Visual Dominance and the Control of Action

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Abstract

Visual dominance refers to the tendency for visual stimuli to dominate awareness of stimuli of similar or lesser intensity presented simultaneously in other modalities. The effect may be seen in simple and choice reaction time studies. When visual and auditory stimuli are presented separately, visual reaction time is typically slower than auditory reaction time. However, when visual and auditory stimuli are presented simultaneously the visual stimulus generally provokes the first response. In this paper we provide a computational account of such visual dominance effects. The simulation extends an existing computational model of routine action selection, accounting for the counterintuitive visual dominance findings whilst providing further support for the original action selection model.

Introduction

Colavita (1974) demonstrated that although simple auditory reaction time is significantly less than simple visual reaction time, visual stimuli appear to dominate awareness when stimuli of equal subjective intensity are presented simultaneously in the visual and auditory modalities. This result — an instance of visual dominance — is somewhat counter-intuitive: one might expect that, on simultaneous presentation, the auditory stimulus would be detected before the visual stimulus and thus, on a serial account of attention, be processed before the visual stimulus. Instead, the detection of the visual stimulus appears to over-ride processing of the auditory stimulus, which, Colavita found, could go undetected.

Visual dominance is not limited to the prepotency of the visual modality with respect to the auditory modality. Posner, Nissen, & Klein (1976) discuss a variety of experimental situations in which information presented in the visual modality takes precedence over other sensory input (including proprioceptive input and tactile input). Posner *et al.* (1976) also provide a theoretical account of visual dominance. They argue that visual dominance phenomena arise from mechanisms designed to compensate for the "low alerting capability of visual signals" (p. 161).

Simple reaction time experiments like those of Colavita (1974) link simple perception (detection of a stimulus) to simple action (effecting a key-press). In previous work (Cooper, Shallice, & Farringdon, 1995; Cooper & Shallice, 1997) we have developed a computational model of the control of routine action based on the contention scheduling theory of Norman & Shallice (1986). Although not originally developed as a theory of visual dominance (or perceptual phenomena), the theory does provide an account of the selection of action in response to both intentional and contextual influences and — crucially in the context of visual dominance phenomena — the resolution of response competition. This paper describes an extension of the contention scheduling model derived by the addition of modality specific input channels. Under a variety of conditions, the extended model exhibits many of the visual dominance effects seen in Colavita's (1974) multi-modal reaction time experiments.

The remainder of the paper begins by reviewing Colavita's (1974) results. This is followed by an outline of the contention scheduling model and a summary of our previous findings. A detailed description of the theoretical and computational extensions required of the model in order to simulate multi-modal reaction time tasks is then given, and simulations of the experiments performed by Colavita (1974) are reported. We conclude by discussing three issued raised by the modelling work: the methodological difficulties arising from the simulation of quantitative reaction time data; the relation between the current model and the theoretical literature on visual dominance; and continuing difficulties with the quantitative modelling of "conflict" reaction time.

Colavita's Reaction Time Tasks

In Colavita's experiments, subjects adjusted the intensity of a light so that it was (subjectively) equal to that of a tone. The light and tone were then used as stimuli in a number of trials in which simple and choice reaction time were assessed. In all trials, subjects placed their index fingers over two keys, one of which was designated the tone key, and the other of which was designated the light key. In simple RT trials, subjects were told before each trial which stimulus to expect, and were required to respond by pressing the appropriate key. After the simple RT trials were complete, subjects were given choice RT trials in which they were not told which stimulus would be presented on each trial. The results are reproduced in table 1, in which reaction times are given in milli-seconds and standard errors are shown within brackets. As can be seen from the table, auditory RT was less than visual RT. This difference was significant. There was no significant difference, however, between RTs in the choice condition.

Table 1: Colavita's Reaction Time Data

	Simple RT	Choice RT
Visual	197 (7.9)	299 (9.0)
Auditory	179 (7.2)	297 (8.3)

Colavita also interspersed "conflict" trials with the standard choice trials. In these trials both the tone and light were presented simultaneously. Subjects were not warned of such trials. On 98% of conflict trials, subjects responding by first pressing the light key.

The Control of Action

Norman & Shallice (1986) argue that action is controlled by a semi-automatic "slave system" (known as contention scheduling). This system may in turn be controlled by a high-level supervisory system (the supervisory attentional system), but such high-level control is only necessary in situations involving attention to detail, planning, trouble-shooting, etc. In particular, supervisory attention is not required when executing routine or repetitious tasks. For such tasks, contention scheduling may be configured appropriately (by supervisory attention) and left to operate autonomously.

