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RESEARCH ARTICLE

On the neurodynamics of the creation of consciousness

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Abstract Consciousness is expected to have a specific temporal dynamics. The COrollary Discharge of Attention Movement (CODAM) model of consciousness is deduced from an engineering approach to attention and motor attention. This model is briefly described, as is support arising from brain dynamics, especially that for the attentional blink. The understanding of known temporal dynamics in the brain associated with the emergence of consciousness is then developed from CODAM, and specifically related to the N2 ERP brain signal. How the pre-reflective self, as content-free, interacts with the content of experience is discussed in terms of the possibility that such experience arises from some proto-self generated by body signals; experiments are described which indicate that no pre-reflective self based on body signals is observable. Only a content-free pre-reflective self is consistent with this data, as CODAM suggests. How such a pre-reflective self can be further fused to give temporal continuity of a sense of self is considered in terms of various mechanisms which could be present for preserving the sense of self. The observation of the N2 signal in hippocampal encoding is proposed as providing a justification for the encoding of the N2–P3 sequence of brain signals. This would correspond to episodic encoding of the sequence of experiences of the pre-reflective self; this will thereby provide the necessary control signals in time so that 'I' is experienced as part of the retrieval of such memories.

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Introduction

The problem of the dynamics of the creation of consciousness is an important topic for the joint communities of cognitive science and non-linear dynamics. However there is considerable controversy over the nature of consciousness itself, so it has proved difficult for these communities to make any real and verifiable progress on the problem. The method used here is to approach consciousness creation through a detailed analysis of attention, and thereby gain an experimental platform of considerable strength and vigour. The analysis of attention is itself proceeding apace by the various increasingly accurate devices of brain imaging as well as through the creativity of experimentalists in designing ever more sophisticated experimental paradigms. In any well-based model of attention the assumption as to when and how consciousness creation occurs will itself be the most controversial point in the analysis. In this paper a particular mechanism (that of internal models of attention control) will allow this assumption to be related to various reported aspects of human experience as well as to various physiological markers, and so lead to a range of testable predictions and correlations with further experimental data. Only by this grounding can the assumptions on consciousness be tested experimentally and developed further in accordance with reality through further testing simulations. It is through this joint experimental/theoretical framework that the work described here has been developed.

Attention is known to be a control system par excellence. Its basic mode of action is to single out inputs which are to be processed to a higher level in a given modality. Attention involves two types of area in the brain: those being controlled, and those achieving the control. The control is by amplification of required inputs, with inhibition of distracters, now considered achieved by competitive feedback from controlling to controlled areas, with modulation by overall multiplication of controlled neural activity, or by biasing response threshold.

It was proposed in Taylor (2000) that engineering control provides a framework to understand attention, as will be reviewed in the next section. Simulations have been performed in this approach, both for sensory attention (Taylor and Rogers 2002) and extended to sensory-motor attention (involving both ballistic motor attention control and an additionally coupled forward motor attention control model, as described briefly in the ''Sensory-motor attention processing'' section. The engineering control approach to attention has been developed further to provide a model of the creation of consciousness, by means of the COrollary Discharge of Attention Movement (CODAM) (Taylor 2000, 2002a, b, 2003a, b), in particular through the creation of the pre-reflective self and its dynamic fusion with the experience of the content of external stimuli. This approach is reviewed in ''The CODAM model of consciousness'' section, with experimental support discussed in the ''Evidence for CODAM: temporal flow'' section, both in terms of timing in the brain and an explanation of the attentional blink. Crucial components in the internal dynamics of CODAM is specifically shown to be supported by more recent data on the N2 ERP observed in the attentional blink (Sergent et al. 2005). In ''The temporal dynamics of consciousness creation'' section the temporal dynamics of the creation of consciousness is considered in more detail, and how the main problem facing Western phenomenology, that of the fusion of the pre-reflective self and that of content, is resolved in terms of the dynamical flow of activity through the various modules of a CODAM style multi-modular brain. The possibility that the pre-reflective self is created through the body is considered in the ''I and my body are distinct'' section, with experimentally based problems shown to make this approach difficult. In ''The nature of self'' section a further possibility is explored to indicate a mechanism for creation of the notion of the enduring pre-reflective self. The final section ''Comparison to other approaches'' contains concluding remarks.

The control approach to attention

There is now good experimental evidence that attention acts in a control manner, as noted in the introduction, with several distinct brain regions being recognised as involved (in the terminology of modern control theory):

1. The plant being controlled (At least sensory and motor cortices).
2. The controller generating attention movement signals (inverse model controller or IMC for short, in parietal lobes).
3. A goal module, needed to process external signals that draw attention and to hold internal goals (termed Goal, and sited in prefrontal cortex).
4. A monitor, to check that the error level in directing attention is low, and suitable motor responses are learnt (the error being calculated in a monitor or Mon for short, sited in cingulate cortex).
5. An observer module, based on the corollary discharge of the attention movement control signal (a working memory site dedicated to the corollary discharge of the attention movement control signal, termed WMcd, in a site or sites yet to be determined).
6. A feedback processor, acting as a buffer, and holding the signal from the amplified sensory input for further processing, such as report (a buffer working memory, denoted WM Sensory, sited in parietal lobes).

A standard control circuit was suggested by analogy to proposed models of motor control in the brain (Sabes 2000; Desmurget and Grafton 2000). Exogenous attention control is achieved through rapid passage of the input signal to the goal module (O'Shea et al. 2004), leading to feedback control from the IMC down to the lower-level sensory (visual) cortices. Endogenous control arises by holding a suitable goal signal on the Goal module, enabling biasing of the competitive process on the IMC to take place to achieve attention focussed on the goal input (such as detecting a face in a crowd). A version of this control circuit is shown below in Fig. 1.

The observer (denoted WMcd for the working memory buffer for the corollary discharge) and the feedback processor (denoted WM Sensory for the working memory buffer for the sensory input) are taken as working memory sites (Baddeley 1986). These sites will have temporal continuation of activity entering them, as corresponds to a buffer site. However in order to hold activity for much longer than the several seconds observed behaviourally and

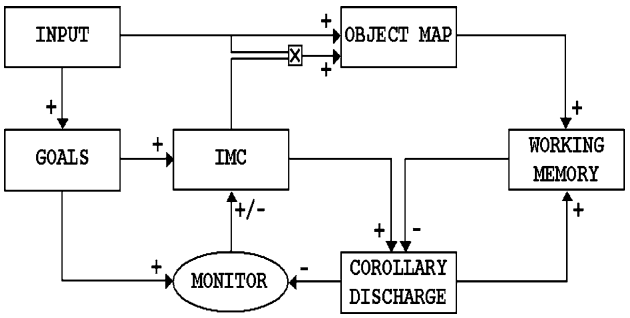

Fig. 1 The basic architecture of the CODAM model for sensory attention. The modules present in the figure consist of the input module (for pre-processing in low-level visual cortex), the object map (where object codes are stored), the IMC as generator of the signal to move the focus of attention in lower cortices, the corollary discharge module where a copy of the attention movement signal is stored temporarily, working memory holding an estimate of the attended target representation, and the monitor producing an error signal given by the difference of the required goal signal and that produced by the corollary discharge module as a predictor of the attended next state or of the working memory module activation

neuro-physiologically (Todd and Marois 2004) rehearsal processes must occur that are thought to involve prefrontal sites causing a continued re-attending to the original material.

The two working memory buffer modules are specialisations to the brain of the more general observer and feedback systems in engineering control. There are a variety of ways in which these observer and feedback modules could combine their outputs to the control signal generator, the IMC, for further direction of attention, as well as combining more direct feed-forward control signals directly from the Goal module to the IMC (as already considered in the motor control case in Desmurget and Grafton 2000, for example).

The resulting architecture of the basic CODAM model of attention control is shown in Fig. 1. It possesses the various modules discussed so far (Goals, IMC, WM buffer) plus the low-level module of the Object map (representing object stimuli below awareness). The × sign on the input to the object module from the IMC denotes that the attention movement control signal from the IMC (to move the focus of attention) to the object map is used as a multiplicative (contrast gain) modulator of the input to the object module, thereby granting attention a more input-specific mode of action than if it were just an additive signal to lower-level stimulus representations, independent of the input to the attended neuron. There is also the Monitor module, which uses a copy—the Corollary discharge or CD signal—of the IMC attention movement signal to create an early error signal by comparison of the CD signal with the goal signal. This error can be used to feed back to the IMC and amplify the IMC signal, so better ensuring achievement of the desired goal. Finally in Fig. 1 there is a working memory buffer for the corollary discharge signal, as noted earlier, which may be used to supplement activity trying to access the WM buffer so as to achieve faster access to awareness and report. There can also be inhibition from the attention copy (corollary discharge) signal to other neurons on the WM buffer not coding for the target, so ensuring that distracters will not creep into the WM buffer to gain reportability and awareness instead of the target stimulus.

The mode of action of CODAM to bring about attention to a given stimulus (or to attend to a highly salient stimulus) is as follows. The input enters the Input module, and then rapidly (possibly by a subcortical route) feeds to the Goal module, where there may already be an endogenous goal. If there is no endogenous goal or not a very strong one, the bias input from the new stimulus-driven goal to the IMC causes attention to be focussed on the position (or features) of the new input. There is then produced an attention feedback signal to the object map (functioning as lower level cortex) that amplifies the input signal. This suitably amplified input signal then accesses the WM buffer map to function as an estimate of the attended stimulus in order to direct attention. The corollary discharge and monitor modules allow for a speed up of attention re-focussing (before the arrival of the amplified low-level attended input) so as to help speed up response.

There is considerable experimental support for certain of the modules introduced above. This comes from numerous brain imaging and single cell experiments (Corbetta and Shulman 2002; Kastner and Ungerleider 2000; Mehta et al. 2000; Nobre 2001), to which the reader is referred, as well as the more expanded discussion in Taylor (2003a, b, c, 2005).

