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Resolving some confusions over attention and consciousness

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Abstract

There is presently an ongoing debate about the relation between attention and consciousness. This debate is being fuelled by results from experimental paradigms which probe various forms of the interaction between attention and consciousness, such as the attentional blink, object-substitution masking and change blindness. We present here simulations of these three paradigms which can all be produced from a single overarching control model of attention. This model helps to suggest an explanation of consciousness as created through attention, and helps to explore the complex nature of attention. It indicates how it is possible to accommodate the relevant experimental results without needing to regard consciousness and attention as independent processes.

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1. Introduction

The debate is intensifying between those who believe that attention is necessary (but not sufficient) for consciousness (James, 1890; Mack & Rock, 1998) and those who regard these two brain processes as independent (Koch & Tsuchiya, 2006; Lamme, 2003, 2006; Pollen, 2003). The debate presently is based on arguments of the latter protagonists, who assume that attention and consciousness are simple processes. However neither of the processes is likely to be simple. The complexity of attention is indicated by the subtle nature of priming and masking effects, and by a variety of deficits in attention such as neglect and extinction, as well as for the fact that there are both exogenous and endogenous varieties of attention as well as attention focussed on sensory input or motor response modes. The complexity of consciousness arises from the wealth of different states of consciousness: in the normal waking state, under various drugs, in meditation (such as in the so-called pure consciousness), in dreaming, hypnosis, dissociation of identity disorder, and so on.

In order to advance the debate, we explore more fully some of these complex features of attention by use of a recent model providing a deconstruction of attention, and thence of

consciousness (Taylor, 2000, 2002a, 2002b, 2003, 2005, 2006, 2007). The model extends to attention the recently successful applications of engineering control concepts to motor control (Desmurget & Grafton, 2000; Sabes, 2000; Wolpert & Ghahramani, 2000). Thus module acting as inverse model controllers and forward models are extended from the motor control domain to attention control. Considerable support has been given for this engineering control approach to attention from recent brain imaging results (Corbetta & Shulman, 2002; Corbetta et al., 2005; Kanwisher & Wojciulik, 2000).

The proposed attention control model uses an efference copy or corollary discharge of the attention movement control signal to provide a precursor signal to the posterior cortical sensory working memory buffer site for the creation of content consciousness. This precursor signal has been proposed (Taylor, 2000, 2002a, 2002b, 2003, 2005, 2006, 2007) as that generating the experience of ownership or of 'being there' (Nagel, 1974) and of leading to the important property of 'immunity to error through misidentification of the first person pronoun' (Shoemaker, 1968). That is why the resulting model is called the COrollary Discharge of Attention Movement Signal, or CODAM for short. This suggestion also allows for the beginnings of rapprochement between science and religion through the explanation, by CODAM, of the meditative state of pure consciousness, seen by many to be at the basis of the religious experience of God across all the world's major religions (Taylor, 2002a, 2002b, 2006). The CODAM model is

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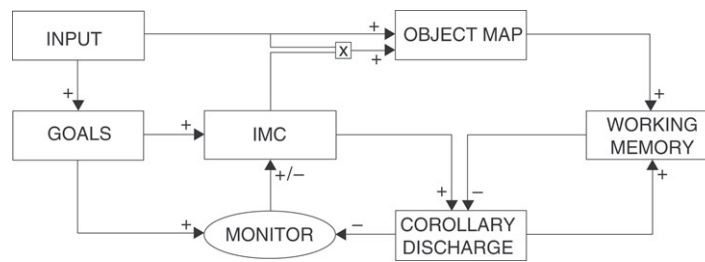


Fig. 1. The CODAM architecture.

applied in this paper to give detailed explanations of the results of the various paradigms being used in the argument about the relation between attention and consciousness.

In the next section an outline of the CODAM model is presented for completeness. It is followed by a description of how the model has been applied to the attentional blink, one of the paradigms at issue, as well as relating it more specifically to recent data (Sergent, Baillet, & Dehaene, 2005). In Section 4 we show how a CODAM-based model can be used to explain object-substitution data of relevance to the argument. Following that in Section 5 we describe how the model can give an attention-based quantitative explanation of some data on change blindness. In Section 6 there is a brief discussion how some recent data on visual object detection in a dual task condition and some motor response data can also be reconciled with an attention-based explanation. The final section as a conclusion, which can be summarised as that consciousness is still best understood as arising through attention paid to a stimulus.

The simulations presented in Sections 3–5 use the CODAM architecture, with the modifications as stated under the various sections. The equations describing the details of the CODAM model are as stated in Fragopanagos, Kockelkoren, and Taylor (2005); there are obvious modifications to these arisings in the specific simulations of Sections 3–5, such as addition of extra inhibition in Section 3, etc.

2. The CODAM model

The basic architecture of the model is shown in Fig. 1.

