting responses, which accounts for the difference in RT and errors. However, the attention network is apparently dominated by the more fundamental conflict involved in executing the instruction to respond based on the ink colour.

The Stroop effect is compelling because it produces such a profound feeling of effort on trials in which the word and ink colour conflict. However, according to our result the selection process is the same as long as the stimulus is a coloured word. This finding supports the idea that the midline frontal areas are involved in resolving conflict, but perhaps are not involved in the feelings of conflict and effort, which must arise more from the conflicting response tendencies and errors produced by incongruent trials.

(c) *Error detection*

One of the functions of the supervisory attention system (Norman & Shallice 1986) was error detection. Error detection has been studied extensively in reaction time tasks within cognitive psychology (Rabbitt 1967) and neuropsychology (Bechtereva 1997). Usually it is thought of as part of a conscious strategy that seeks to adjust the speed of performance to an adequate level of accuracy.

A negative component of the scalp recorded electrical activity (error-related negativity) is recorded following the subject's detection of an error (Gehring *et al*. 1993). This error negativity occurs about 80 ms after the key press and appears to be localized in the anterior cingulate gyrus (Dehaene *et al*. 1994; Luu *et al*. 1998); see figure 3.

Error negativity does not occur if the error is undetected by the subject. However, if the subject receives feedback from the experimenter concerning a prior error, negativity can also be recorded (Miltner *et al*. 1998). The error detection process may also relate to the emotion of making an error, since errors are frequently accompanied by negative vocalization and negative facial expression. Recently, it has been shown that the amplitude of error-related negativity is correlated with self reports of negative emotionality, one of the temperament and personality dimensions most frequently found in psychological self-report scales (Luu *et al*. 1998). Since the cingulate is anatomically an important part of the limbic system involved in the coding of emotions, its relationship to negative emotionality seems appropriate.

Thus, cognitive tasks involving different operations, all related to executive control, have been shown to activate areas of the anterior cingulate. These observations seem unified only by their involvement in higher level attentional activity related to focal aspects of voluntary control. It is not clear if the same group of cingulate neurons is involved in these various cognitive operations. To explore this question, an experiment was run in which two tasks known to activate the cingulate gyrus were studied in the same trials with the same subjects (Badgaiyan & Posner 1998). The subject was instructed to generate the use of a visually presented noun and do so within a pre-specified window of time. The window was constructed so that about half the time, subjects' responses fell within the selected window, and half the time they were outside of it. When subjects were outside the window, they received error feedback.

There was evidence of midfrontal activity in the generate use task in comparison to reading aloud. This activity was quite far forward, at about the same location reported previously (Abdullaev & Posner 1997, 1998). However, it occurred somewhat later in time, perhaps reflecting the level of practice or the dual nature of the task in generating the word within an appropriate temporal window. When error feedback trials were compared with correct trials, another activation of the anterior cingulate was found. This activation was much more posterior and clearly different than that obtained for the generate task. Since the two tasks involved the same subjects and trials, it appears that different tasks activate distinct sets of cingulate and that the cingulate does not act as a single unit for processing complex cognitive tasks.

The finding that areas of activation of the cingulate differ according to task demands helps to explain the failure to find common activation in the cingulate during a meta-analysis of nine tasks (Shulman *et al*. 1997*a*,*b*). When passive presentation of the stimuli and responses was subtracted from active performance of the tasks there was activity in the supplementary motor area but not in the cingulate (Shulman *et al*. 1997*a*,*b*). However, a common cingulate focus of activation was found when merely presenting the stimuli was compared with passive presentation of fixation. This finding could suggest that there is an area of the cingulate related to awareness involved in the passive reception of verbal or non-verbal stimuli. However, each task demand may require processing from different areas of the cingulate.

We have reviewed evidence that areas of the anterior cingulate are involved in many of the features of executive control over mental processing in a wide variety of task domains. It appears that a common area of the cingulate may be involved in the reception of the input, perhaps related to awareness, but that very different areas are involved with different task demands. This data may seem surprising since the anterior cingulate does not appear at first to be likely to be involved in non-emotional responding as in the many cognitive tasks we have examined. We turn now to the question of how this form of brain organization may have arisen in development.