Recent data gained by using transcranial magnetic stimulation (TMS) to knock out particular brain modules in the attention circuitry, especially in the mid-brain, in a subject while they perform various visual search tasks have also supported this overall view. In particular it has been observed (Chambers et al. 2004) that there are two periods of vulnerability of a particular region called the supramarginal gyrus (SMG) in the parietal lobe involved in the process of moving attention, these periods being at 90–120 ms and 210–240 ms post-stimulus. It can be envisaged that the first period of vulnerability involves a rapid feed-forward flow to complement the goal-bias signal arriving from prefrontal cortex mentioned earlier (O'Shea et al. 2004), all to be fed to the IMC to draw

attention. The second period would then involve the attention-amplified signal being created and received. In either of these periods there would be vulnerability to activity damage, as experimentally observed. It may be that the SMG is functioning in this situation as the WMcd suggested in Fig. 1, since the IMC appears to be placed in the superior parietal lobe (SPL) according to the earlier references (Corbetta and Shulman 2002). The early activation at 90–120 ms is to be expected as part of the upward sweep of stimulus-driven activity. It is the later 210–240 ms activation that may be crucial, as found by deficits arising in the simulation of CODAM when the attention signal copy in the WMcd is removed (Fragopanagos et al. 2005).

Of considerable interest also is the recent observation of inhibition between the N2 of the second target and the P3 of the first target in an experimental investigation of the AB using EEG (Sergent et al. 2005); we will turn later to analyse that data and its relevance to CODAM and the temporal flow of the creation of consciousness. Table 1 contains proposed sites for the various modules of the attention control system, as well as timing patterns of input during processing. The final two columns contain suggested representations in the sites as well as the function being performed by the module, as deduced from a range of experimental paradigms.

We present below further evidence for the existence of the sites mentioned in Table 1, along with some details supporting the representation and functional assignments of the last two columns of the table.

Input

There are now many results from brain imaging as to the amplification of activity in relevant lower level cortical areas when attention is applied in a particular visual task. There is also detailed single cell evidence as to how receptive fields are modified by attention, such as the increase of the amplitude of the response of an orientation-sensitive V4 neuron under attention, with the width and mean of the tuning curve remaining unchanged (McAdams and Maunsell 1999).

Table 1 Tabulated support for the basis in the brain of the various control modules in Fig. 1

Module	CX site	Timing	Representation	Function
IN	V1–V4	50 ms C1	Features	Earl proc
OBJ	FG	170/400	Columns	Semant
IMC	IPS/TPJ	200 N2	Spa/Obj	Control
WMSens	Par	300	WM map	Report
WMcd	?	?	CD	Hold CD
Goal Exog	VFC	120–140	Spa/Obj	Exog
Goal Endog	8/9/46	For task	Spa/Obj	Endog
MON	CG	ERN	Error	Correct
VAL	AM/OFC	100/130	Sem/Act	Valence

Object

Again there is now considerable evidence from brain imaging for the existence of sites coding for various object representations acting as sites of semantic memory. These can be activated without attention, such as observed in the attentional blink or by masked stimuli, leading to later priming of semantically related stimuli.

IMC

There is now also considerable evidence that there is separation of functionality of the attention in the brain into: (a) a controlled region (the spatial and object maps mentioned above) and the earlier feature analysis modules (such as in V1, V2, V4) and (b) a controlling region, the source of the control signal to the controlled region. Thus it was written in a recent review that ''Attention-related activity in frontal and parietal areas does not reflect attentional modulation of visually-evoked responses, but rather the attentional operations themselves.'' (Kastner and Ungerleider 2001). This same result has been noted in other more recent reviews.

There is also clear evidence from multi-unit activity recordings that the amplification of V4 and V2 cells arises from feedback from a higher area (Mehta et al. 2000).

Thus there must be at least a module or network of modules acting to produce the control signal achieving the modulation of lower-level activity mentioned above.

WM sens

The evidence for this module is based on considerable psychological evidence in terms of the working memory theory of Baddeley and colleagues (Baddeley 1986). There has more recently been considerable justification of this theory in term of the existence of the phonological store and the visuo-spatial sketch pad. In these sites activity is observed to be continued for a certain length of time, of the order of 1.5 s (for the phonological store from psychological results (Baddeley 1986)). At the same time there is a further component of the working memory (WM) system in the prefrontal cortex, which enables subjects to hold activity over the full period needed for a task—sometimes for up to 60 s or

more. This continued activity has been observed both by brain imaging methods as well as by single cell recordings in monkeys. More recent results have begun to explore the relation of working memory capacity and response capabilities (Todd and Marois 2004; Vogel and Machizawa 2004).

WMcd

This module is the only one of those in Table 1 for which there is presently little evidence for its existence. The main property required of this module is that it should hold a copy of the attention control signal from the IMC in order to help amplification of the input stimulus representation on the WMSens as well as be used as a fast error generation signal in the MON so as to prevent error. It is this latter function that plays an important role in the AB, providing a mechanism for increasing the activation on the IMC, and thereby speeding up the movement of attention to the desired site. This is a role that has been emphasised and shown to be carried out in motor control, using a corollary discharge of the appropriate movement control signal. There is much less evidence of the existence of such a signal in the case of attention. Data in support of the existence of this module arises from the existence of an early signal arising in the re-orienting of attention, at about 200 ms after stimulus onset (Hopf et al. 2000). This signal has two components, one in SPL at 180–220 ms, and on in TL at about 240–280 ms. Similar results were reported in Ioannides and Taylor (2003). There are also many recordings of 'expectancy' and 'readiness' signals during the same period in language processing. However none of these show that the related signal is that of a copy of the relevant attention movement signal. The evidence from Sergent et al. (2005) will be reported below.

Exogenous goal

There are now results from brain imaging methods indicating that rapid stimuli can access the attention control signal by means of the ventral route (Corbetta and Shulman 2002). This route is also related to the valenced limbic system, as to be expected from the need to provide rapid valuation to help determine the break-in of any sudden stimulus into the attention control signal, over-riding whatever is presently at the centre of attention. Also loss of ventral prefrontal cortex can lead to increased distractibility, so implying that ventral prefrontal cortex ix the site of exogenous goals.

Endogenous goal

There is similar data to that reviewed in Corbetta and Shulman (2002) indicating that endogenous attention is now mainly thought to function by the dorsal cortical route. In particular the loss of prefrontal cortex is well established as causing deficits in keeping to attention goals, due to increased distractability. Thus there is strong evidence that the dorsal prefrontal cortex is the site of goals being able to be held by the working memory system mentioned earlier. The case of Phineas Gage (who lost considerable prefrontal cortex in a railway accident, and subsequently became very difficult to employ due to his instability and inability to hold to his goals for work or social interactions) is well known, and is in support of the existence of goal sites in prefrontal cortex (both dorsal and ventral).

Monitor

There is good evidence that this exists as a separate module, and is placed at least in the cingulate cortex. The mode of action of this error system has so far been considered solely in the domain of motor control. Here we extend such a function to the case of attention.

Sensory-motor attention processing

It has been suggested by Rushworth et al. (2001a, b) that there exists a distinct mechanism of motor attention localized in the anterior parietal cortex. This mechanism involves premotor areas that control limb movements, and parietal areas, such as the SMG, where effector-centred, rather than head-centred, visuo-spatial representations can form. Rushworth and colleagues found motor attention-related activity not only localized anterior to the area concerned with orienting, but also somewhat lateralized to the left hemisphere, as compared to visual attention control more lateralized to the right hemisphere and in the angular gyrus of the parietal lobe.

An extension of a simplified version of the above control system to include motor attention is shown in Fig. 2 (Taylor and Fragopanagos 2003); for simplicity the new control system has been shown without the buffer observer modules described above, but only contains ballistic (feed-forward) control components.

In Fig. 2 we assume that in the pathway from the visual input-to-motor response there are three stages of processing, which involve visual attention (deciding where/what to attend to), motor attention (specifying

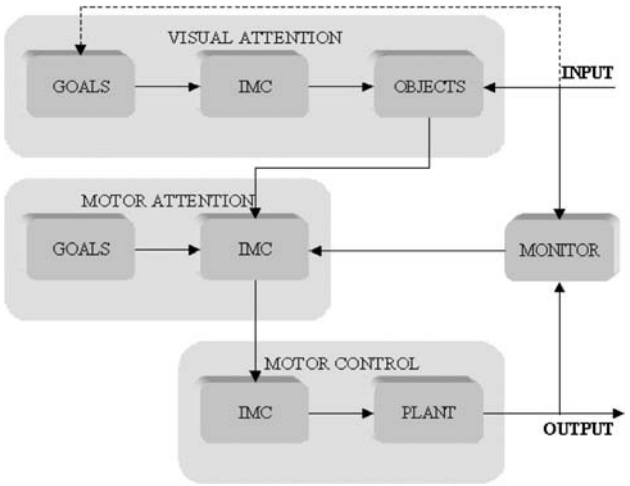

Fig. 2 A model of sensory-motor attention control. The model consists of a ballistic-type of visual attention control model plus two concatenated such models for motor control, one (the ballistic motor attention control model) controlling through its output to the lower-level motor ballistic control model at the level of the latter's IMC (thus singling out the motor plans to be selected, these plans being at the plant (muscles) level

where/what to act on) and automatic motor control (implementing the attended motor action).