The figure shows the modules of the CODAM model of attention control, based on engineering control mechanisms. Visual input, for example, enters at the **INPUT** module and is sent, through a hierarchy of visual processing modules, to activate the object map module, **OBJECT MAP**. At the same time in the exogenous case it rapidly accesses the **GOAL** module, so causing bias to be sent to the inverse model controller denoted **IMC** in the figure (the generator of the signal to move the focus of attention). This sends a modulatory feedback signal to the object map, of multiplicative or additive form, to amplify the requisite target activity entering the object map. As the attention feedback signal is created by the **IMC** – the inverse model controller, as generator of the attention movement control signal – a corollary discharge of this signal is sent to the **MONITOR** module, acting as a buffer for the corollary discharge signal (the main output of **IMC** is destined to amplify activity in lower level cortical regions). This can

then be used both to support the target activity from the object map accessing its sensory buffer, the **WORKING MEMORY** module, and to be compared with the requisite goal from the **GOAL** module. The resulting error signal from the monitor module is then used to enhance the **IMC** attention movement signal and so help to speed up access as well as to reduce the activities of possible distracters.

The modules present arise as observed by brain imaging paradigms (Corbetta & Shulman, 2002; Corbetta et al., 2005; Kanwisher & Wojciulik, 2000), plus an extension by use of engineering control models to include an efference copy buffer. CODAM extends thereby numerous models of attention control, especially that of ‘biased competition’ of Desimone and Duncan (1995) and the more neurally based models of Deco and Rolls (2005), Hamker and Zirnsak (2006), Mozer and Sittin (1998). These models can be seen to be based on ballistic control, rather than the more efficient and sophisticated control by means of forward models and error correctors. The modules in CODAM in figure one are explained more fully in the figure caption.

Event related potentials (ERPs) arise from the interactive processing of input up and down the hierarchy of modules in Fig. 1, with a stimulus entering low-level sensory cortex and attempting to reach its relevant sensory buffer (working memory). This is aided or inhibited by the corollary discharge signal (biased by a goal) so as to allow buffer access to a target stimulus and prevent that access to any distracters. As seen from Fragopanagos et al. (2005) these ERP signals give a description both of activity at the various sites as processing time proceeds as well as how the various sites interact through either excitatory or inhibitory feedforward or feedback effects (as observed by the cortical layer in which the activation commences (Mehta, Ulbert, & Schroeder, 2000)). Such interactions are enhanced when a number of stimuli are present in a short period, when the excitatory discharge signal is seen to enhance the growth of the sensory buffer signal or the inhibition from the sensory buffer inhibits further processing in the attention movement signal generation module. These interaction are now being observed in the attention blink paradigm (Sergent et al., 2005), as discussed in the next section.

Other attention phenomena that can be explained in terms of reduced versions of the CODAM mode are: the Posner attention paradigm (Taylor & Rogers, 2002), working memory rehearsal (Korsten, Fragopanagos, Hartley, Taylor, & Taylor, 2006) and the N2pc as well as numerous other attention tasks as demonstrated by the modelling through the other models mentioned earlier, as regarded as simpler versions of CODAM.

More detailed aspects of the feedback control have also been studied at the micro level (Taylor, 2006), which implies that the attention feedback is of sigma-pi or multiplicative form.

3. Modelling the attentional blink

The attentional blink requires a subject to be able to recognise a given letter, say as the first target (T1) in a rapid visual stream of stimuli presented at about 10 Hz. The subject is then required to recognise a further letter (T2) presented several lags later. The success level in recognising T2 as the lag is increased from 1 to 10 has a well-established U-shape; the dip of the U occurs for a lag of about 3, or for a time gap between T1 and T2 of about 300 ms.

A detailed simulation of the attentional blink has been presented recently (Fragopanagos et al., 2005). This uses the interaction between the P3 of T1 (assumed to be created on a sensory buffer) and the N2 of T2 (assumed created from an efference copy of the attention movement control signal). The N2 is itself observed to be complex (Hopf et al., 2000; Ioannides & Taylor, 2003).

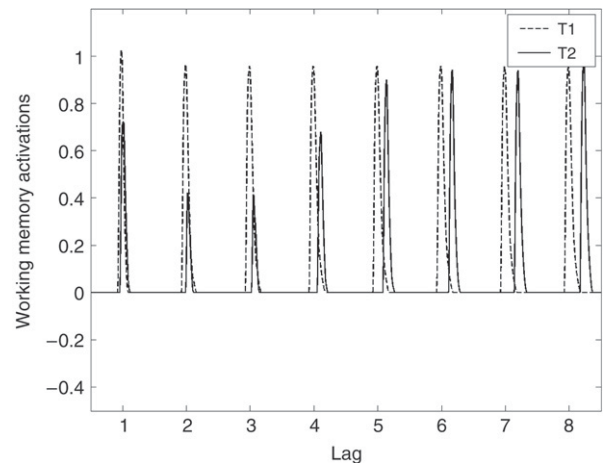
The result of an extension of the original model of (Fragopanagos et al., 2005) by addition of inhibition from the corollary discharge buffer of Fig. 1 to other modes on the sensory buffer are shown in Fig. 2, for levels of the inhibitory connection strengths of 0, 0.5 and 1.0. As seen from the figure, there is a progressive change in the activity at various lags as the inhibition is increased. This is particularly clear for the P3 of T1.