The contention scheduling system is held to consist of a set of action schemas participating in an interactive activation network. Action schemas are hierarchically structured. At the lowest level they correspond to action primitives such as *pick-up* or *press-button*. At higher levels they comprise goal-oriented sets or sequences of lower-level schemas.

A number of influences act upon schema activation within the interactive activation network. Firstly, schemas may be excited (or inhibited) by environmental factors (such as the presence of a button, which may excite the *press-button* schema). In the absence of appropriate control such environmental triggering is held to cause utilisation behaviour (Shallice, Burgess, Schon, & Baxter, 1989) and capture errors (Reason, 1984). Secondly, schemas may receive excitation from higher-level schemas within the network. This top-down activation is gated such that it only flows when the parent schema is selected. Schemas are selected when their activation exceeds a threshold. Once selected, a schema will excite its component schemas (i.e., those schemas immediately below it in the hierarchy), thus increasing the likelihood that one or more of the component schemas will also be selected. Thirdly, schemas compete through the mechanisms of self activation and lateral inhibition. All schemas are self excitatory. Self excitation tends to maintain schema activation values. This maintenance is countered by lateral inhibition. Schemas are said to compete if they share resource requirements. Schemas inhibit their competitors by an amount proportional to their own activation. Fourthly, schemas at any level may receive activation directly from the supervisory system. If necessary this excitation may be directed at schemas corresponding to primitive actions, causing (under normal functioning) the direct selection of those actions. Finally, a small degree of random excitation and inhibition of schemas is assumed to exist. This random noise may ultimately lead to minor variations in the system's behaviour.

The various sources of activation, and in particular the competitive sources, lead to a system in which one schema from each set of competing schemas will become highly active (and hence be selected). Selection at the lowest level of the hierarchy leads to the execution of the primitive action corresponding to the selected low-level schema. Once performed, the activation of the schema is inhibited, allowing another low-level schema to become active. When all necessary component schemas of a high-level schema have been performed the activation of that high-level schema is also inhibited, allowing a further high-level schema to become selected. This system of inhibition after execution leads, in theory, to a dynamic system capable of performing organised sequences of action without continuous supervisory control.

The original verbal specification of the contention scheduling theory specified how actions were selected, but not how the arguments of those actions were selected. Thus, whilst the theory could account for sequencing of actions, no attempt was made to account for the selection of the objects to which those actions were to be applied (or, indeed, for the selection of the specific effectors to perform the actions). The contention scheduling theory has, however, been extended in recent computational work (Cooper et al., 1995; Cooper & Shallice, 1997) so as to incorporate argument selection. The basic mechanism consists of further interactive activation networks. Within one network, effectors compete for the "effector roles" of actions. Thus, in the case of *pick-up*, left and right hands may compete to be the hand that carries out the action. Similarly, object representations compete for the object argument roles of schemas (which specify, for example, the particular object to be picked up).

The viability of the contention scheduling theory as a theory of the control of routine action has been demonstrated by the simulation of behaviour in the complex hierarchically structured task of coffee preparation (Cooper et al., 1995; Cooper & Shallice, 1997). Successful completion of this naturalistic task, which involves the addition of various coffee-related substances to a mug of hot water, requires the execution of three intermediate-level schemas, each of which comprises four primitive actions. The actions within the intermediate-level schemas must be performed in an appropriate sequence (e.g., opening a packet of sugar before pouring the contents into the mug), but the order in which the intermediate-level schemas themselves are performed is not critical. In addition, the intermediate goals (e.g., sugaring the coffee) can be achieved by a variety of means (using either a sugar sachet or a sugar bowl).

A significant concern in this work was to demonstrate that the contention scheduling theory could account for both normal behaviour and behaviour resulting from various forms of neural damage or malfunction. Indeed, the coffee preparation task was chosen because of the availability of data concerning the errors made by neurological patients during the preparation of coffee within an institutional setting (cf. Schwartz, Reed, Montgomery, Palmer, & Mayer, 1991). With this in mind it was shown that reduced top-down activation within the schema network leads to a general disorganisation of action similar to that of Action Disorganisation Syndrome (confirming the arguments of Schwartz et al., 1991). It was also shown that reduced self activation (or equivalently increased lateral inhibition) within the schema network leads to greatly slowed initiation of action, as is seen in Parkinson's Disease.

Modelling Reaction Time Data

In order to apply the contention scheduling model to reaction time data it is necessary to augment the model by 1) relating the selection of action to real time, and 2) including modality-specific input channels. We consider each in turn.