The model is an extension of the earlier sensory attention control framework of ''The control approach to attention'' section to motor attention. In more detail the modules are:

1. The inverse motor attention model controller (IMC) module: This module receives the object data selected and amplified in the visual attention processing stage and combines it with motor response, in order to guide the motor control IMC. It is biased by the associated motor attention goals module (distinct from the visual attention goals module) and monitored by the monitor module so as to learn the appropriate visuo-motor responses.
2. The motor attention goals module. This module contains relevant visuo-motor combinations according to the rules of the task and is used to bias their learning within the IMC.
3. The monitor module: This module checks for errors by comparing the motor output with the visual input, and then sends a training signal to the IMC which increases the learning when the error rate rises and decreases the learning when the error rate falls.
4. The inverse model controller (IMC) module: This module is driven by the motor attention IMC via control signals that correspond to the motor response selected in the motor attention processing stage, which it translates into a motor command that controls the motor plant.
5. The plant module: This module is the controlled motor cortex/spinal chord motor signals of the motor system.

The model of Fig. 1 was used to simulate two sensory-motor attention paradigms (Taylor and Fragopanagos 2003). The first of these (Rushworth et al. 1997) is a choice reaction task, which requires subjects to make different responses to different visual stimuli. The second paradigm (Schluter et al. 2001) concentrates on a motor preparation task, determining the benefit in reaction time that attended valid motor responses gain compared to invalid ones (where change to an expected valid response must be made). The effects of left or right hemisphere parietal lobe deficits were also determined in the second paradigm from patients with relevant deficits. Both simulations achieved reaction time values close to experimental values.

We note that the sensory motor model of Fig. 2 is still incomplete, due to the absence of any forward model of prediction for a future sensory state given the present one and an action. This component gives a different fusion between sensory and motor processing than that in Fig. 2, but importantly provides, with an additional monitor component, information allowing the forward model and other internal models involved to be learnt through experience (as does an infant). A possible such architecture is shown in Fig. 3.

In Fig. 3 there is a forward model FM(a, m) (a, m denoting attention to motor) which accepts action attention outputs from the motor attention inverse model controller IMC(a, m) (as a proposed motor control signal) as well as inputs from the visual WM buffer. The output form FM(a, m) is then a predicted attended visual state of the attended stimulus. This can access the error module, used to help train the various modules, as well as be returned to the visual WM buffer to provide further recurrence if a sequence of visual states is being imagined. There are also the visual attention IMC module, denoted IMC(a, v), the input 'Plant' of low-level visual cortices and also the higher level semantic representations of objects; these various modules were all already present in the CODAM model in Fig. 1.

There is strong support for the sensory-motor attention model in Fig. 3, which is presently being simulated in various motor action paradigms in the GNOSYS and MATHESIS EC projects. Extensions have also been made to the architectures of Figs. 1–3 by addition of value maps based on TD-learning,

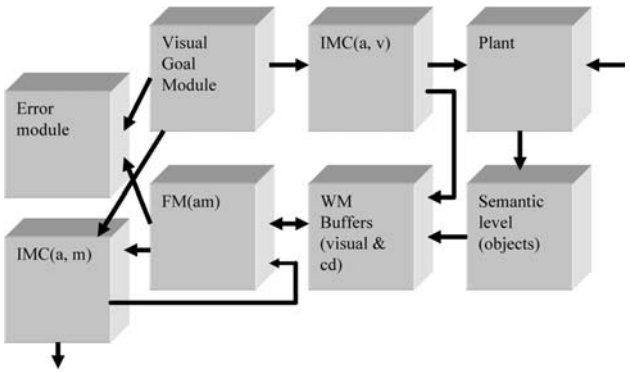

Fig. 3 The sensory-motor attention control system. This extends the ballistic-level model of visuo-motor attention in Fig. 2 to include the attended visual state estimator used to pass information on to the forward model (FM) that enables the prediction of the change of the attended visual state of an attended stimulus after a given action (generated by the IMC for attention actions denoted IMC(a, m) in the figure

suggested as arising from the combination of VTA, OFC and the amygdala.

The CODAM model of consciousness

It has been proposed (Taylor 2000, 2002a, b, 2003a, b) that the corollary discharge buffer WMcd, in Fig. 1 is a crucial element in the circuitry to create consciousness. There is support for the presence of such a corollary discharge component in the overall attention control circuitry by analogy with motor control, from the evidence for predictor modules for such control (Desmurget and Grafton 2000; Sabes 2000; Wolpert and Gharahrmani 2000). We therefore introduce the WMcd module as a crucial component to give the sense of ownership in conscious experience; the module is a crucial pillar in the CODAM model of the creation of consciousness (Taylor 2000, 2002a, b).

We require there to be an inhibitory process between the observer, WMcd, and the sensory buffer, WM sensory, in order for there to be an action of the corollary discharge signal to ensure only the attended stimulus activity from lower cortices accesses the WM sensory, so leading to the crucial property of 'immunity to error through misidentification of the first person pronoun' (Shoemaker 1968). This error-free character resides in the certainty of correctness of the claim by a subject that they were sure they had had a particular sensation. Thus you cannot ask someone 'Are you sure it is you who is in pain' if they say they are in pain. You just have to accept this claim. The 'I' has been so constructed in the human psyche that it is able to be sure of its knowledge; it has immunity to being wrong (although it can be about more reflective knowledge, such as possessing a beard or moving a limb: these could all be faked by an evil outsider. Thus the 'I' is sure of the fact that it owns the contents of its experience, not what they imply about its 'selfness'.

Further detail has to be given as to how processing in the observer/buffer/monitor sites can lead to such a highly crafted consciousness. This has been outlined in Taylor (2000, 2002a, b, 2003a, b): the initial corollary discharge signal on WMcd, when arriving there, creates an expectation (a signal of ownership) of future input from the relevant sensory cortex, and provides support to the signal from lower cortex trying to access the sensory buffer. The latter is amplified over some 100 ms or more (Mehta et al. 2000), so as to be able to overcome inhibition from previous input activations in various sites, especially the WM Sensory buffer itself. When the amplified cortical signal becomes large enough, it can overcome the barrier to its entry to WM Sensory, so that awareness of the input is then supposed to arise (Taylor 1996, 1999). The activity on WM Sensory then also inhibits WMcd, so as to be able to be used for the next target. However before that occurs, awareness of the attention movement itself has arisen, as the experience (by the signal on WMcd) of ownership of the about-to-arrive content. The gap between the pre-reflective self of Western phenomenology and Eastern Buddhism and the content-full consciousness of Western cognitive neuroscience can be bridged in this manner, as explored more fully in Taylor (2002a, b).

Evidence for CODAM: temporal flow

The crucial component of the architecture needed for CODAM, beyond that elements already known to be present (sensory, IMC, goal, monitor and WM Sensory modules), is the buffer site WMcd. There are already preliminary hints for the existence of the related corollary discharge (CD) early signal noted in Ioannides and Taylor (2003), as well as new data presented there, and the data of Sergent et al. (2005). A brief overview will be given here of the temporal flow of activity in the brain, based on EEG, fMRI and MEG data (Hopf et al. 2000; Luck et al. 2000; Shapiro et al. 1997, 2002; Chambers et al. 2004) and a number of related sources.

A sequence of peaks and troughs are observed post-stimulus in averaged EEG brain signals: P1 (80–120 ms)/N1 (140–180 ms), N2, N4 (300 ms), P3 (300–500 ms). The functions of these various components is still controversial but some agreement is being reached as to what each of these is doing in overall processing, especially under attention.

The P1/N1 complex has been found to be modulated under attention in paradigms in which attention has already been directed to a given stimulus or position in space. However the results of electrode probes in monkey brain (Mehta et al. 2000) indicate that this early activity, thought to arise in lower visual cortices, is not the source of any attention control signal, Under exogenously driven attention the latter feeds back to V4 and then V2 (and only a small signal to V1).

The P1/N1 complex is attenuated for extinguished as compared to consciously observed contralesional stimuli on bilateral trials in extinction patients. Also in the attentional blink (AB) (in which there is a rapid input of the second of two targets, T2, during the 'blink' period when the first target, T1, is being processed) there is unattenuated P1/N1 or N400 for various T1/T2 asynchronies, although the N2 and the P300 were strongly reduced during the blink (Luck et al. 2000; Shapiro et al. 1997, 2002). Altogether these experimental facts support the position that the P1/N1 complex arises from processing in low-level cortical sites which are able to be modulated by feedback attention signals but which do not create any attention signals in their own right (other than allowing passage of input activity to higher stages where that could occur). Modulation of the P1/N1 signal only arises from higher-level attention feedback signals.

The N2 signal is known to have parietal-occipital and temporal lobe generators. There has been particular interest in the N2pc (denoting the N2 posterior contralateral signal), which is observed in symmetrical visual displays when the ipsilateral activation is subtracted from the contralateral one in a target search paradigm, for example. In such a paradigm there can be observed an increased negativity on the contralateral side which is the N2pc, thought to arise from either inhibition of distracters or from amplified attention to the target (Woodman and Luck 1999; Eimer 1996) or both causes. Various manipulations have been performed on stimulus presentation paradigms which explore the N2pc further, such as applying TMS to different sites in the brain during target search; application to right posterior parietal cortex causes considerable reduction of the N2pc signal (Fuggetta et al. 2006). There is also interest in the sustained posterior contralateral negativity (SPCN) (observed between 300 and 500 ms post-stimulus), which is now considered as involving preparation of attended material for entry into the buffer WM (Jolicoeur et al. 2006). The SPCN was also completely suppressed during the attentional blink (Jolicoeur et al. 2006), and has been suggested as also being involved in consolidation into the sensory working memory buffer, so in a similar manner to the posterior N2 and P3 signals.

The conclusion on ERP functionality, from a variety of paradigms in healthy individuals, is as follows:

1. P1/N1 involves initial low-level hierarchical bottom-up pattern processing (with various sources of the P1/N1, both posterior and anterior).
2. N2 arises from early attention processing; with preparation of material to access the buffer WM for report, especially involving separation of targets from distracters.
3. N4 arises from semantic spreading, and is related to more general object map activation that can occur outside attention.
4. P3 and the SPCN arise as part of attention-amplified access to buffer working memory sites for higher processing.