We note that the results of Fig. 2 can be compared with the recent results of Sergent et al. (2005) which showed that there is an inhibitory effect, in the case of awareness of T1 from the N2 of T2 to the P3 of T1. This effect is observed most clearly in Fig. 2(c), with inhibitory connections of 1.00. The fall-off of the sensory buffer activity of T1 is largest, by ten percent, with the largest inhibitory effect of the corollary discharge buffer signal of T2 being the cause of this fall-off.

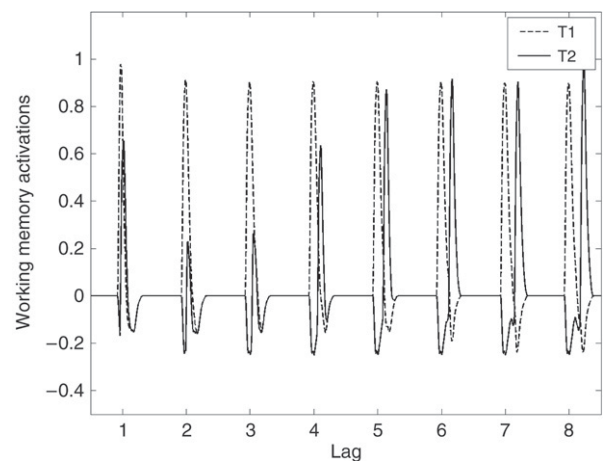
We interpret the results of Sergent et al. (2005) as evidence for the crucial mechanism posited for the AB in Fragopanagos et al. (2005), that of prior boosting of the sensory buffer by that of the efference copy for the same code, with corresponding inhibition from the P3 of T1 to all positions on the attention movement signal generator. This can be simulated by the CODAM model, thus fitting this paradigm, and its manipulation of awareness, into an attention control framework (albeit a non-trivial one).

4. Modelling object substitution

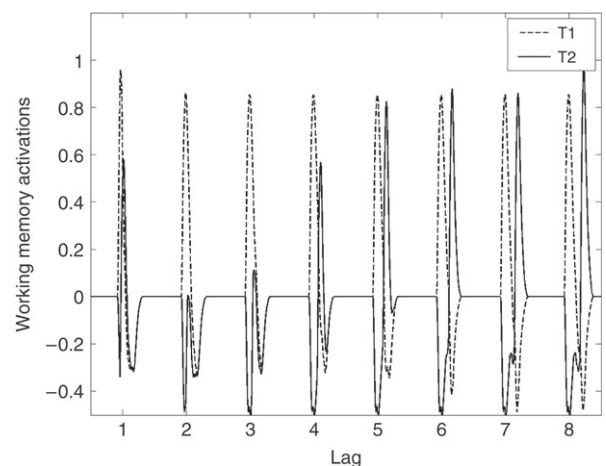
A related question is that of understanding the results presented on object-substitution masking by Woodman and Luck (2003). When a subject is presented with a masked object, the experimenters observed an N2 to the object even though it did not reach awareness. This would correspond in CODAM to the presence of the corollary discharge signal but with no sensory buffer signal above report threshold. We simulated this by activating two objects at the same time on the object map,



(a) Corollary discharge buffer to sensory buffer inhibition = 0.0.



(b) Corollary discharge buffer to sensory buffer inhibition = 0.5.



(c) Corollary discharge buffer to sensory buffer inhibition = 1.0.

Fig. 2. Simulation results from CODAM, showing the P3 of T1 (as a broken line, only detection of T1 was required here) and of T2 (as a continuous line, where detection of both T1 and T2 were required) for different lags for the presentation of T2. Note the increased reduction of the P3 of T1 as the inhibition from the corollary discharge buffer to the sensory buffer increases, as seen in passing from 2(a) to 2(b) to 2(c) (with inhibition values of 0, 0.5 and 1 respectively).