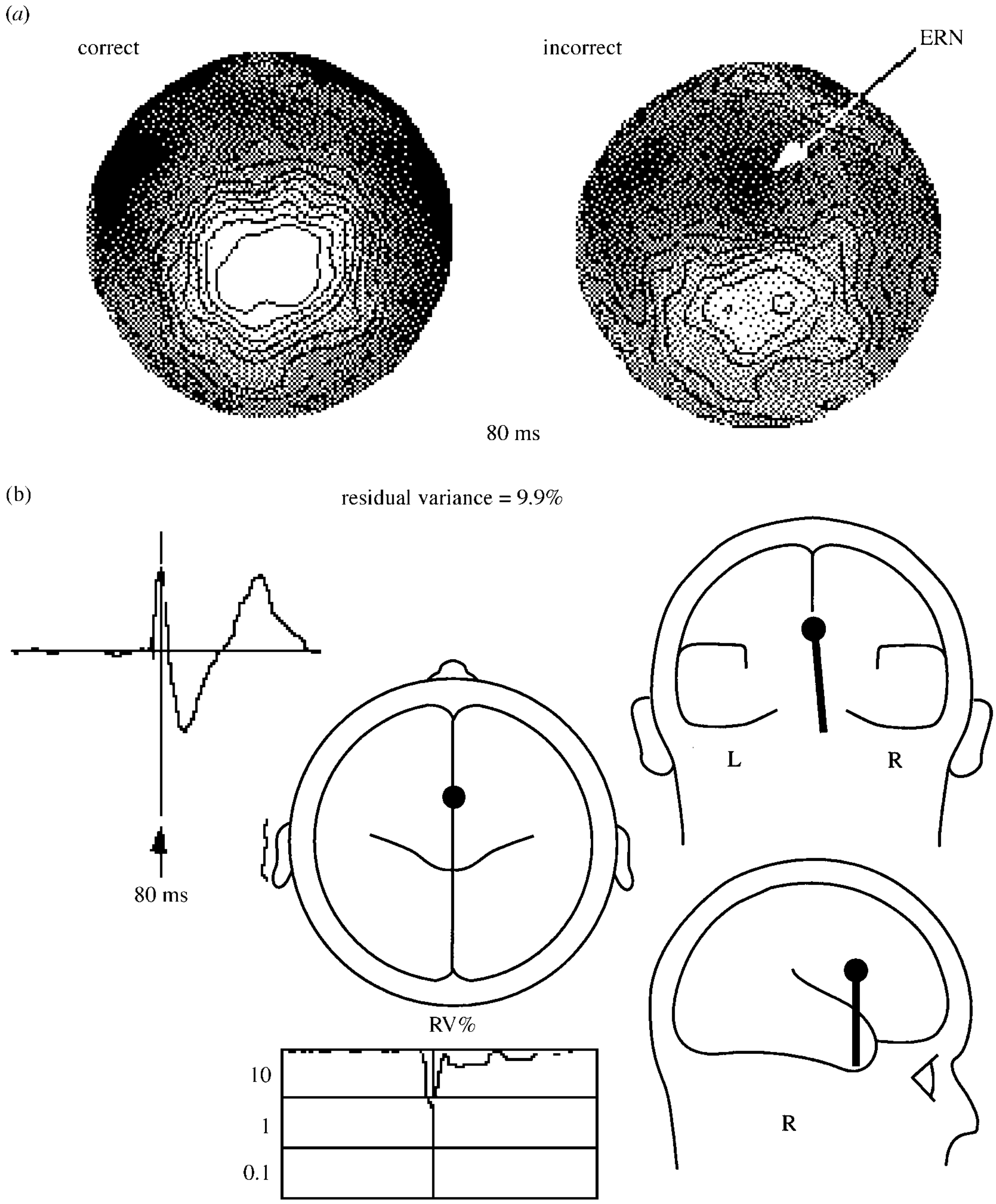

Figure 3. Scalp electrical activity at 80 ms following correct and incorrect (error) trials (*a*) in a speeded reaction time task with distractors. (*b*) Shows best fitting dipole solutions (Luu *et al.* 1998).

4. DEVELOPMENT

The human infant has the longest period of dependence upon care-givers of any mammal. During this period, infants must gain control of their behaviour and mental state. As we have seen in the last section, it appears that adults exercise a degree of central control over their thoughts and action, and this control involves specific areas within the frontal midline. We ask now how this form of control develops.

Luria (1973) distinguished between an early developing, largely involuntary biological attention system and a later developing, more voluntary social attention system. A major theme emerging from our work shows that Luria (1973) was roughly correct in making a distinction between voluntary and involuntary attention systems, but that contrary to his original belief, both are shaped by a complex interaction between biology and socialization that together determine their regulatory properties.

(a) ***Soothing***

There is clear evidence that anterior cingulate activity is a part of the brain's system for evaluating pain (Rainville *et al.* 1997) and for distress vocalization (Devinsky *et al.* 1995). The pain studies have shown cingulate activity when heat stimuli were judged as painful in comparison to merely warm. Moreover, the cingulate appears more involved in the distress caused by the pain rather than merely in the sensory stimuli involved (Rainville 1997). When an effort was made to control the distress produced by a given stimulus using hypnotic suggestion, the amount of cingulate activation reflected felt distress while the somatosensory cortex reflected stimulus intensity rather than perceived pain. A PET study using both pain and

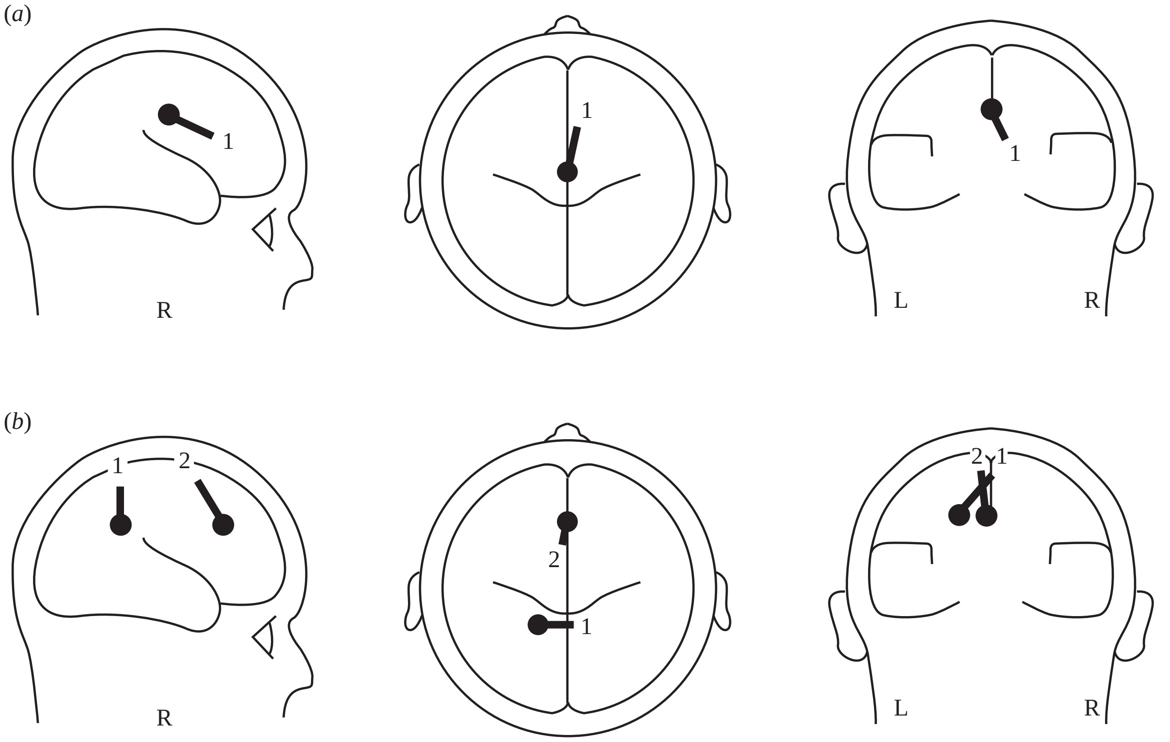

Figure 4. Best fitting dipole solutions to 128 channels of ERP following error feedback (*a*), and use generation (*b*) (after Badgaiyan & Posner 1998).

Stroop trials with the same subjects (Derbyshire *et al.* 1998) found that both types of trials activated anterior cingulate sites, but there appeared to be different loci when individual subjects were examined.