A recent MEG study (Hopf et al. 2000), performed during a conjunction search paradigm, has shown important structure and topography in the N2 signal. It was found to consist of at least two components: an early parietal source (180–200 ms) and a later occipito-temporal source (220–240 ms). The first is consistent with activation of IMC to move attention; the second is involved with object/feature analysis. The crucial CODAM signal is that of the WMcd refreshment during movement of the focus of attention, which have been seen already in the N2 signal. The site of the WMcd access signal is unclear.

There is also a wealth of TMS-based data arising from various attention search paradigms (Chambers 2004, 2006; Fuggetta et al. 2006). These are now helping clarify the complex attention processing being carried out by the parietal lobes at the early stage (100–300 ms post-stimulus). This data has still to be expanded to give a complete analysis of the flow of information round the various parietal and prefrontal components, and thereby allow updating of the CODAM model.

The CODAM model has been applied to the attentional blink (AB) paradigm (Luck et al. 2000; Shapiro et al. 1997, 2002). The AB arises, as noted briefly earlier, in the case of rapid serial visual presentation, with about a 90–100 ms gap between stimuli. There is a maximum lose of the ability to detect a second target, T2, in the stimulus stream (such as a white letter), about 250 ms after the correct initial detection of a first, T1, such as a white X (Shapiro et al. 1997). The N2 signal is lost in the AB, as is the P3, while the N1 and the N400 are preserved.

We note that the existence of the AB depends on the presence of a mask M1 for T1 and a mask M2 for

T2. Thus if there is no M1 there is then a much reduced AB, while there is no AB if there is no M2 (although the processing of T2 to report is delayed in terms of a later P3 being observed for it). This implies that the 'scarce resource' or 'bottleneck' character of attention is especially arising by masking, where M1 in particular causes severe distraction to T1 detection leading to the AB. We therefore need to protect T1 against M1 damage, with resulting greater inhibition of T2. Such a mechanism arises naturally in CODAM if the monitor is used to feed back an early error estimate, equal to the difference of the goal activation level and that of the WMcd. This provides an extra resource to the incoming input T1 to attain its sensory buffer. The resulting CODAM simulation of the AB (Fragopanagos et al. 2005) leads to good agreement with AB data in association with masking.

In more detail of the simulation, the goals for T1, T2 are separated into two distinct nodes for each target: one for the exogenous bias of attention (identical to the masks' goal node), and one for the endogenous bias of attention. The latter is fed a constant pulse with amplitude of 5% of that of the input pulse (which drives the exogenous goals), and starts before any stimulus onset and lasts for about 2 s. The two nodes for the endogenous bias of attention for T1 and T2 are not allowed to be active at the same time, by requiring the endogenous T1 goal to inhibit the endogenous T2 goal until the endogenous T1 goal is turned off by a signal that arises from the T1 WM sensory buffer activation crossing a near the peak threshold (so when T1 has gained access to the sensory working memory buffer). This access occurs at about 500 ms from T1 stimulus onset (for the parameter range used in the simulation).

The output of the endogenous and the exogenous goals for each of the two targets is added together to jointly bias the IMC, through the monitor module. This latter module compares the endogenous goal activations for the two targets with their corresponding corollary discharge activations. It captures the endogenous goal activations only at the interval that the exogenous goals are active and buffers them to compare with the corollary discharge activations that follow. The difference of the two signals—the error signal—is used to compensate for damage from distracters, and especially to protect the targets T1 and T2 from further damage from the following incoming stimuli by being fed into a self-recurrent neuron. That spreads inhibition onto all the nodes in the IMC, apart from the target node under protection. In the case of T1, in particular, the nodes that will be inhibited by this protector neuron include the secondary target T2, which at that time poses a potential threat to T1's further processing. This inhibition lasts until confirmation arrives from the WM sensory buffer that the target has reached a significant level of activation, i.e. awareness.

The discrepancy for the T1 monitor node is constant across the lags because it only arises from the deterioration of the IMC signal caused by the battle (in the IMC) with the mask M1. On the other hand, the discrepancy for the T2 monitor node varies across the lags and depends on the level of (endogenous) goal activation that T2 has been allowed to have (by the inhibitory mechanism with the T1 goal node described above) and the level of corollary discharge activation that survives the inhibition caused by the WM sensory buffer activation of T1. For the parameters chosen for the simulation, the difference between the two signals is almost zero for those lags and doesn't elicit an error signal in the monitor.

Important results arising from a recent EEG study of the AB (Sergent et al. 2005) has led to considerable support for the CODAM model, and in particular for the identification of the attention copy signal claimed present in the architecture in Fig. 1 with a component of the well-known N2 signal in EEG (as already discussed above, conjectured already in Taylor (2002a, b), and even earlier considered in terms of a 'breakthrough to attention' in Taylor (1996, 1999)). Let us consider this data to appreciate its importance for CODAM.

The results of Sergent et al. (2005) shows clearly the presence of inhibition from the N2 associated with the second target in the AB affecting the P3 of the first target T1 when the inter-stimulus gap between T1 and T2 is about 270 ms (so at the height of the blink). This inter-target time for the maximum AB effect fits nicely with the mechanism basic to CODAM (Taylor 2003, 2005), and was also the foundation of the simulation of the AB in Fragopanagos et al. (2005). The essence of the CODAM model is that the first target T1 is completing its access to its buffer WM site to allow its content to be reported to other sites or relevance to use this attended content at about the peak of the P3 of T1; this happens perhaps at about 450 ms after T1 onset. However the N2 of T2, commencing at about 200 or so milliseconds after the onset of T2, will attempt to inhibit this interloper (at least as seen from T2's point of view). This is detected by the reduction of the P3 for T1 when the time interval between T1 and T2 is set to obtain a maximum AB effect, at about 250 or so milliseconds post-T1 onset. This supports the explanation of the AB by the CODAM model of Fig. 1, since in a reciprocal manner it is posited (Fragopanagos et al. 2005) that T1

will also maximally inhibit T2 through a similar mechanism as noted in Sergent et al. 2005, where the P3 for T2 is zero for those targets T2 of which there was unawareness (and the possibility of T2 becoming aware on some trials is to be ascribed to noise effects in the stimuli, for example). We conclude that this provides good evidence for the proposed temporal flow of activity as evinced in the CODAM architecture of Fig. 1, and discussed in detail in Fragopanagos et al. (2005).

Further support for the CODAM model in the attentional blink has arisen from an analysis of recent MEG data on the blink (Hommel et al. 2006). The main result of this analysis is that there is a high-level bottleneck for access to report of T2, which arises from at least two sites: the tempero-parietal junction and the prefrontal-parietal loop. This bottleneck is related to a variable time window of opportunity for a stimulus to access the buffer site for report, depending on the target difficulty (masked or not, for example) and on the nature of distracters present. These results fit nicely into the CODAM framework, where the length of the window of opportunity in CODAM is determined by the level of the error monitor signal to the IMC and the buffer site to protect the target processing as well as to speed it up. There are various speed-up features, depending on masks and distracters, noted in Hommel et al. (2006) which fit very well into the CODAM framework. Moreover the prefrontal lead in the creation of the P3 signal as observed by MEG (Hommel et al. 2006) again fits well with the CODAM style of use of goals to monitor for completion or error, and in particular leads to the expectation of an early prefrontal T2 goal signal to indicate the processing of T2 has been successful. However much still needs to be done in the construction of the CODAM model, both for the attentional blink and attention search more generally, to give clear-cut agreement to experiment.

The temporal dynamics of consciousness creation

Let us now turn to the more specific topic of the paper: the temporal dynamics of the creation of consciousness. What can we conclude about this from the above discussions and evidence. There are a number of questions of relevance here. Does consciousness of a stimulus arise only when the P3 has been attained on the buffer WM? Or is there a 'pre-conscious' period, when consciousness is beginning to be experienced? If so, what is the nature of that experience?

There is a large body of descriptive knowledge which is relevant to these questions: that of the Pure Conscious Experience (PCE) in meditation. This has already been related to the CODAM model in Taylor (2002a, b). In particular we used two especial characters of this fusion: (1) the 'stillness' or 'content free' character of the PCE and (2) the ability to explain through CODAM how attention could develop a prefrontal goal state in which all content was inhibited from entering awareness. Thus the state of the CODAM-type of attention control system in a mediator's brain in the PCE would be content-free, involving a temporally extended activation of the corollary discharge buffer, which from the data described in the ''Evidence for CODAM: temporal flow'' section only lasted for a hundred milliseconds or so.

For the above process to be accepted, considerable temporally sensitive brain imaging, using both fMRI, EEG and MEG, is needed to tease out the spatial and temporal distributions of activity in the various predicted modules of Fig. 1 as the PCE state is developed over the periods of meditation. Let us assume that this has been done (and it is now moving on by the use of TMS in conjunction with these brain imaging techniques, as described in the ''Evidence for CODAM: temporal flow'' section) and the CODAM model of the creation of the PCE state is validated, at the same time giving more detail to the interaction between the component modules of Fig. 1. This model implies that, in normal experience of the external world, the pre-reflective self is thereby experienced in a brief flash (perhaps for 100 ms or so) of content-free 'ownership' of the about-to-appear content, as evinced by suitable components of the N2 EEG ERP signal. Contentful experience of content will then arise at about 450 ms, as evinced by the P3 (and noting that the P3 disappears in the case of the attentional blink, Vogel et al. 1998).

We have thus given a specific model for the creation of consciousness. It involves two phases in time:

(1) The pre-reflective period (the 'ownership' period, with no content);
(2) The content period (when the owner has the content of the expected experience filled out).