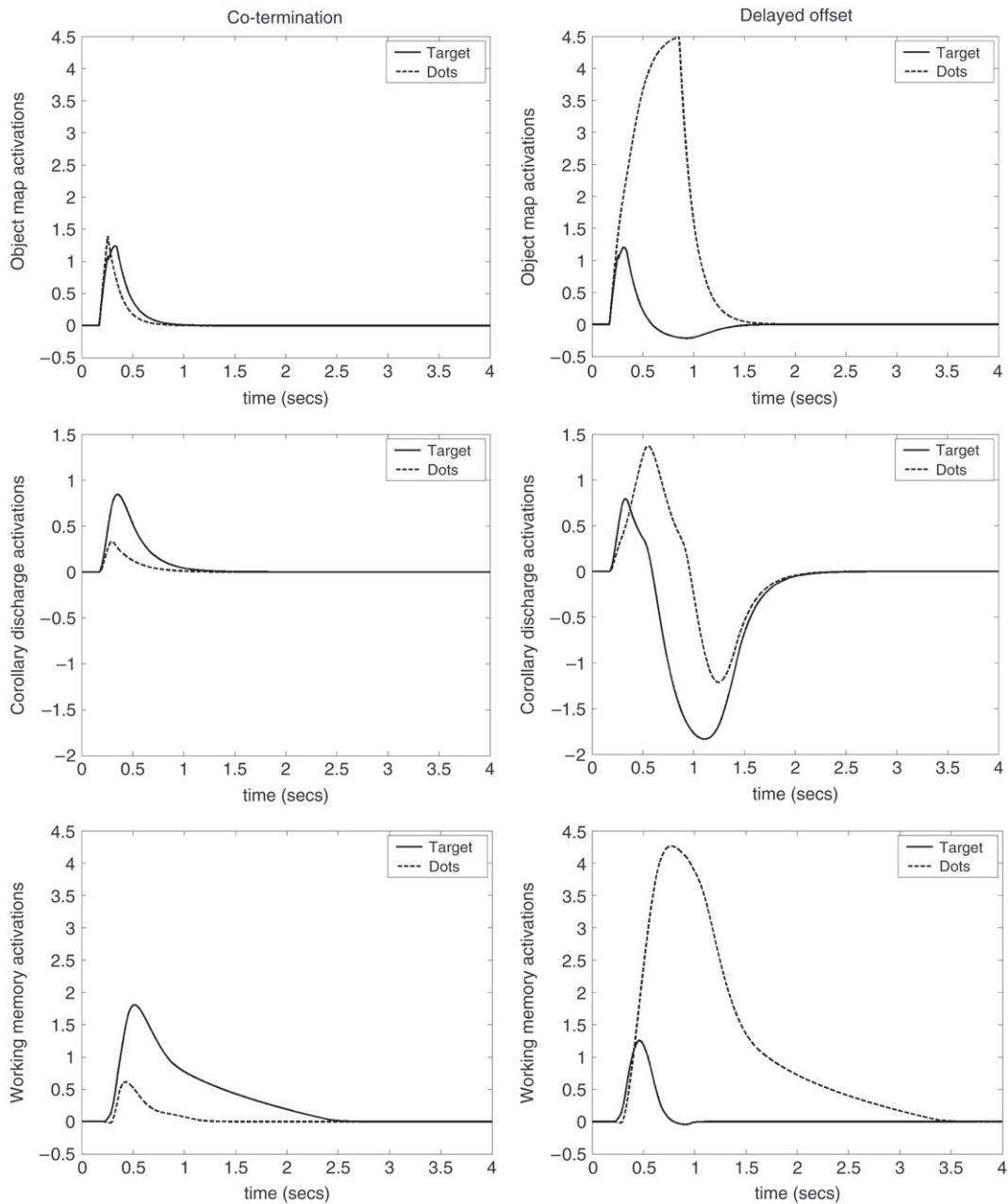


Fig. 3. Activations on various modules of the CODAM architecture in a simulation of the object-substitution paradigm.

with one of them persisting longer than the other (so as to represent the four dots). The first object was on for 83 ms, the second starting at the same time as the first but either co-terminating or continuing on for another 600 ms (in the object-substitution case). In the second case we expected a lower level of the sensory buffer activity for the first object, although there should also be a corollary discharge signal in both cases. Noise could then be added to obtain more detailed fits (not done in the simulation). We tested if the sensory buffer level is lower for the first (83 ms exposure) stimulus when the second stimulus was on for 500 ms. The results are shown in Fig. 3.

The plots are in two columns, the first arising from co-termination of the object and the mask and the second from delayed offset of the mask. Each column shows the temporal

development of activity in, respectively, the object map (first row), the corollary discharge module (second row) and the sensory buffer module (third row).

As seen in the third row in the co-termination phase (first column) the target activity is twice as large as the mask, so leading us to expect awareness of the target in this case. In the delayed offset phase (second column) the mask is considerably more active than the target, so awareness will switch to the mask. However in both phases the corollary discharge signal activity on its buffer for the target is very closely the same between the phases. Therefore if the N2 for the target can be detected in the co-termination phase so it can in the delayed phase. That agrees with the results in Woodman and Luck (2003).

5. Modelling change blindness

Change blindness has been studied by many different paradigms (Mack & 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, Spekreijse, and Lamme (2003) in which:

- I. 8 objects are presented simultaneously, placed equidistant round a circle;
- II. After 500 ms a uniform grey mask is presented for 200–1500 ms (so that only the dorsal route is uniformly activated, with zero activation in the ventral route);
- III. There is re-presentation of the objects, with one of them possibly changed (but with no change in positions overall of the objects, nor more specifically of the unchanged objects), until the subject responds as to there being a change in orientation to an object at a cued position.

There are three cue conditions:

C1: A cue as to where to look for a change in object is presented during the first presentation of the objects (by increasing activation at the position of the relevant object);

CM: A cue as to where to look for a change in object is presented during the presentation of the mask (by again increasing the activation at the position of the relevant object);

C2: A cue as to where to look for a change in 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 & Thornton, 2000) were that accuracy levels respectively for C1, CM & 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 happened 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 of the objects to remember and serially rehearse them. In case (a) there will be a degradation of the 'picture' held in memory during the mask so that only imperfect recall will occur. In case (b) only of order of 4 objects are expected to be able to be stored, so explaining the 60% level of accuracy in that case.

CM: This will correspond to an intermediate position between the cue conditions C1 and C2, and so lead to an intermediate level of accuracy between them, as observed.