How does the cingulate become involved in the control of both pain and in cognitive tasks? In our view this may arise from the experience of early life. The early life of the infant is concerned with the regulation of state, including distress. During the first year of life, attention appears important in developing this form of control. Care-givers provide a hint of how attention is used to regulate the state of the infant. Earlier than three months, care-givers usually report holding and rocking as the main means of quieting their infant. However, at about three months, many care-givers, particularly in western cultures, attempt to distract their infants by bringing their attention to other stimuli. As infants attend, they are often quieted and their distress appears to diminish.

We have conducted a systematic study of attention and soothing in three- to six-month-old infants (Harman *et al.* 1997). Infants first become distressed to over-stimulation from lights and sounds, but then strongly orientate to interesting visual and auditory events when these are presented. While they orientate, facial and vocal signs of distress disappear. However, as soon as the orientating stops, for example, when the new object is removed, we found that the infant distress returned to almost exactly the levels shown prior to presentation of the object. Apparently the loss of overt signs of distress is not always accompanied by a genuine loss of distress. Instead, some internal system which we termed 'the distress keeper' appears to hold the initial level of distress and it returns if the infant's orientation to the novel event is lost. In our later studies, we quieted infants by distraction for as long as one minute without changing the eventual level of distress reached once orientating is ended. The effectiveness of a novel stimulus in achieving sustained orientating in the infant also appeared to be reduced at six months over its influence at 3–4 months.

There are possibly related phenomena present in the adult. Adults who report themselves as having good ability to focus and shift attention, also say they experience less negative affect (Derryberry & Rothbart 1988). Attention may serve to control levels of distress in adults in a somewhat similar way to that found early in infancy. Indeed, many of the ideas of modern cognitive therapy are based upon links between attention and negative ideation.

We do not yet know very much about how orientating serves to control distress either in infancy or for adults. However, as we have noted in the control of pain, a system in which distress and attention are closely coordinated lies in the anterior cingulate gyrus. Of course pain has a very intrusive character and this could be related to its close physical proximity to the anterior attention network.

Recent studies of negative emotion in the adult suggest that distress is related to activity in the amygdala (Irwin *et al.* 1996). When pictures depicting frightening or horrible scenes are shown to subjects, there is a strong area of amygdala activation. Evidence now exists that activation of the amygdala is modulated by left prefrontal cortical activity. These findings suggest a negative correlation between left prefrontal and amygdala activation in both non-depressed and depressed subjects. One effort to move beyond correlations has been made in studies of rats in which lesions of the medial frontal areas were shown to interfere with extinction of a classically conditioned fear response, suggesting an inhibitory control of the amygdala by midfrontal regions (Morgan *et al.* 1993).

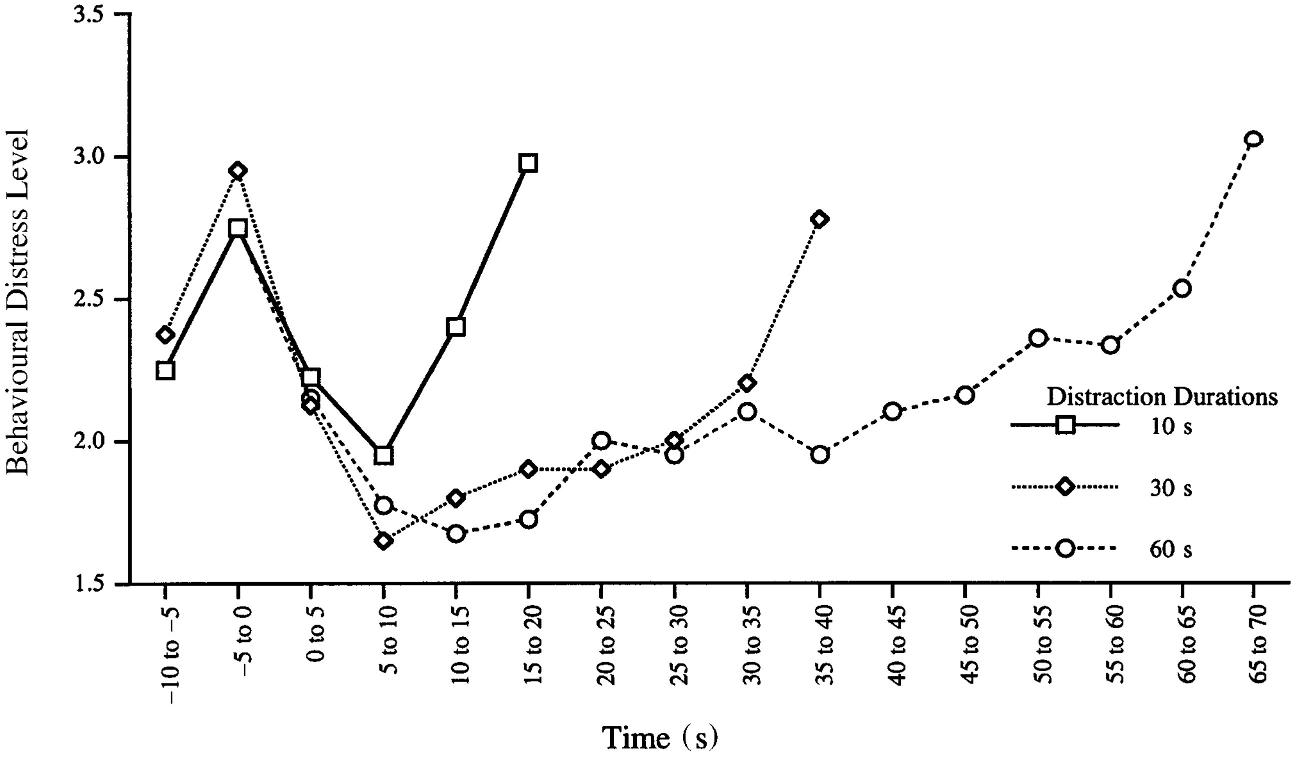

Figure 5. Pattern of distress ratings before, during and after presentation of an orientating stimulus to four- and six-month-old infants for 10, 30 or 60 s (Harman *et al.* 1993).