These two periods are in general lasting over a total time of about 500–600 ms (depending on the complexity of the incoming attended stimulus). Such a sequential process begins to meet the task faced by the Western phenomenologists who have teased out the pre-reflective self most ably from the contentful experience (Zahavi 1999), but who could not answer how the pre-reflective self, the 'I', could interact with the external world to create a fully fledged consciousness experience. This problem was side-stepped by appealing to the 'body', as a source of a 'core' self, which

would allow an infant brain to latch onto the signals arising from its body to create a more complete sense of self.

We have to face up to serious problems with such an approach, which we will explore below. It involves aspects of the temporal dynamics of bodily processing, as well as various difficulties arising from defects of proprioception. We will turn to these next.

I and my body are distinct

General

The claims of phenomenology, that body and the pre-reflective self are one, requires that there be three different sorts of mental states:

(1) Those outside consciousness, involved in unconscious, automatic processing.
(2) Those mental states involved in the creation of conscious awareness of content.
(3) Mental states involving bodily processing of proprioceptive feedback that are outside content consciousness, but of which there is awareness of a pre-reflective kind.

Let us consider experimental results relevant to this claimed third body state. One way to observe the third state would be by investigating any deficits possessed by those without various forms of kinaesthetic or proprioceptive feedback. They would be expected to be lacking in some of the experiences of normal subjects. The pre-reflective self is regarded as important for consciousness. If it is at the very basis of consciousness, such that without it there would be no consciousness of content, no experiencing, then their conscious experience should be severely compromised. So also should their ability to respond to various movement responses. Let me turn to discuss evidence on movement first, before considering the effect of the loss of kinaesthesis/proprioception on experience itself.

One experiment indicated no difference between a de-afferented subject and other subjects without such a deficit (Bard et al. 1999). The task was to guide the upper extremity of a 1.5 m pointer, mounted on a universal joint on the floor, rapidly from an initial position close to their body to a target position about 30 cm away. The target position was indicated by a green LED, at one of several positions. Initially the subjects fixated a central light, simultaneously with a peripheral LED turning on. The subject then made a saccade and moved the tip of the pointer as rapidly as possible to the target. In some target movement trials, the target LED was switched off when the eye reached one-third of its trajectory (near the peak of saccadic suppression) and an adjacent LED, 6° away, was switched on. The subjects were able to correct the movement of the pointer, without awareness of the target switch. If the movement was required to be directional then either an early correction occurred (by the occurrence of peak velocity of the movement) or no correction; if the requirement was also for a correct amplitude of the overall movement, then there could also have been late corrections.

The experiment showed the importance of feedback from the saccadic movement in reprogramming the movement of the pointer, at about equal levels of accuracy in the de-afferented subject and the others. In other words, the eye kinaesthetic signal (in the notation of Gallagher 2000) played a crucial role in the correction process outside consciousness. And it occurred at about an equal level in the de-afferented subject and the others.

The site in the brain involved with the automatic correction process was shown, in a separate experiment (Desmurget et al. 1999) to critically involve the posterior parietal cortex (PPC). A similar double-step perturbation paradigm was used. It was found that TMS applied specifically to the left posterior parietal cortex during the target jump, disrupted the path corrections to moving targets, but had no effect on those directed to stationary targets. The authors concluded that after the completion of the saccade, the central nervous system refined its estimate of the target location based on combined input from the retinal and extra-retinal signals. Concurrently, dynamic proprioception and efferent copy signals were linked together by the PPC to estimate the location of the hand. This structure then compared the two spatial codes and computed the motor error, subsequently used by the motor centres to update the ongoing trajectory. Thus proprioception was involved in the overall process, but the experiment of Bard et al. (1999) indicated that it was not crucial, but only helped to improve accuracy of the overall automatic correction process. There was no hint of any pre-reflective self in the automatic movement corrections, yet the subjects possessed proprioception and kinaesthetic feedback as critical components, especially the latter. So where is this extra state? It is silent in the experiments discussed so far, in which it should have emerged as a critical feature.

Where is the third state?

A further experiment is of crucial importance in determining if there is a third state of the body. This

state would be expected to show itself at some point in the overall control processes of movement control. A recent experiment searched for the 'automatic pilot', observed in action in the previous experiments (Bard et al. 1999; Desmurget et al. 1999), but now switching between automatic and controlled responses (Pisella et al. 2000). These authors investigated the ability of the automatic component to resist voluntary control during a pointing action. In any struggle between the two extreme states, the third state would be expected to show its presence in some manner, if it exists.

The subjects had two sets of paradigms, in one they were instructed to point to a green light. This remained unperturbed in 80% of cases, but jumped to the right or left (triggered by movement onset) in the remaining 20%. In the other paradigm it was the colour that unexpectedly changed instead of the movement perturbation. The subjects were advised as to whether the paradigm was stop or go. Those in the stop group had to stop their hand movement immediately they observed a perturbation of the target; those in the go group were asked to correct their movement in the presence of a target perturbation. Thus there were in all four sort of trials: location stop or go, and colour stop or go.

In the location stop trials, there were a significant percentage of corrective movements, despite the stop instructions. After touching the displaced target, it was noticed by the authors that subjects were aware of their mistakes, spontaneously expressing strong frustration. Motor corrections were then made to the new target location. Moreover the earliest corrections in both the location-go and location-stop groups of trials had almost identical timing, and so appeared to arise from a common, automatic, visuo-motor control system (outside awareness). There was a later pool of corrections in the location-go group, beyond the early temporal window of 200–240 ms. This was considered by the authors to have been intentionally produced. There seemed to be no other peaks in the histograms at which corrections were observed. No third state, a conclusion that further analysis of the distribution of movement times supported.

The results for the colour-go and colour-stop trials supported this further. The colour-go had a only a single peak in the distribution of movement times, at about 400 ms, so of controlled form. There was complete control of the movement of colour-stop subjects, by about 280 ms. This again supports the absence of any intermediate control system: only controlled processes could use the colour signal to cause either a perturbation or a cessation of the movement.

To justify the automatic feature of the location trial controls, a subject with loss of bilateral posterior parietal cortex was also tested in the four different movement perturbation trials. The subject had very few fast movement corrections for the location-go condition; however they could produce no corrective responses in the location-stop condition.

Altogether the results of this experiment show the presence of only two states of the body, or two control systems: an automatic, fast one, outside awareness, and a controlled, conscious, slow one. There is no hint of a third system used in control. Nor was there in the experiments reported earlier. Either the experiments are not sensitive enough, or there is indeed no third body state. In the first case more experiments need to be performed, but there is no hint as to their nature. Indeed the motor control approach (Sabes 2000; Desmurget and Grafton 2000; Wolpert and Ghahramani 2000; Miall and Wolpert 1996) gives no hint of any need for such extra control structures in motor control, across a broader range of experiments than the three discussed so far. That is a strong argument against the third body state, and associated control structures.

There are further points that indicate difficulties for the 'body is I' thesis, which I will develop in the next sub-section. They are concerned with imagination, and its differentiation from actual motor movements themselves.

They know not what they do

Imagined movements have been thought for many years to use the same brain circuitry as the real thing. However a recent study of a bilateral stroke subject CW (Schwoebel et al. 2002) has discovered that he cannot prevent his imagined hand movements from making the actual movements themselves, even though he has no awareness of such movements. This implies that it is possible to remove the inhibitory signals, normally present when imagined movements are made, so that they become actual. There must therefore be at least some separation of the region involved in actual movements and those in their imagined version. This helps understand how it is that imagined movements can be distinguished from the real thing, otherwise there is a puzzle if the circuits for both sorts of movements were the same.

However there is more to the story of CW. It was discovered (Schwoebel et al. 2002) that he was more accurate for his left hand in making imagined movements than the real thing. When asked to touch

his thumb to a particular finger, for example, he made more mistakes when trying to make the movement than when he was asked to imagine it. The results is strange if looked at as the difference between making a simple motor act (as an actual movement) and making an imagined one (which is also a real movement for CW). For the imagined one is only expected to be the real one plus an extra inhibitory signal to prevent the real movement being made. How could there be a difference in accuracy between the two?

It was suggested in Shwoebel et al. (2002) that the difference (in the accuracy of the imagined and real movements) arises by the motor system using a forward model. A forward model is an estimator of what is going on in the target system being controlled, and was introduced in the architecture of Fig. 3. This forward model can help produce more rapidly estimates of feedback errors than would arise by waiting for actual feedback from the target system. The forward model contains information about the muscles, limbs and joints, essentially the proprioceptive/kinaesthetic information discussed earlier, and the basis of the claims about the 'body is I' thesis under discussion there. Thus the case of CW is highly germane to the present discussion.

Indeed, Shwoebel and his colleagues suggested that the difference between the imagined and intended movements arises due to impairment in the system computing any error between the predicted movements and the actual sensory feedback. If the latter actual sensory feedback is absent, although the predicted target values are not, then there will be error in the actual movement. This is not the case for purely imagined movements, so explaining the accuracy of the imagined movements themselves.

This is further support for the existence of engineering control-style models (forward and inverse models) for motor control. The relevance of these models is that they depend crucially on proprioceptive/kinaesthetic feedback to function effectively. As seen in the case of CW, this is a case when such feedback becomes unavailable due to stroke. This is supported by the study of illusory volitional movements, such as reaching for objects or waving goodbye, of the phantom limbs of amputee patients Ramachandran and Hirstein (1998). These authors claimed that it is likely that these movement commands were concerned with body image. In a normal person, messages from the frontal lobes are sent either directly, or via the cerebellum, to the parietal lobes which monitors the commands and simultaneously receives feedback from the arm about its position and velocity of movement. For phantom limb experiences, the monitoring of motor commands would still be expected to occur. In this way such experiences of the phantom moving in its various ways could arise.