We now consider how these cases can be simulated using CODAM. There was observed to be a progression of increased accuracy as learning occurs in the subjects; that can be considered as arising from the subjects changing from the naïve strategies of (a) and (b) applied to code the images as H or V in a sequence and learning the sequence of 8 Hs and Vs. This is a chunking process which should end up in about 100% accuracy through the masking period, as observed in subjects in session 3 in Landman et al. (2003). We will only consider the naïve subject results here. We note there is both spatial and object coding of stimuli in the paradigm.

We have two choices: only try to keep one CODAM model, representing some fusion of the dorsal spatial and the ventral object routes, or alternatively double up the CODAM models so that one represents the dorsal, the other the ventral routes. 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; this model can be considered the dorsal route, with the orientations coded in the goal modules (representing FEF/SEF) and also in other modules (the IMC, the posterior visual cortex, the monitor and the buffer working memories). The nodes in each of these modules are doubled up at each spatial point, so that each pair of nodes represents a vertical and a horizontal oriented bar; only one was allowed to be active at each time. The requisite cueing is assumed to create a relevant goal in the spatial prefrontal map so as to bias the attention signal and thence to amplify by attention 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 the buffer working memory. However the capacity of the buffer is only for objects, so not all eight 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 of attention on each shape, as in case (b) mentioned above, with only four shapes being able to be held efficiently. Over numerous test, on average only four objects 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 one cued position. During the mask period there will be decay, but if the cue appears early in this period there will 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 condition, there will be a successive

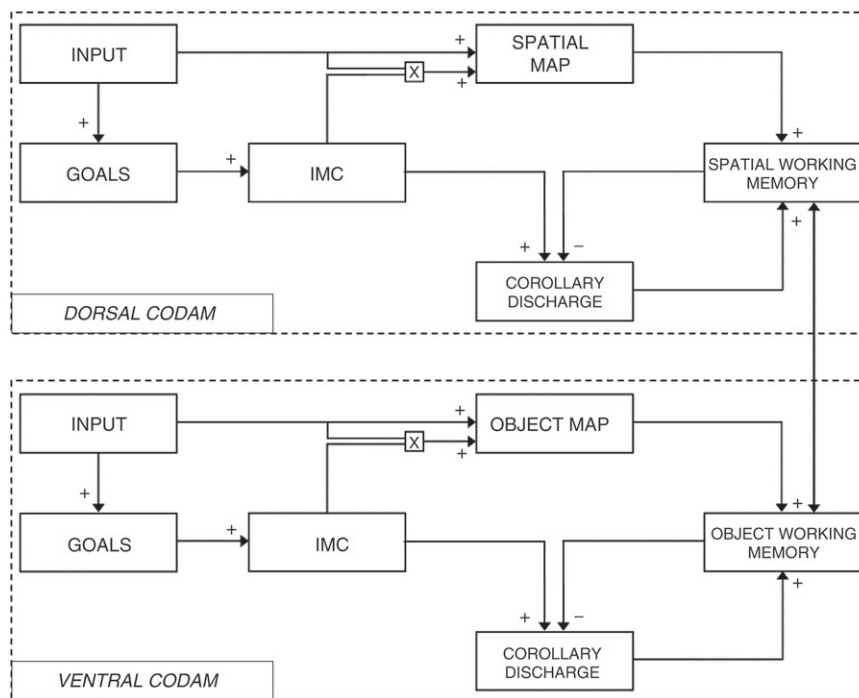


Fig. 4. The two-route (dorsal plus ventral) CODAM model architecture that could be used for a simulation of the change blindness paradigm. The upper module has a spatial map, the lower one an object map, with the connection between the object and spatial working memory modules made explicit (although it is expected that there are many other connections between the two routes). Each of the two models has its own inverse model controller (IMC), that for the spatial route having been observed in the superior parietal lobe, that for the object route very likely in the temporo-parietal junction (TPJ).

reduction of ability to detect the shape above 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 subject rehearsing the orientations of as many of the bars as possible, so as to have those still available for inspection when the cue finally comes on at stimulus period 2.

What arises from this discussion is that there could be a continued representation on the 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 buffer activity, due to the increased competition between the object activations on the IMC. There would also be increased competition on the sensory buffer due to the corollary discharge activity causing competing inhibition on the sensory buffer among the various object nodes (either of these competitions contributing to the capacity limit of four). The sensory 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 the data.

The alternative approach is to take two CODAM models, one for the dorsal and one for the ventral routes, as shown in Fig. 4.

The dorsal route would simply code for the 8 positions of the bars round a circle; the ventral route would code for the orientation 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 horizontal one. There would be hard-wired connections between the ventral-route object map and the dorsal spatial map, so that if a change in orientation occurred during the mask period this would be implemented by a corresponding change in connections of the object and spatial maps. Similar connections could be taken between the buffers for the object and spatial maps.

In either architecture we are most interested in the level of activity in the buffer map persisting in the stimulus-2 period 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 sensory buffer at the end of the stimulus-2 period. For the dual-route architecture the relevant activity is that activated in the ventral buffer map by the stimulus input at the cued position.