One way of measuring emotional awareness of individuals (called the level of emotional awareness) has them describe how they feel about situations, coding their use of emotional terms and descriptors in their written responses (Lane & Schwartz 1992). In a recent study, 12 subjects were shown each of three highly emotional movies and three neutral movies during a PET scan (Lane *et al.* 1998). Differences in anterior cingulate blood flow between the emotional and neutral movies was correlated with the person's level of emotional awareness score. These data suggest that something about the subjects' awareness of their emotions during sad or happy events is related to changes in the anterior cingulate.

We have no direct evidence that the exquisite control of negative affect by attention in our infant experiments is mediated by midfrontal control systems as might be suggested by the literature above. However, if it were, we might be able to explain why it is that midfrontal areas are so frequently seen as a control system involved in the self-regulation of behaviour.

It is not so much the stimulus of pain or distress that activates cingulate, but the feelings of distress related to the pain or efforts to cope with or control these feelings. Thus amygdala–cingulate interaction might be a reasonable candidate for the earliest form of self-regulation in the infant. In the infant, control of orientating is partly in the hands of care-givers' presentation of relevant information. However, the infant is clearly also involved in soliciting attention from the adults (Stern 1985). During the first years of life, more direct control of attention passes from care-givers to infant. It seems likely that the same mechanisms used to cope with self-regulation of emotion are then transferred to issues of control of cognition during later infancy and childhood.

(b) *Executive control*

Many psychologists agree with Denckla (1996) that 'the difference between the child and adult resides in the unfolding of executive functions' (p. 264). Luria (1973) referred to the development of a higher level more voluntary attentional mechanism during the second year of life. Individual differences in executive attention have important implications for the early development of behavioural and emotional control (Rothbart & Bates 1998).

The central issue of this paper is to describe an approach to examining executive function as a developmental process in early childhood. Our goal is to provide an experimental means to link individual differences in self-regulatory behaviours developing in early childhood to the maturation of underlying neural systems. According to the Norman & Shallice (1986) model discussed above, executive attention comes into play in adults in resolving conflict, correcting errors, and planning new actions. There appears to be excellent data that the ability to resolve conflict undergoes development in early childhood.

For example, Diamond (1991) showed the stages from 9–12 months through which the child passes in resolving conflict between reaching and the line of sight in order to retrieve an object in a box. At nine months, the line of sight dominates completely. Even if the child's hand should touch the toy through the open side of the box, if it is not in line with the side they are looking, infants will withdraw their hand and reach along the line of sight, striking the closed side. Three months later, they are able to look at a closed side but reach through the open end to retrieve the toy.

However, being able to reach for a target away from the line of sight is only a very limited form of conflict resolution, and Gerstadt *et al.* (1994) extended a verbal conflict modelled on the Stroop paradigm to children as young as 3.5 years. Two cards were prepared to suggest day and night to the children: one depicted a line-drawing of the sun, the other a picture of the moon surrounded by stars. Cards for the control condition were intended to suggest neither day nor night. Children in the conflict condition were instructed to reply 'day' to the moon card and 'night' to the sun card. Children in the control condition were divided into two groups and instructed to say 'day' to either a checkerboard or ribbon card and 'night' to the other. At every age, accuracy scores were significantly lower for conflict relative to control trials. Although all children performed at 80% accuracy or better for the first four trials of the session, by the last four trials, performance of the youngest declined to chance. Older children were able to maintain above-chance performance throughout the 16-trial session. Latency scores for conflict relative to control trials were also significantly longer for 3.5- and 4-year-old groups, suggesting that younger children needed more time to formulate their responses when faced with conflict. Other efforts have been made with Stroop-like tasks (Jerger *et al.* 1988), and with the Wisconsin card sort task (Zelazo *et al.* 1995), to study children as young as 31 months; little evidence of successful inhibitory control below three years has been found.

However, we believed that children as young as 18 months might be undergoing a development in frontal midline areas that would allow the limited conflict resolution related to eye position to become more general. We have found that children at 18 months can show context sensitive learning of sequences (Clohessy 1993; Posner *et al.* 1999). This is a form of learning which in adults appears to require access to the kind of higher level attention needed to resolve conflict. Adults can learn sequences of spatial locations implicitly when each location is invariably associated with another location (e.g. 13241324). This occurs even when the adult is distracted with a secondary task known to occupy focal attention (Curran & Keele 1993). The implicit form of skill learning seems to rely mainly upon subcortical structures. However, when distraction is present, adults are not able to learn context sensitive sequences (e.g. 123213) in which each association is ambiguous.

We found that infants as young as four months could learn the unambiguous associations, but not until 18 months did they show the ability to learn ambiguous or context sensitive associations (e.g. 1213). Individual children showed wide differences in their learning abilities, and in our study the ability to learn context sensitive cues was correlated with the care-givers report of the child's vocabulary development.

According to the analysis of the last section, a more direct measure of the development of executive attention might be reflected in the ability to resolve conflict between simultaneous stimulus events as in the Stroop effect. Since children of this age do not read we reasoned that the use of basic visual dimensions of location and identity might be the most appropriate way to study the early resolution of conflict.

The variant of the Stroop effect we designed to be appropriate for ages 2–3 years involved presenting a simple visual object on one side of a screen in front of the child and requiring the child to respond with a button that matched the stimulus they were shown (Gerardi 1996). The child had been trained to 'pat' the button that matched the stimulus they were shown. The appropriate button could be either on the side of the stimulus (congruent trial) or on the side opposite the stimulus (incongruent trial). The prepotent response was to press the button on the side of the target irrespective of its identity. However, the task required the child to inhibit that prepotent response and to act instead based on identity. The ability to resolve this conflict is measured by the accuracy and speed of their key press responses.

Results of the study strongly suggested that executive attention undergoes dramatic change during the third year of life. Performance by toddlers at the very beginning of this period was dominated by a tendency to repeat the previous response. Perseverance is associated with frontal dysfunction and this finding is consistent with the idea that executive attention is still very immature at 24 months. Even at this young age, however, toddlers were already showing a significant accuracy difference between compatible and incompatible trials (63% versus 53%). Children at the end of the third and beginning of the fourth year showed a strikingly different pattern of responses. Children who were 36–38 months old performed with high accuracy for both compatible and incompatible conditions (92% and 85%, respectively), showing the expected slowing for incompatible relative to compatible trials (30% longer reaction times).