Another experimental study (Fourneret and Jeannereod 1997) indicated that subjects have limited awareness of the signals generated by their own movements. The experiment required a subject to draw a line on a graphic tablet connected to a computer. The subject saw, in a half-silvered mirror, a version of the continuous line they were drawing to a target, after the actual line they were drawing was modified, by a small sideways shift to the left or to the right, by the computer. If the subject drew a vertical line, then the line they saw was slanted a certain number of degrees to the left or right of the vertical. They also drew, with their eyes closed, a copy of the line they had previously been drawing. There were a variety of responses by various subjects performing the task, but in all cases normal subjects appeared to be poorly, if at all, aware of the details of their motor performance and were unable to correctly consciously monitor the signals generated by their own movements. What appears from this study is that any kinaesthetic/proprioceptive feedback does not play an important role in the conscious experience of the subjects' movements, and especially these signals are not available to conscious monitoring.

Altogether the control manner in which proprioception/kinaesthesia is used has become clear, and is supported by many abnormal case studies and their detailed investigation, as well as by comparison with normal subjects. In general such feedback provides an important early signal to speed up response, and prevent errors occurring. Especially the early copy of motor control signals are heavily involved here, as well as derived estimates of sensory responses arising from the motor commands leading to actions to be taken. The later sensory feedback is then combined with their previous estimates to produce slightly later and updated motor command signals taking account of any unexpected changes in the environment or in the motor response system.

The above picture begins to fill in the processing sequences involved in what was incorrectly termed (Zahavi 1999) 'immediate self-sensitivity'. In actuality, this 'self-sensitive' feedback arises initially sequentially from a copy of the motor control signal. There is then updating of the estimated sensory feedback by the actual values.

So far the picture is clear of how information flows in the various networks involved with motor control in the brain. There is no separation of the feedback

signals from those arising from forward models. Thus the kinaesthetic/proprioceptive signals have no special purpose or circuitry. Nor do they show up in giving any third route in timing of motor responses. There does not appear to be any intermediate state between consciousness of a body state and it being completely automatic.

Let us now turn to consider a more general approach, considering if there are fundamental, more theoretical, arguments against the thesis of 'body is I'.

The body as centre of consciousness of the world?

Can the body really function in the way desired of it by phenomenology, as the basis of the pre-reflective self? Or are there already basic reasons why it cannot, in addition to the experimentally based considerations of the previous section? To obtain an answer we have to go back to the nature of the inner self or PRS as arising from writings of the continental phenomenologists (Zahavi 1999; Gallagher 2000). Most importantly in these references inner self is proposed as intrinsic, non-relational, and with no content other than ownership. These properties are counter to the contents of the signals of kinaesthesia/proprioception. As we have seen in the previous two sections, these signals are full of content, about the estimated or actual values of sensory feedback. Motor signals from proposed limb movements produce expected sensory effects of a variety of forms, such as future or present input in the appropriate modality. These have content, and are relational, not intrinsic. They might consist of the expected level of pressure feedback from a cup wanting to be picked up. They might consist of the expected textural experience in touching a silk dress. Altogether this information cannot be present in a non-relational, non-structured pre-reflective self.

It is claimed that such kinaesthetic feedback is immune to error. But that is clearly false in the case of the subject CW: remarked on earlier: his real or actual feedback is incorrectly used to produce the attended movement that he has been asked to make. Conversely the phantom limb patients make movements of which they are aware but which they never make; the motor command feedback is completely fooling them. It produces estimates of expected sensory feedback. But the movement never happens: they cannot wave goodbye: their arm has been amputated. So it is correct that they think it is they who are moving their arm, but no movement occurs. This is the converse to immunity to error (Shoemaker 1968), but still corresponds to an error in attribution. Instead of being sure it is you who is in pain when you say 'I am in pain', the corresponding case is that you are actually not in pain, in spite of claiming that you are. In this case it is the internal model signals which are leading you into error.

Another aspect of the body, claimed to make it pre-reflective (Zahaiv 1999), is the need for the body to act as the null point or zero of the experienced world. This is supposedly not relational. But that cannot be true. If a point is to be chosen as the zero or origin of co-ordinates for the spatial world of experience, then it has a relation to all the other points in space. It is crucially relational. So again the body cannot be the basis of the pre-reflective self.

These arguments, and the experimental results considered in the previous two sections, show that the body signals claimed as the basis for the pre-reflective self are neither intrinsic nor are immune to error through misidentification. They therefore do not function correctly to be the pre-reflective self. We are left with the need to return to the original version of the creation of consciousness through CODAM: the pre-reflective self is composed of a totally content-free copy of the relevant attention movement control signal, and is not related to any motor control or proprioceptive signal whatsoever. The attempt, for example of Frith (1992) to generate consciousness through motor control signals may be relevant to some aspects of the experience of schizophrenics, but not to the more fundamental problem of the nature of and creation of the pre-reflective self; only through the faculty of attention can a system be employed which has the possibility of re-directing attention to itself, and so leading to the PCE.

The nature of self

The self is complex, with the problem still open as to how the sense of the pre-reflective self is fused with the reflective self to give the sense we have of our continuous internal experience as a person. In order to make progress on this very deep problem we need to tackle the related problem as to how episodic memory carries the tag of 'I': how does this arise? A necessity for long-term memory is attention: without attention there is no episodic memory. The further signals associated with the attention signal are those of the N2 and P3, as discussed in the ''Evidence for CODAM: temporal flow'' section. We have suggested that it is the N2 signal which carries the signature of the pre-reflective self. Does this signal get fused into the episodic memory being laid down in the hippocampus? In relation to this we should take note of a number of recent brain imaging investigations which have

indicated that the reflective self has various brain midline modules involved in coding for the several components in terms of which such a self is reflectively coding, such as personal idiosyncracies, personality traits, etc. The relevant activities in these sites must be fused in some dynamical manner with the activations for the pre-reflective self. This thereby will form an adjunct to the knowledge possessed in these representations to fill out the reflective self so as to imbue that knowledge in some manner with that of the pre-reflective self. It achieves the effect 'I was there' for the event coded in episodic memory. There are not yet simultaneous fMRI and EEG recordings taken when subjects are thinking about their own personal characteristics; these are needed to detect the nature of this division of self into pre-reflective and the reflective component. Without the former the latter has no experiential content for the subject.

Let me go into a little detail as to how the knowledge of 'I was there' may be coded. I suggest that it is in the 'I' of the pre-reflective self-arising from the attention copy signal (as evinced by the N2) earlier in the paper. It achieves the effect 'I was there' for the event coded in the episodic memory. Thus I can remember going to the Royal Ascot horse race meeting some days before completing this paper, not only in terms of the other people I met there and the horses flashing past the winning post (some of which I had a small bet on) but also the fact that it was 'I' who was there. I was at the centre of those events. How can it be that this shadowy part of the self—with no supposed content whatsoever except that of ownership or presence - can intrude in such a powerful manner into memories of the past? These memories are thoroughly permeated with the sense of 'I'. How is that achieved? A similar question must be answered in terms of what is now becoming known about the nature of the interaction of memory and attention.

The pre-reflective self can be fused with the reflective self in a similar manner to the fusion of the contents of an attended stimulus with the pre-reflective self by means of the earlier N2 attention copy signal being used to help create in this case not an attentionally amplified object representation but instead one involving reflective attributes of your self (stored internally). Thus one's image as a picture, with the details of one's beard or general clean-shaveneness, of one's bodily characteristics, of one's general personality characteristics and general quirks, all of these, are now known to be stored in or near midline cortical sites. They can be internally amplified by bringing them into attention focus (by a signal from the attention movement IMC, guided by the goal to call up these characteristics from memory) and thereby brought into consciousness when considering your reflective self. This process has the same temporal characteristics as does the emergence into consciousness of content in external stimuli.

The more difficult question concerns the manner in which episodic memories have fused into them the knowledge that 'I' was there. There are a number of possible mechanisms which could be used to create such a memory of self, able to be re-excited when an episodic memory recall is attempted, among which are:

(1) Initial encoding of the attention copy signal for 'I' as part of the total episodic memory itself (so included in any attractor net in hippocampus through use of 'I' as a critical part of the context).
(2) The automatic (default) inclusion of a tag for 'I' when any attended episode is remembered. Since it could only have been remembered by the early 'wake-up-call' role carried out by the attention copy signal (as explained earlier, and more fully in Taylor 2000, 2002a, b, 2003, 2004, 2005). This corresponds to the automatic re-excitation of 'I' (as an attention copy signal) by any attempt to recall the given episodic memory.
(3) The use of the pre-reflective self-signal for 'I' needs to be turned on in order to be able to re-activate the content of an episodic memory.

Note that there is a crucial difference in (2) and (3) above: 'I' enters automatically in (2), whilst it has to be activated effortfully in some manner so as to be able to re-activate the appropriate episodic memory content.

Let me consider each of these possibilities in turn, and see if any of them will do. In the first mechanism for fusion of the pre-reflective self (PRS) and content of episodic memory, the PRS only enters in a subsidiary manner as context. This latter is at the heart of many approaches to long-term memory, as discussed, for example, in Burgess and Hitch (2005). Such a mechanism treats the PRS as an input arising at the same time as the other contextual features, as well as the main items of the episode. Such coding does not seem to lead to any easy mechanism of regaining the PRS on retrieval of the episodic memory, in terms of any early signal allowing or aiding retrieval of content (as discussed earlier as to how the sense of I is fused with content). Thus it would appear that something more is required to achieve a suitably effective episodic memory.

An automatic encoding of I with content appears to face a similar problem, in case (2) as in actuality does case (3): they both have not specified the relative timing to the coding of elements of the episode. Thus we need to turn to a fourth possibility.

(4) Each of the components of the episodic memory is composed of a pair of sequentially encoded items: firstly the 'I' signal, and secondly the signal of the content, containing both context and main items. The hippocampus is thought to be able to support such short memory chains, especially since this will be no longer than about a second, if that.