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 activity in the relevant buffer 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 the sensory buffer activity for the orientation for the relevant bar in the second stimulus period which is expected to determine the level of accuracy of the change detection. However, on being cued, either during the mask period or in the stimulus-2 period, a subject will be expected to immediately query what the orientation is of the

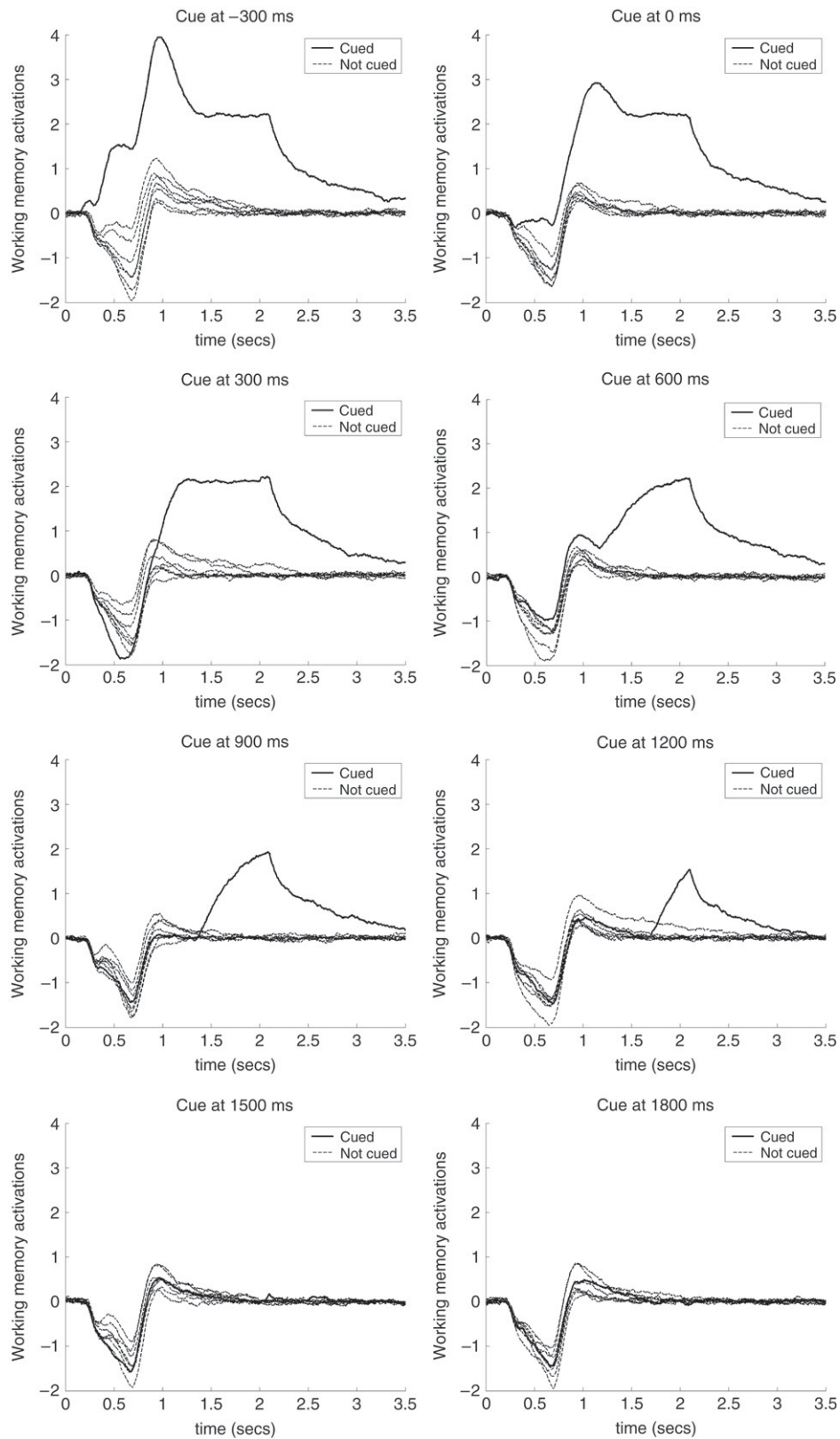


Fig. 5. Sensory buffer activations for different cue times.

object at the cued position (where in the stimulus-2 period the new stimulus can be left in the outside world until it is needed for comparison. The stored representation of the old stimulus will then be available when preparation is made by the subject

to look at the new stimulus and make the comparison of the orientations of the two images. So the crucial quantity, for each time of cueing, is the activation level of the stored stimulus from period-1. These activations are shown from the simulation using

the double-route architecture of Fig. 4 for various cue times in Fig. 5. This simulation uses the double-route architecture of Fig. 4, with the cue times (when a subject has to report on ‘change or no change’ in the new stimulus set presented) as specified in each of the figures. The plots of the figure are of the membrane potentials of the working memory module of the ventral CODAM. The solid line corresponds to the object whose location has been cued whereas all the other lines (dashed) are from uncued objects. The level of response can be read (as before) from the line of the cued object (solid line). Note that as the cue time is increased the activity on the various modules decrease, until at a cue time of 1500 ms and beyond there is little difference from the activity when there is no cue.