The transition between these two extremes appears to take place at about 30 months. Cluster analysis divided 30-month-olds into three groups: one group (50%) performed similarly to 24-month-olds, one group (37%) approximated 36–38-month-olds' performance, and a very small group (13%) responded almost exclusively to the location of the stimulus rather than to its identity. In other words, if the picture appeared on the left, these toddlers responded on the left and vice versa, regardless of picture identity.

It was also possible to examine the relationship of our laboratory measures of conflict resolution to a battery of tasks requiring the young child to exercise inhibitory control over their behaviour. We found substantial correlations between these two measures. Even more impressive, elements of the laboratory task were significantly correlated with aspects of effortful control and negative affect in parental reports of infant behaviour in their normal environment. Cingulate activity relates to the control of distress and the cognitive measure of conflict resolution also relates to aspects of infant self control in daily life as reported by their parents.

In the Stroop effect, conflict is introduced between two elements of a single stimulus. We reasoned that an even more difficult conflict might be introduced by the task of executing instructions from one source while inhibiting those from another (L. Jones and M. K. Rothbart, unpublished data). This conflict task is the basis of the 'Simon says' game. Previous studies had suggested that the ability to perform this task emerged at about four years of age (Reed *et al.* 1984). In a recent study we asked children of 40–48 months of age to execute a response when they were given the command by a bear toy but to

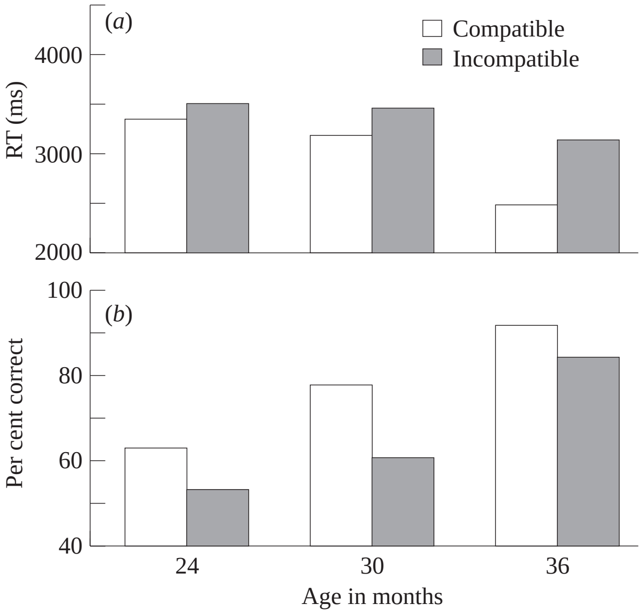

Figure 6. RT and per cent correct for compatible (open columns) and incompatible (closed columns) trials of a conflict task (in which responses must be made based on identity, but location also varies) as a function of age between two and three years. (Gerardi 1996.)

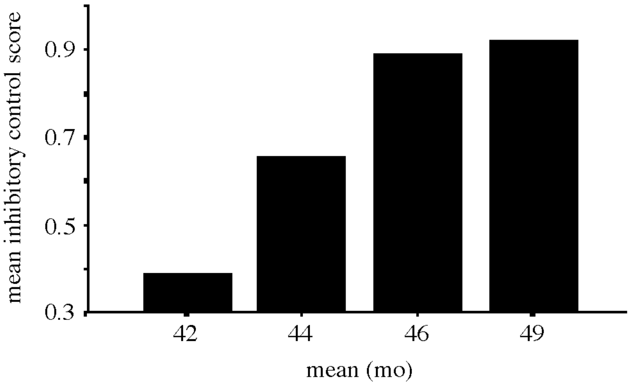

Figure 7. Ability to withhold a response to one animal while executing the instruction of another animal (inhibitory control score) as a function of age between 3.5 and 4 years. (L. Jones and M. K. Rothbart, unpublished studies.)

inhibit it when given by a toy elephant. Children up to 42 months were unable to carry out the instruction at better than a chance level. However, just two months later they were virtually perfect. The older children tend to use physical control to inhibit themselves from executing the commands given by the elephant. It is quite amazing to observe the lengths they go to control their own behaviour (see figure 7).

One remarkable aspect of this study was that children whose performance was at chance showed by their behaviour that they also had some recognition they were not supposed to respond to the elephant. This was demonstrated by the pattern of slowing down on trials following an error that is characteristic of error detection (A. Revutchi, L. Jones and M. K. Rothbart, unpublished data). This and the fact that they responded more slowly to the elephant than to the bear suggested they somehow were experiencing the conflict when receiving the instruction from the elephant. As shown in figure 8, the pattern of slowed response following an error emerged well before children were able to do the task, suggesting that error monitoring is in place well before inhibitory control is shown.

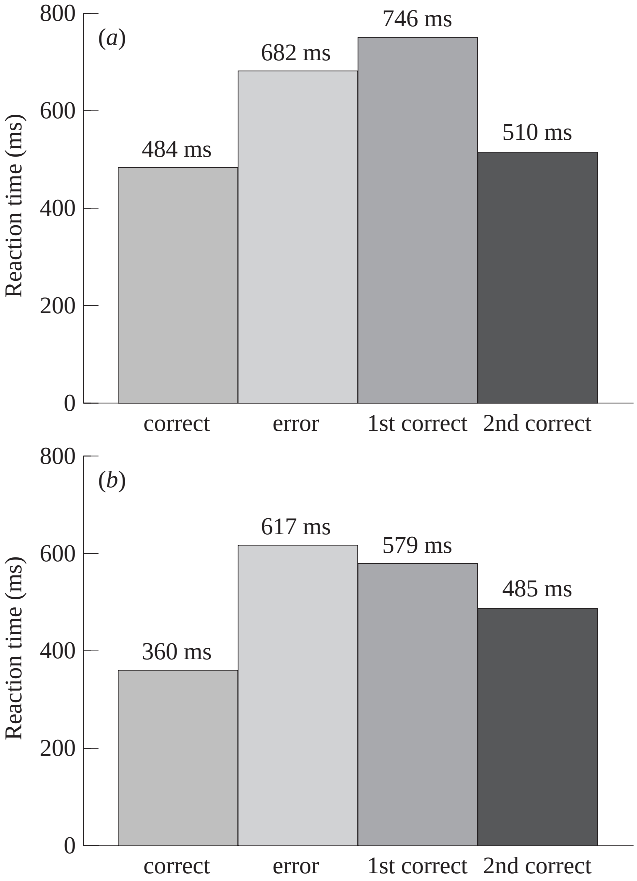

Figure 8. Reaction time for correct trials, error trials and correct trials following an error trial for children of 40–42 months who cannot inhibit (*a*) and 43–50 months who almost always successfully inhibit (*b*). (A. Revutchi, L. Jones and M. K. Rothbart, unpublished studies.)