It is this fourth mechanism which can be looked at with greatest interest, since it begins to capture the temporal flow of activity of the encoded material from working memory buffer sites, as contained in the CODAM approach to consciousness outlined earlier in ''The CODAM model of consciousness'' section. Thus playback of this material involving the hippocampus will specifically be that of the temporally correct sequence to allow initially for the recreation of the experience of pre-reflective self in the appropriately encoded corollary discharge buffers and shortly thereafter the experience of the content in working memory buffers and their associatedly bound lower-level sites for giving the details of that content in terms of object/spatial and lower order feature map encodings. Thus it is this fourth mechanism that should be regarded as the most likely one to achieve proper encoding of episodic memories.

This fourth mechanism leads to an important prediction as to hippocampal and related activity in episodic retrieval: there should be the proper temporal flow of activity both in and away from the hippocampus during episodic recall. This flow would involve recall of the N2 and P3b components of the incoming episodic material. Analysis of hippocampal activity on recall has been considered using fMRI recently but has not looked in detail at the temporal flow of such activity. Neural network modelling of the hippocampus has concentrated on attractor-type models of the capacity of the CA3 region of recurrence in the hippocampal cell fields, or on the nature of phase recession in place cells during navigation tests as generated by underlying theta activity. None of these and other approaches take any notice of the need to have some detailed form of temporal flow of activity enabling the pre-reflective self to be involved so as to provide the memories being re-activated with the important signal 'I was there during this earlier episode'.

In order to pursue further the nature such activity might take in hippocampus and related areas, we need to go back to data on the distribution of the sources for the N2, and in particular ask if there is any evidence for a generator of the N2 in the hippocampus. The sources of the N2 have been investigated by numbers of groups. A recent study (Praamstra and Oostenveld 2003) has shown there exist separate posterior and centrally localised N2 waves, the first (termed N2pc) being associated with visuo-spatial attentional selection and the second (N2cc) being involved with visuo-spatial selection processes that serve the selection or suppression of competing responses. A study of patients using intercranial electrodes (Clarke et al. 1999) observed a posterior hippocampal N254 which was affected by visual field manipulation but not by task. There were also task-dependent N2 amplitudes in dorsolateral prefrontal and anterior hippocampal sites, among other brain regions. At single cell level the N2 has been observed, among other ERPs, by single cell methods in the hippocampus of awake rats (Shinba 1999). These and numerous other papers on ERPs in a variety of paradigms show the presence of the N2 in a network of brain regions, both cortical and sub-cortical (thalamus, basal ganglia, etc.).

In conclusion the N2 appears to be well distributed in the brain, with some components depending on task stimuli, others only on spatial distribution of the target stimulus. In particular there does seem to be good evidence of hippocampal sites of the N2 in a number of these paradigms, if not all (not all were able to observe the hippocampus). Consistent with, and supported by the data, then, the N2 signal, proposed as the early component involved in the pre-reflective self, appears to be encoded as part of episodic memories encoded in hippocampus.

But we still need to answer the difficult question: How can we relate the proposed interpretation of the N2 signal in the brain with the observed distribution of N2 signals across a network of sites, with possibly different characteristics of each other in terms of sensitivity to task constraints? Of course not all of the observed N2 signals may be relevant, but even with two such signal we have the following more specific questions:

(a) How is the experience of unity of 'I' achieved with such a network of disparate N2 signals?
(b) How is the experience of continuity of 'I' achieved by such a model?

Both questions need thorough answers, which can only be obtained from further experimental data. However an initial suggestion as to unity would be through the presence of a connected network including the specific component of awareness under consideration. Thus the relevant network expected for visual awareness would involve that based on the N2pc, so in the posterior sensory network. For motor somatosensory awareness the relevant network would be expected to be that supporting the N2cc component.

There may be fusion of the two awareness components in fast responses to sensory stimuli; such would help produce the experience of unity. At the same time the experience of continuity would arise through the flow of activity in working memory buffers from a sensory to a motor component N2 network.

Returning to the question of self in episodic memory, it is clear there is enough experimental evidence to expect that the N2 hippocampal component will be incorporated in the overall episodic memory in the manner suggested earlier—as in a temporal sequence of activity, with the N2 component arising first and leading to the P3 working memory buffer component later. Such a model predicts, as noted briefly earlier, that there should be a temporal aspect to episodic memories, with the associated N2 $\rightarrow$ P3 sequential flow required to provide the full richness of the conscious experience.

Finally we should add that there are numerous cases of hippocampal deficit where awareness of stimuli does not seem to be severely damaged, but episodic memories of ongoing events are completely lost. There is even one famous case, that of Clive Wearing (2005), who had lost the ability to lay down any new episodic memories after a severe viral infection some years earlier had severally damaged his hippocampus. He had only short periods of knowing that he himself was present as an 'I', would then lose that sense, and then it would reappear, only for it to disappear again. Thus the continuity of his sense of 'I' was thereby almost destroyed.

We note it also relevant to mention Baddeley's suggested 'episodic working memory', required by him to act as a buffer site to enable short-term holding of episodic memories (Baddeley 2000). It may be here that the essential encoding of the PRS occurs, and can be regarded as a tag to give the sense of self on retrieval under attention.

It is thus feasible to conclude that the sense of continuity of self, as the continuity of the experience of a fused pre-reflective and reflective self or of a fused pre-reflective self and of content arises partly through the contribution of a hippocampal or nearby (episodic buffer) component. There may be other components as well, as arising from continued activity over seconds as in the parietal and temporal lobe buffer sites of working memory. The sense of unity is expected to arise from the connectivity between elements of the network of sites involved in the N2 and through their fusion with later activity during the creation of the P3 as the later component of consciousness. Possible dissociation of experience across modalities is known to occur, for example if inputs are very noisy.

Comparison to other approaches

There are numerous neural models that have been proposed to explain the creation/emergence of consciousness in the brain. They can be divided into two complimentary sets:

(a) Those in which no place in the brain is singled out, but consciousness arises through the suitably complex behaviour of activity in a large enough set of neurons.
(b) Those in which specific sites are needed that are necessary and sufficient for consciousness to arise.

In the former class are suggestions of chaotic dynamics through large regions of the brain (Freeman and colleagues; see Taylor and Freeman 1997; Taylor 2003a). Another mechanism suggested as necessary is that of binding through 40 Hz synchronised oscillations (Crick and Koch 1998). In the latter proposals are those concerned with feedback to lower sites (Pollen 2003; Grossberg 1999; Lamme 2003) and the use of attractor relaxation (as by Aleksander, Harth and colleagues presented in Taylor and Freeman 1997). The use of episodic memory in creating consciousness was emphasised in the Relational Mind approach (Taylor 1999).

In particular the approach of Lamme has emphasised the existence of feedback loops in lower cortices, which he has used to support the existence of a distinction between attention and awareness (Lamme 2003). There exist feedback loops in most areas of the brain. One particularly important is in the hippocampus, with a feedback of activity from entorhinal cortex to the dentate gyrus to the cell field CA3 and thence to CA1 and finally back again to entorhinal cortex. However this loop is not essential for consciousness, as cases who have lost their hippocampi from disease or surgery show (remember the case of Clive Wearing mentioned earlier - he had lost his hippocampus through a viral disease but was still conscious). Lamme however bases his claims on various experiments which purport to bear out his separation of attention and awareness. One such involves the phenomenon of change blindness. This occurs when a subject has no awareness of any alteration to an object not at the focus of attention. Change blindness has been studied by many different paradigms (Mack and Rock 1998). A number of these involve realistic outdoor scenes but do not give quantitative data relevant to the problem of differentiating between attention and consciousness. However this is different for

the CB paradigm of Fernandez-Duque and Thornton (2000), see also Landman et al. (2003) in which:

I. Eight objects are presented simultaneously, placed equally round a circle (so the spatial map is that of a circle).
II. After 500 ms a uniform grey mask is presented for 200–1,500 ms (so that only the dorsal route is uniformly activated, with zero activation in the ventral route).
III. There is re-presentation of objects, with one of them possibly changed (but with no change of positions overall of the objects, nor more specifically of the unchanged objects), until the subject responds as to there being a change of orientation to an object at a cued position. There are three cue conditions:

C1: A cue to where to look for a change of object is presented during the first presentation of the objects (by increasing the activation of the position of the relevant object).
CM: A cue to where to look for a change of object is presented during the presentation of the mask (by again increasing the activation of the position of the relevant object).
C2: A cue to where to look for a change of object is presented during the second presentation of the objects (again by increasing the activation of the position of the relevant object).

The task is to determine, under any of the three cue conditions, if the relevant object at the cued position has been changed during the presentation of the mask. The results for subjects (Fernandez-Duque and Thornton 2000) were that accuracy levels respectively for C1, CM and C2 were 100%, 90% and 60%. This corresponds, as expected, to perfect memory for the cued object and its comparison, a slight loss of memory when cued during the mask and a greater loss of remembered objects at the relevant positions when cued after the mask.

A general description of what is happening during the processing for the various cue states could go as follows (in a CODAM-based approach):

C1: Attention is directed to the object at the cued position, and it is held in working (or more permanent) memory until the report stage is reached; this is expected to lead to 100% accuracy, as observed, and already noted in Landman et al. (2003).
C2: The subject does not know which object needs to be remembered until report, so can either (a) attempt to store all of the objects as a general picture (they are all expected to be inside the focus of covert attention in the paradigm) or (b) select as many as possible to remember and serially rehearse. In case (a) there will be degradation of the 'picture' during the mask so that only imperfect recall will occur. In case (b) only of order of four objects can be stored, so explaining the 60% level of accuracy observed.
CM: This will correspond to an intermediate position between the cue conditions C1 and C2, and so lead to an intermediate accuracy level between these two, as observed.