Let us repeat the interpretation of the sequence of curves in Fig. 5. It is 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 probability proportional to the maximum height of the cued stimulus activity on its sensory buffer. These values, read off from the figures, are:

–300 ms: 4; 0 ms: 3; 300 ms: 2; 600 ms: 2; 900 ms: 1.9; 1200 ms: 1.5; 1500 ms = 1800 ms = 0.9 (background).

Thus there is a gradual decrease in 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 the report probability is needed to attempt a quantitative fit and will be given elsewhere. This requires a model of how responses are made, in particular a quantitative relation between the buffer level of activity and response time.

6. Further paradigms

There have been further recent claims (Koch & Tsuchiya, 2006; Lamme, 2003; Sumner, Tsai, & Nachev, 2006) that consciousness and attention have a certain degree of independence. So far we have used the CODAM model to simulate the results of various paradigms used in the attack on attention as the entry to consciousness. Here we consider these further paradigms in a qualitative manner. The main thrust of our argument against these new results is that attention itself is far more complex than considered in the three important papers of Koch and Tsuchiya (2006): Lamme (2003), Sumner et al. (2006). Thus attention is known to be present in two forms: sensory and motor (Rushworth, Paus, & Sipila, 2001) and it possesses the possibility of multiple foci, at least for vision (McMains & Somers, 2004). It also controls the transfer of laborious sequences of motor actions, for example, to chunked versions, with each chunk being able to be run off automatically without attention in different brain sites (Pollmann & Maertens, 2005). It also not only arises from top-down control circuitry but has many components of the top-down circuitry involved in bottom-up ‘break-through’ (Balan & Gottlieb, 2006). These properties allow us to re-analyse the data presented in Koch and

Tsuchiya (2006), Lamme (2003), Sumner et al. (2006) so as to show how attention is still to be regarded as a filtering operation before consciousness can arise, such that consciousness occurs only when attention is directed to a stimulus.

Let us turn to discuss the experimental data of Koch and Tsuchiya (2006). The authors reported tests of the ability of subjects to report without increased response time on the presence or absence of animal figures in stimuli presented simultaneously in the periphery together with a central letter task. Such subjects underwent up to ten hours of prior training on the stimuli, so it is quite possible that they had developed an automatic route for response to the peripheral animal pictures to which they were exposed (Pollmann & Maertens, 2005). It was also possible that they were able to use multiple foci of attention to detect the presence of both the peripheral target as well as the main central one (McMains & Somers, 2004). Either of these possibilities could be tested for by brain imaging the subjects during the testing: circuits observed in automatic processing (Pollmann & Maertens, 2005) would then, if observed during the paradigm, imply the presence of the use of an automatic route. Due to lack of such data, the strong conclusion drawn by the authors (attention and consciousness are independent) need not be accepted, and only the simpler hypotheses that either suitable automatic response patterns had been learnt over the training time or that two attention foci had been used. Either explanation does not force consciousness and attention to be independent.

The results of Sumner et al. (2006) were that increased inhibitory priming of a motor action arose from subliminal commands whilst decreased inhibition occurred in response to reportable commands. This result can be explained as involving two forms of attention: motor and sensory. The former produces these counterintuitive effects: direct stimulus input to motor command centres in the subliminal case increase motor inhibition of return (IOR), a motor analogue of the well-known visual IOR, whereas the aware stimulus would have been processed in a visual working memory. This latter form of processing is expected to activate a different circuit than the direct lower level visual input in the subliminal case, and cause inhibition of IOR effects. Again the experimental results can be explained inside the attention control framework, with no need to conclude that consciousness is independent of attention and can function outside it.

We have already discussed the experimental results used by Lamme (2003) on which he based his claim that attention and consciousness are independent. We have presented an attention based set of simulations of those we consider the most important (the attentional blink, change blindness, and object substitution). Thus we also consider the simpler explanation of the paradigms considered in Lamme (2003) to be that attention is necessary for consciousness.

Further discussion of this relation was given in Lamme (2006), where it was stated that the independence of attention and consciousness was shown by results arising from investigations of blindsight (Kentridge, Heywood, & Weiskrantz, 1999). This is a particularly important set of results since the authors discovered that in blindsight the subject GY

had attention drawn to a visual stimulus in his blind field even though he was not aware of it.

The paradigm consisted of an arrow cue being presented briefly, pointing left or right, and then a target being presented in GY's blindfield, validly cued for 80% and invalidly cued for the other 20% of the presentations. It was GY's task to report the orientation of the target (a bar oriented either vertically or horizontally) as rapidly as possible. GY was able to discriminate target orientation much better than chance in all conditions of cueing and stimulus onset asynchrony. As the authors concluded "Attention cannot therefore be a sufficient condition for awareness." (although they stated its necessity).

The result of this experiments can be understood in terms of CODAM as there being a corollary discharge and attention feedback amplification of the target stimulus, with the attention focus already having been directed to the correct side (in 80% of the tests) by the cue (which was in awareness). This then allowed response to be made through an automatic route (or from the partially activated sensory buffer) so as to be more successful than chance. Thus it appears incorrect to separate consciousness and attention, the error being caused by taking 'attention' as a unitary entity, whereas it is a complex control system. When looked at in the latter manner, it becomes clear how one could explain such results as in *Kentridge et al. (1999)* and their earlier results on blindsight.