There is also some direct evidence that the anterior cingulate is developing during this part of childhood in a way that might support the data on conflict and error correction. In children aged 5.3–16 years there is a significant correlation between the volume of the area of the right anterior cingulate and the ability to perform tasks relying upon focal attentional control (Casey *et al.* 1997*a*). Moreover, in a recent fMRI study, performance of children aged 7–12 years and adults was studied when performing a go–no-go task in which they were required to withhold pressing to an X while responding to non-Xs. This condition was compared to control tasks where subjects responded to all stimuli and thus never had to withhold a response. Both children and adults showed strong activity in prefrontal cortex when required to withhold responses. Moreover, the number of false alarms made in the task was significantly correlated with the extent of cingulate activity (Casey *et al.* 1997*b*).

5. VOLITION AND AWARENESS

The problem of consciousness includes both awareness and volition. In this paper, we have concentrated chiefly upon evidence linking activation of specific brain areas to voluntary control of behaviour. In part our choice reflects the importance of self-regulation to the individual and to collective human interest in the socialization of children. This perhaps is not the most usual concern of neuroscientists striving to develop a model of consciousness, but it does fit with classical issues raised about consciousness by philosophers concerned with the relation of the individual human to society.

As we have seen, Luria (1973) remarked on the social construction of consciousness. The infant development data we have reviewed provides concrete reality to the importance of a slow progression of self control in early life. This development allows society to influence the child's own control mechanisms through socialization. However, we believe that Luria (1973) stressed too strongly the social nature of this higher form of attention, because our review shows it to be woven out of specific biological tissue. If our story is accurate, control begins with the regulation of distress and most likely involves the specific interaction of midfrontal (cingulate) systems with the amygdala. The effort to develop ways of controlling distress provides a locus of control in the cingulate which may, step-by-step, generalize to other situations where conflicting demands must be resolved. Many years are devoted to development of systems of self-regulation. Indeed it seems likely that this development continues into adolescence and may be open to change in adult life, providing a basis for what is attempted in therapy.

Self regulation is a key to a successful society, as the philosopher Bergson has pointed out:

> Society, which is the community of individual energies, benefits from the efforts of all its members and renders effort easier to all. It can only subsist by subordinating the individual, it can only progress by leaving the individual free: contradictory requirements, which have to be reconciled. Human societies . . . bring about that individual wills should insert themselves in the social will without losing their individual form . . . . here too, across innumerable obstacles, life is working both by individualization and integration to obtain the greatest quantity, the richest variety, the highest qualities, of invention and effort.
>
> Bergson (1920, p. 33)

How does the issue of self-regulation relate to the other major aspect of consciousness that involves our awareness of the sensory world? We have found that the development of visual orientating precedes the major events we have described for cingulate development by at least a year (Posner & Rothbart 1992). Infants seem to function well visually at a time when their volitional self-regulation has not yet undergone the development we have described above. This suggests that Crick may be right in his idea that visual awareness is a simpler function of consciousness and perhaps the one easiest to study.

On the other hand, the meta-analysis of cortical activity conducted by Shulman *et al.* (1997*a*,*b*) suggests that specific areas of cingulate activity accompany the presentation of almost any stimulus to a subject, even when the instruction is to make no effort to process it. While it is unclear exactly what subjects do with this instruction, it is likely that they are aware of the stimulus, but do little else with it. This result suggests a possible connection between cingulate activity and awareness of the stimulus.

It is also clear from studies of complex scenes that the presentation of a stimulus does not lead very automatically to awareness of its presence (Schneider 1995). Even though subjects report themselves as aware of the whole scene, only when their attention is drawn to a change in the scene do they become aware of that change. Attention may be summoned to the location of the change as the result of energy transients, or as the result of voluntary search. Focal attention is therefore a necessary condition for awareness of detail within a scene as well as a mechanism of voluntary control. Perhaps the distinction between focal attention to limited aspects of the external world and a more general ambient awareness of the scene as a whole (Iwasaki 1993) will prove important in understanding the parts of the brain related to consciousness of sensory events.

Certain conditions of the organism lead to dissociations between awareness and volition. We have discussed in previous papers the conditions of vigilance in which subjects suspend thought while awaiting an infrequent near-threshold signal (Posner & Rothbart 1992, 1994). Several studies have shown that the clearing of the mind of conscious content necessary to avoid missing the signal is accompanied by a reduction in activity within the anterior cingulate.

One condition in which voluntary control is lost but awareness, at least in the form of dream content, can remain high is during REM sleep. Most people would regard the dream as consciousness that is imposed without regard to volition. One PET study of the REM state (Maquet *et al.* 1996) showed activation of the anterior cingulate together with the amygdala and other parts of the subcortical arousal systems and portions of the parietal lobe. Another study (Braun *et al.* 1997) compared waking, slow wave and REM sleep and again found increased activity in the cingulate during REM which was accompanied by other arousal and sensory brain areas. Thus, we find substantial reason to suppose that cingulate activation is a part of systems related to awareness as well as to cognitive control.

There is no reason to suppose that the distinctions between awareness and volition made in scientific and philosophical speculations will prove to neatly divide anatomical or developmental systems. Nonetheless, we believe progress has been made in understanding mechanisms of self-regulation, and that it will be important to continue to study aspects of the anatomy, circuitry and development of mechanisms that provide the basis for our voluntary control of thought, emotion and action.

REFERENCES

Abdullaev, Y. G. & Bechtereva, N. P. 1993 Neuronal correlates of the higher-order semantic code in human prefrontal cortex in language tasks. *Int. J. Psychophysiol.* **14**, 167–177.

Abdullaev, Y. G. & Posner, M. I. 1997 Time course of activating brain areas in generating verbal associations. *Psychol. Sci.* **8**, 56–59.

Abdullaev, Y. G. & Posner, M. I. 1998 Event-related brain potential imaging of semantic encoding during processing single words. *Neuroimage* **7**, 1–13.