We now consider how these cases can be simulated using CODAM. There is progression of increased accuracy as learning occurs in the subjects; that can be considered as arising by the subjects changing from the naïve strategies of (a) and (b) above applied to the direct visual images to coding the images as H or V in a sequence, and learning the sequence of eight H's and V's. This is a chunking process which should end up with about 100% accuracy through the masking period, as observed in subjects at session 3 in Landman et al. (2003). We will only consider the naïve subject results here. We have two choices: try to keep to only one CODAM model, representing some fusion of the dorsal spatial processing route or double up the CODAM models, so that one represents the dorsal route, the other the ventral. Connections between these two routes must be established accordingly.

Let us first consider the single CODAM model, especially since this would present a certain economy of architecture. To proceed we consider the single CODAM model as the dorsal route, with the orientations coded in SEF/FEF as possible goals and also in the other modules (IMC, plant map, monitor, buffer WMs). The nodes in each of these maps are doubled up at each spatial point, so that each pair of nodes represents a vertical and a horizontal bar; only one was allowed to be active at any time. The requisite cueing is assumed to create a relevant goal in the spatial prefrontal map, so as to bias the spatial attention signal and thence to attentionally amplify the relevant object activity at that position.

The most important assumption to be made in the simulation is the manner in which the cue is used by each subject. For C1, it is assumed that the cue acts in the goal map to hold the orientation of the object at the cued position in the buffer working memory, for use in report after the second stimulus offset. For C2, it is assumed that each subject holds activity representing the whole set of objects in buffer working memory. However the capacity of that buffer is only 4, so not all

8 objects can be held efficiently at once. We suppose that the subject tries to preserve an activation of shapes as observed in the first stimulus presentation period. This could be done by a sequential focussing on each shape, as in case (b) mentioned above, with only 4 being able to be held efficiently. Over numerous tests, on average only 4 would be able to be stored in this manner. However the results of the CM cueing case indicate that more shapes are initially held in the buffer, possibly solely as a general spatial map which has then to be questioned by the cue. This questioning would correspond to modifying the attention signal so as to focus more tightly on only the one cued position. During the mask period there is decay, but if the cue appears early in the mask period there will still be a sharper effect of the shape map (less degradation by noise) and so there will be a higher level of accuracy. As the mask period continues before the cue is presented in the CM cueing condition, there will be successive reduction of ability to detect a shape above the background noise. Finally in the final period the C2 cue will only have four stimuli to be able to pick out, as corresponds to the known capacity of the buffer. The alternative strategy (of case (a) mentioned earlier for C2) uses the strategy of the subject to rehearsing the orientations of as many as possible of the bars, so as to have those still available for inspection when the cue finally comes on in the stimulus period 2.

What arises from this discussion is that there could be a continued representation on the WM sensory buffer from all the stimuli having been attended to in the stimulus 1 period, although the amplification by attention would be lower on the object map, hence a lower WM buffer activity, due to the increased competition between the objects on the IMC. There would also be increased competition on the WM buffer due to WMcd competing inhibition onto the WM buffer amongst the various object nodes (either of these competitions being a source of the capacity limit of 4). The WM buffer representation will continue through the rest of the mask period, and so be able to be used in the stimulus period, or questioned during the mask period. The resulting decay with time of the cue is richly explored experimentally in Landman et al. (2003), and a similar rich analysis of the simulation results is possible to compare with this data.

The alternative architectural approach is to take two CODAM models, one for the dorsal and one for the ventral routes. The dorsal route would simply code for the eight positions of the bars round a circle; the ventral route would code for the orientations of each of those objects Thus the ventral object map would consist of two dedicated nodes, one for a vertical bar, the other for a ventral one. There would be hard-wired connections between the ventral route object map and the dorsal spatial map, so that if a change of orientation occurred during the mask period, this would be implemented by a corresponding change of connections of the object and spatial map. Similar connections could be taken between the buffer WMs for the object and spatial maps.

In either architecture, we are most interested in the level of activity in the buffer WM persisting in stimulus period 2 that can be used for report of the orientation of the bar at the relevant cued position. In the single route architecture this will be the activity at the cued position in the single buffer WM at the end of stimulus period 2. For the dual route architecture the relevant activity is that in the cued position in the ventral WM buffer map. The nature of the task for the subject is to determine if there has been a change in orientation of the bar at the cued position. We assume that the level of the buffer WM for the orientation, in either architecture, gives the memory of the orientation in the first stimulus period. This can then be compared against the actual bar orientation in the second stimulus period, which can be taken from the actual stimulus input. Hence it is the level of buffer WM activity of the orientation for the relevant bar in the second stimulus period which would be expected to determine the level of accuracy of the change detection. However, on being cued, either during the mask period or in the stimulus two period, a subject will be expected to immediately query what the orientation is of the object at the cued position (where in the stimulus 2 period, the new stimulus can be 'left out' in the outside world until it is needed in the comparison stage They will then store the result of the query about the old stimulus in some form of rehearsal memory, so as to be available when they prepare to look at the new set of stimuli and compare the new orientation at the cued position with what the orientation they have stored. So the crucial quantity, for each time of cueing, is the maximum level of the old target stimulus, during the mask. The activations during the stimulus presentation (with no stimulus 2 interference, as corresponds to the above strategy) were obtained by direct simulation.

The simulations were run on the model of two coupled CODAMs, one for the dorsal and one for the ventral brain pathways. It was assumed that a subject, once cued to a position expected to be asked after the masking, will query in their sensory buffer which stimulus orientation occurs at the cued position. This will then be remembered, say using an 'H' or 'V' mnemonic. The querying is assumed to be correct with a probability proportional to the maximum height of

the cued stimulus activity on their sensory buffer. These membrane activity values, when read off from the simulation curves, were as follows:

cue at 0 ms : 2.1; cue at 300 ms : 2.0;
cue at 600 ms : 1.5; cue at 900 ms : 1.2;
cue at 1,200 ms : 0

Thus there was found to be a clear decrease of probability (as measured by the membrane potential) of recall of the cued orientation as the cue is presented increasingly later in the mask period. This fits qualitatively with the results of Landman et al. (2003). A more detailed analysis of report probability as determined by membrane potential on the sensory buffer, is needed to attempt a quantitative fit, and will be given elsewhere. However the results indicate that suitable model parameters can be chosen to give a qualitative fit to the change blindness data on the basis of the CODAM model. This model is based on attention as a higher-level process, as is now accepted by many from results, for example, on the attentional blink. However it does not assume that consciousness is separate from attention; an attempt is made to determine what sort of further subtleties attention must possess in order for some form of consciousness to arise that is consistent with other known aspects of that subtle entity, in particular the nature of the inner self.

In any case the feedback or other approaches to consciousness give important components involved ultimately in the creation of consciousness. Yet none of the approaches other than CODAM mentioned above in this section begin to tackle this 'hard problem', that of giving an 'inner self' or a sense of 'what it is like to be' to the system. It is that which has been addressed directly by CODAM, in terms of allowing the pre-reflective self to be created by suitable buffering of the corollary discharge of the attention movement signal being used to prepare an input for consciousness. As buffer sites are known to be localised in the brain, the CODAM model is therefore of the second class, of localised models of the creation of consciousness. It fits with the great detail on neglect as arising from localised parietal deficits, mainly due to stroke, and other features of brain-based mental deficits (Taylor 2006).

How do these other approaches to consciousness deal with the problems noted above? Not at all, is the short answer. They just do begin not solve the hard problem. Thereby they cannot handle the loss of the experience of ownership of conscious content. They can only generate an explanation of how that content could become degraded. But that is not what the patients are reporting of their own experience. As Sigmund Freud wrote: ''The libido of the schizophrenic withdraws from the outer world onto its own ego''. With no model of such an ego there is no explanation. CODAM provides the outline of a model of the ego, in terms of activity on the WMcd giving the brief spurt of ownership of future content.

Conclusion and discussion

The use of an engineering control approach to attention was shown above, and more specifically in the references cited, to lead to a general engineering control model of the movement of attention which was able to be used successfully to simulate several attention paradigms, both for visual attention and for visuomotor attention. The control framework was extended to include a buffer for an efferent copy of the attention movement control signal. This signal was interpreted as giving the experience of ownership of the about-to-arrive signal of the content of awareness. The model was noted as being able to explain how the attentional blink, a very attention-demanding task, is sensitive to masking of either target (Fragopanagos et al. 2005). Moreover it was noted that the pre-reflective self is not bound up with the body, as claimed by some, as shown by an argument based on the experimental results of various detailed psychological paradigms, as argued in the ''I and my body are distinct'' section. Finally the manner in which the N2 is sited in various parts of the brain allowed the simple beginnings of an understanding of the unity and of the continuity of consciousness to be developed in ''The nature of self'' section, as well as how the pre-reflective self can be coded in hippocampally based attractors as short sequences of representations.

Various features of this model need further detailed analysis to support its character as a general model of attention control. The complexity of processing in the parietal lobe is now becoming apparent through TMS and related techniques (Chambers 2004, 2006), and a lot more work must be done to bring any attention copy model like CODAM properly into agreement with this data. It is as crucial to obtain more support for CODAM as a model of the creation of consciousness. This latter aspect has already been briefly explored from the viewpoint of inner experience of schizophrenics in the early stage of their disease (Taylor 2003c). The loss of a sense of an inner self, in particular, needs to be explored by means of brain measurements on such patients, so as to relate to those regions of the

brain that CODAM would suggest would be damaged or under-developed. The most crucial of these is clearly the WMcd component, for which initial evidence was presented in the previous sections in relation to the N2 signals with sources in various parts of the brain. However more careful analyses detecting amplification effects from the corollary discharge signal as well as the presence of the corollary discharge buffer are required, as are more detailed analyses of sites of the N2 both in cortex, sub-cortically and in the hippocampal complex.

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