In addition there are the claims that consciousness can be explained through recurrence (*Lamme, 2003, 2006; Pollen, 2003*). These claims are consistent with the present approach through CODAM, which also possesses to a considerable degree recurrent processing. But this recurrence is embedded in the control circuitry of attention through CODAM, preserving the necessity but not sufficiency of attention for the creation of consciousness. However it could be claimed that CODAM's use of the corollary discharge to create the owner experience brings consciousness back to part of the attention circuitry, and hence to attention. However the decomposition of attention into various components, as in CODAM, allows us to say that attention, regarded purely as the attention feedback control signal to input stimulus activations, is not sufficient for consciousness.

In all cases we conclude that there is no need to attempt to separate attention from consciousness, and attention is still seen as a necessary condition for consciousness.

7. Discussion

7.1. Summary of results

Certain of the paradigms of interest have been simulated satisfactorily by CODAM, and two other relevant paradigms have been analysed in a more general attention control framework consistent with CODAM. Thus we can use the interpretation of the dynamics of the various CODAM modules to begin to tackle the thorny problem of the details of the relation between attention and consciousness. To begin with we consider in more detail the implications of the model in understanding attention.

7.2. Implications for attention

The simulations give more support to the general type of model of which CODAM is a particular case, those of attention copy or ACE. This general class of models is of an engineering control form, with many varieties, as known from the range of motor control models proposed as existing in the brain. But in particular there is support given for the existence of the corollary discharge of attention movement signal, especially from the motor theory of attention (*Rizzolatti, Riggio, Dascola, & Umiltà, 1987*). The further identification of this signal as being observed as part of the N2 signal is supported by experimental data (*Hopf et al., 2000; Ioannides & Taylor, 2003*). In all the CODAM approach is given an experimental justification allowing it to be explored further in its relevance to consciousness, from the results presented in this paper: there is no data showing that the neural activity for the creation of consciousness is not to be found by a more careful investigation of the attention control system.

7.3. Implications for consciousness

The CODAM model has been interpreted as possessing the ability to create both the conscious experience of content, as well as providing a neural underpinning for the phenomenological experience of ownership (the sense of the 'inner self'). This latter experience is proposed in CODAM to have arisen from the signal on the buffer for the corollary discharge, itself being used to stimulate the relevant code on the sensory buffer, and hence leading uniquely to the relevant experience of content. Only the expected target activity is allowed, by the activity of the corollary discharge signal, to attain the sensory buffer, so gaining report status. It is this filtering process which has been noted as corresponding to the crucial property of conscious experience, that of 'immunity to error through misidentification of the first person pronoun' (*Shoemaker, 1968*).

We note the presence of cases of subjects being unaware to change blindness but yet sensing it occurred (*Fernandez-Duque & Thornton, 2000*). We note their result that accuracy was highest for cases without awareness. We can attempt to explain these effects by the dragging of attention to the new object by use of the corollary discharge of the attention movement signal, with or without access to the sensory working memory buffer being achieved in the two cases (either unaware or aware). How would this mechanism lead to the 'sense' of orientation change, even though it was outside awareness? We can assume that the response to a stimulus is governed by the strength of that stimulus on the object map; if that is amplified by the attention movement signal, even though it was not amplified enough to reach the sensory buffer, it will still lead to a more rapid response and hence to a sense of having observed change.

7.4. Implications for the relation between attention and consciousness

The CODAM model or variants of it have in general a boosting effect from the corollary discharge to speed up

the access of stimulus activity from lower level semantic maps onto their associated buffer sites for report and use at a cognitive level. The corollary discharge also provides various levels of inhibition of distracters to prevent their access to buffer sites. Overall the process of consciousness creation, according to CODAM, involves activation of two sites: ownership on the corollary discharge buffer site and content on the sensory buffer. The second of these activations is expected to have correlated lower level activity (brought about possibly through synchronisation or by amplitude correlation, such as by attention feedback). The ownership activity is not correlated with these low-level cortical sites, but may still involve a network of similar sites providing a sense of the unity of self, and also rapid access to material.

As an overall conclusion, we see that in all this discussion of the dynamical processes involved in various attention-based paradigms, there is a clear message: attention is necessary for consciousness, where by attention is meant a signal generated by the attention movement controller. Without that there will be no efference copy, nor any amplification of lower level cortical activity to achieve access to the sensory buffer. But on the other hand with the attention signal there will not necessarily be consciousness unless the corollary discharge and the amplified lower level activity both attain their appropriate buffers; there can be an earlier N2 but the P3, from present experiments seems to be absent even with an N2, but is always absent with no N2, as in the AB reported in Vogel, Luck, and Shapiro (1998). If various modules involved in the generation of the attention control signals are damaged then it is to be expected that the sense of self will itself be compromised. This can occur, for example, in Alzheimer's disease or in schizophrenia, as well as in other diseases of a cognitive nature, such as neglect. At the same time varieties of consciousness – in dreams, under drugs – begin to be explicable in terms of the deconstruction of consciousness that can be achieved through CODAM.

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