Badigaiyan, R. & Posner, M. I. 1998 Mapping the cingulate cortex in response selection and monitoring. *Neuroimage* **7**, 255–260.

Bechtereva, A. 1997 *On the human brain*. St Petersburg: Notabene.

Bench, C. J., Frith, C. D., Grasby, P. M., Friston, K. J., Paulesu, E., Frackowiak, R. S. J. & Dolan, R. J. 1993 Investigations of the functional anatomy of attention using the Stroop test. *Neuropsychologia* **31**, 907–922.

Bergson, H. 1920 *Mind-energy: lectures and essays*. New York: Holt Co.

Block, N. 1995 On a confusion about a function of consciousness. *Behav. Brain Sci.* **18**, 227–287.

Braun, A. R., Balkin, T. J., Wesensten, N. J., Carson, R. E., Varga, M., Baldwin, P., Selbie, S., Belenky, G. & Herscovitch, P. 1997 Regional cerebral blood flow throughout the sleep–wake cycle: an $H_2^{15}O$ PET study. *Brain* **120**, 1173–1197.

Bush, G., Whalen, P. J., Rose, B. R., Jenike, M. A., McInerney, S. C. & Rauch, S. L. 1998 The counting Stroop: an inteference task specialized for functional neuroimaging—validation study with functional MRI. *Hum. Brain Mapp.* **6**, 270–282.

Carter, C. S., Mintun, M. & Cohen, J. D. 1995 Interference and facilitation effects during selective attention: an $H_2^{15}O$ PET study of Stroop task performance. *Neuroimage* **2**, 264–272.

Casey, B. J., Trainor, R., Giedd, J., Vauss, Y., Vaituzis, C. K., Hamburger, S., Kozuch, P. & Rapoport, J. L. 1997*a* The role of the anterior cingulate in automatic and controlled processes: a developmental neuroanatomical study. *Devl Psychobiol.* **3**, 61–69.

Casey, B. J. (and 12 others) 1997*b* A developmental function MRI study of prefrontal activation during performance of a go-no-go task. *J. Cog. Neurosci.* **9**, 835–847.

Clohessy, A. B. 1993 Anticipatory eye movement learning in infants and adults: using visual cues to predict event locations. Unpublished PhD thesis, University of Oregon.

Crick, F. 1994 *The astonishing hypothesis*. New York: Basic Books.

Curran, T. & Keele, S. W. 1993 Attentional and nonattentional forms of sequence learning. *J. Exp. Psychol.: Learn. Mem. & Cogn.* **19**, 189–202.

Dehaene, S., Posner, M. I. & Tucker, D. M. 1994 Localization of a neural system for error detection and compensation. *Psychol. Sci.* **5**, 303–305.

Demb, J. B., Desmond, J. E., Wagner, A. D., Vaidya, C. J., Glover, G. H. & Gabrieli, J. D. E. 1995 Semantic encoding and retrieval in the left inferior prefrontal cortex: a functional MRI study of task difficulty and process specificity. *J. Neurosci.* **15**, 5870–5878.

Denckla, M. B. 1996 A theory and model of executive function: a neuropsychological perspective. In *Attention, memory and executive function* (ed. G. R. Lyon & N. A. Krasnegor), pp. 263–278. Baltimore, MD: Paul H. Brookes.

Derbyshire, S. W. G., Vogt, B. A. & Jones, A. K. P. 1998 Pain and Stroop interference tasks activate separate processing modules in anterior cingulate cortex. *Exp. Brain Res.* **11**, 52–60.

Derryberry, D. & Rothbart, M. K. 1988 Arousal, affect, and attention as components of temperament. *J. Personality Social Psychol.* **55**, 958–966.

Devinsky, O., Morrell, M. J. & Vogt, B. A. 1995 Contributions of anterior cingulate to behaviour. *Brain* **118**, 279–306.

Diamond, A. 1991 Neuropsychological insights into the meaning of object concept development. In *The epigenesis of mind: essays on biology and cognition* (ed. S. Carey & R. Gelman), pp. 67–110. Hillsdale, NJ: Lawrence Erlbaum.

DiGirolamo, G., Heidrich, A. & Posner, M. I. 1998 Similar time course and neural circuitry across congruent and incongruent Stroop condition. Cognitive Neuroscience Society Poster, April, San Francisco.

Duncan, J. 1986 Disorganization of behaviour after frontal lobe damage. *J. Cog. Neuropsychol.* **3**, 271–290.

Frith, C. D. 1992 *The cognitive neurosychology of schizophrenia*. Hove, UK: Lawrence Erlbaum.

Gehring, W. J., Gross, B., Coles, M. G. H., Meyer, D. E. & Donchin, E. 1993 A neural system for error detection and compensation. *Psychol. Sci.* **4**, 385–390.

George, M. S., Ketter, T. A., Parekh, P. I., Rosinsky, N., Ring, H., Casey, B. J., Trimble, M. R., Horwitz, B., Herscovitch, P. & Post, R. M. 1994 Regional brain activity when selecting response despite interference: an $H_2^{15}O$ PET study of the Stroop and an emotional Stroop. *Hum. Brain Mapp.* **1**, 194–209.

Gerardi, G. 1996 Early development of attention and self regulation. Unpublished PhD thesis, University of Oregon.

Gerstadt, C. L., Hong, Y. J. & Diamond, A. 1994 The relationship between cognition and action: performance of children 3.5–7 years old on a Stroop-like day–night test. *Cognition* **53**, 129–153.

Harman, C., Rothbart, M. K. & Posner, M. I. 1997 Distress and attention interactions in early infancy. *Motivation & Emotion* **21**, 27–43.

Iwasaki, S. 1993 Spatial attention and two modes of visual consciousness. *Cognition* **49**, 211–233.

Jerger, S., Martin, R. C. & Pirozzolo, F. J. 1988 A developmental study of the auditory Stroop effect. *Brain Lang.* **35**, 86–104.

Lane, R. D. & Schwartz, G. E. 1992 Levels of emotional awareness: implications for psychotherapeutic integration. *J. Psychother. Integration* **2**, 1–18.

Lane, R. D., Reiman, E. M., Axelrod, B., Yun, L.-S., Holmes, A. & Schwartz, G. E. 1998 Neural correlates of levels of emotional awareness: evidence of an interaction between emotion and attention in the anterior cingulate cortex. *J. Cog. Neurosci.* **10**, 525–535.

Luria, A. R. 1973 *The working brain*. New York: Basic Books.

Luu, P., Collins, P. & Tucker, D. M. 1998 Mood personality and self-monitoring: negative affect and emotionality in related to frontal lobe mechanisms of error detection. *J. Exp. Psychol. Gen.* (Submitted.)

Maquet, P., Peters, J.-M., Aerts, J., Delfiore, G., Deglueldre, C., Luxen, A. & Franck, G. 1996 Functional neuroanatomy of human rapid-eye-movement sleep and dreaming. *Nature* **164**, 163–166.

Marcel, A. J. 1983 Conscious and unconscious perception: experiments on visual masking. *Cogn. Psychol.* **15**, 197–237.

Miltner, W. H. R., Braun, C. H. & Coles, M. G. H. 1998 Event related potentials following incorrect feedback I a time-estimation task: evidence for a 'generic' neural system for error detection. *J. Cog. Neurosci.* **9**, 788–798.

Morgan, A. H., Romanski, L. M. & LeDoux, J. E. 1993 Extinction of emotional learning: contributions of medial prefrontal cortex. *Neurosci. Lett.* **163**, 109–113.

Neeley, J. H. 1977 Semantic priming and retrieval from lexical memory. The role of inhibitionless spreading activity and limited capacity attention. *J. Exp. Psychol. Gen.* **106**, 1–66.

Newell, A. & Simon, H. A. 1972 *Human problem solving*. Engelwood Cliffs, NJ: Prentice-Hall.

Norman, D. A. & Shallice, T. 1986 Attention to action: willed and automatic control of behaviour. In *Consciousness and self regulation* (ed. R. J. Davidson, G. E. Schwartz & D. Shapiro), pp. 1–18. New York: Plenum Press.

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. *Proc. Natn. Acad. Sci. USA* **87**, 256–259.

Posner, M. I. 1978 *Chronometric explorations of mind*. Hillsdale, NJ: Lawrence Erlbaum.

Posner, M. I. 1994 Attention: the mechanism of consciousness. *Proc. Natn. Acad. Sci. USA* **91**, 7398–7402.

Posner, M. I. & DiGirolamo, G. J. 1998 Executive attention: conflict, target detection, and cognitive control. In *The attentive brain* (ed. R. Parasuraman), pp. 401–423. Cambridge, MA: MIT Press.

Posner, M. I. & Petersen, S. E. 1990 The attention system of the human brain. *A. Rev. Neurosci.* **13**, 25–42.

Posner, M. I. & Rothbart, M. K. 1992 Attention and conscious experience. In *The neuropsychology of consciousness* (ed. A. D. Milner & M. D. Rugg), pp. 91–112. London: Academic Press.

Posner, M. I. & Rothbart, M. K. 1994 Constructing neuronal theories of mind. In *High level neuronal theories of the brain* (ed. C. Koch & J. Davis), pp. 183–199. Cambridge, MA: MIT Press.

Posner, M. I., Clohessy, A. B. & Rothbart, M. K. 1999 Development of the functional visual field. *Acta Psychol.* (Submitted.)

Rabbitt, P. M. A. 1967 Time to detect errors as a function of factors affecting choice-response time. *Acta Psychologia* **27**, 131–142.

Raichle, M. E., Fiez, J. A., Videen, T. O., MacLeod, A.-M. K., Pardo, J. V., Fox, P. T. & Petersen, S. E. 1994 Practice-related changes in human brain functional anatomy during nonmotor learning. *Cerebr. Cortex* **4**, 8–26.

Rainville, P., Duncan, G. H., Price, D. D., Carrier, B. & Bushness, M. C. 1997 Pain affect encoded in human anterior cingulate but not somatosensory cortex. *Science* **277**, 968–970.

Reed, M., Pien, D. L. & Rothbart, M. K. 1984 Inhibitory self-control in preschool children. *Merrill-Palmer Quart.* **30**, 131–147.

Rothbart, M. K. & Bates, J. E. 1998 Temperament. In *Handbook of child psychology. 3. Social, emotional and personality development* (ed. W. Damon & N. Eisenberg), pp. 105–176. New York: Wiley.

Schneider, W. X. 1995 VAM: a neurocognitive model for visual attention control of segmentation, object recognition and space based motor action. *Visual Cogn.* **2**, 331–375.

Shallice, T. & Burgess, P. 1996 The domain of supervisory processes and temporal organization of behaviour. *Phil. Trans. R. Soc. Lond.* B **351**, 1405–1412.

Shulman, G. L., Corbetta, M., Buckner, R. L., Fiez, J. A., Miezin, F. M., Raichle, M. E. & Petersen, S. E. 1997*a* Common blood flow changes across visual tasks. I. Increases in subcortical structures and cerebellum but not in nonvisual cortex. *J. Cog. Neurosci.* **9**, 624–647.

Shulman, G. L., Fiez, J. A., Corbetta, M., Buckner, R. L., Miezin, F. M., Raichle, M. E. & Petersen, S. E. 1997*b* Common blood flow changes across visual tasks. II. Decreases in cerebral cortex. *J. Cog. Neurosci.* **9**, 648–663.

Snyder, A. Z., Abdullaev, Y., Posner, M. I. & Raichle, M. E. 1995 Scalp electrical potentials reflect regional cerebral blood flow responses during processing of written words. *Proc. Natn. Acad. Sci. USA* **92**, 1689–1693.

Spitzer, M., Bellemann, M. E., Kammer, T., Friedemann, G., Kichka, U., Maier, S., Schwaartz, A. & Brix, G. 1996 Functional MR imaging of semantic information processing and learning-related effects using psychometrically controlled stimulation paradigms. *Cog. Brain Res.* **4**, 149–161.

Stern, D. N. 1985 *The interpersonal world of the infant*. New York: Basic Books.

Taylor, S. F., Kornblum, S., Minoshima, S., Oliver, L. M. & Koeppe, R. A. 1994 Changes in medial cortical blood flow with a stimulus-response compatibility task. *Neuropsychologia* **32**, 249–255.

Zelazo, P. D., Resnick, J. S. & Pinon, D. E. 1995 Response control and the execution of verbal rules. *Devl Psychol.* **31**, 508–517.