The mechanism of interactive activation is modelled within the implementation of contention scheduling by a cyclic process. On each cycle the activations of all nodes are updated. Schemas whose activation exceeds the selection threshold are also marked as selected, and actions corresponding to any low-level schemas are performed. Within such models reaction time may be related to the number of processing cycles elapsed between stimulus presentation and action execution. For simplicity the current work assumes a linear relationship between processing cycles and time. Thus, each cycle is assumed to take a fixed number of milli-seconds, t_c, and processor time, expressed in milli-seconds per cycle, is a parameter of the simulations reported here.

Our assumption of a constant cycle time requires some justification. The time-course behaviour of interactive activation networks is crucially dependent upon the precise equations used to update activation values, and a variety of equations yield qualitatively similar behaviour (compare, for example, McClelland & Rumelhart, 1981; Houghton, 1990; Cooper et al., 1995). In order to overcome this difficulty, we consider behaviour of the model with two different activation update equations, and with a variety of different (but constant) processor cycle times. Regularities which hold over these variant implementations are more properly understood to arise from theoretical commitments within the contention scheduling theory, rather than from implementational details relating to any one particular implementation (cf. Cooper, Fox, Farringdon, & Shallice, 1996).

The contention scheduling model may be extended to reaction time tasks by the inclusion of modality-specific input channels. These channels are assumed to feed into the object representation networks which may in turn excite schemas. As figure 1 shows, these input channels are assumed to be independent, and to have separate time parameters. In the figure, t_v is the time elapsed between presentation of a visual stimulus and notification of that stimulus to the contention scheduling system, t_a is the equivalent time for an auditory stimulus, t_{cs} is the time taken by the contention scheduling system to select a response, and t_e is the time taken to press the button once the contention scheduling system has selected a response (including nerve transmission time and time to overcome effector inertia).

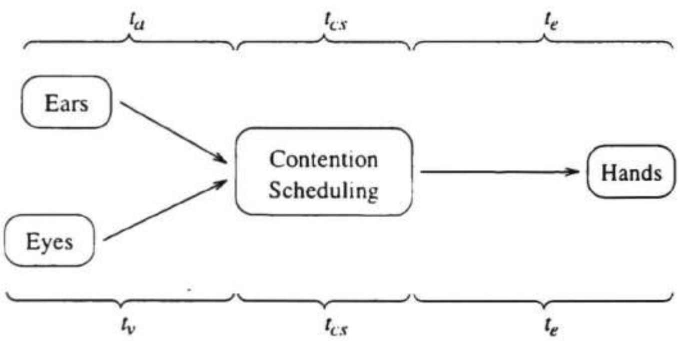

Figure 1: Hypothesised processes from percept to act

Total visual and auditory reaction time may be expressed in terms of the parameters introduced in figure 1:

$$\begin{aligned} \mathrm{RT}_v &= t_v + t_{cs} + t_e \\ \mathrm{RT}_a &= t_a + t_{cs} + t_e \end{aligned} \tag{1}$$

This may be simplified by merging effector time and channel time:

$$\begin{aligned} \mathrm{RT}_v &= l_v + t_{cs} \\ \mathrm{RT}_a &= l_a + t_{cs} \end{aligned} \tag{2}$$

l_v and l_a are referred to as visual and auditory lag, and are given by:

$$\begin{aligned} l_v &= t_v + t_e \\ l_a &= t_a + t_e \end{aligned} \tag{3}$$

Furthermore, as noted above we assume a linear relationship between processing time and processing cycles:

$$t_{cs} = \text{\# of processing cycles} \times t_c \tag{4}$$

The behaviour of input channels is assumed to be influenced by a second parameter, the channel's strength (or weight). A channel's strength determines the impact of signals travelling through that channel on the contention scheduling system. Within the model, visual dominance is held to arise from the interaction of strength and timing parameters within the different modalities. In particular, the strength of the visual channel is assumed to be greater than that of the auditory channel (leading to dominance of the auditory channel by the visual channel under simultaneous stimulus presentation), but the auditory channel's time lag is assumed to be less than that of the visual channel (leading to shorter reaction times in the auditory modality than in the visual modality when stimuli are presented separately).

In sum, the extended model, with auditory and visual perceptual channels, includes 5 parameters above and beyond those present in the original model: auditory lag (l_a), auditory channel strength (s_a), visual lag (l_v), visual channel strength (s_v), and cycle time (t_c). An extensive investigation of regularities that hold across this 5-dimensional parameter space is necessary before sound conclusions relating to the application of the contention scheduling theory to visual dominance phenomena can be drawn.

In order to simulate Colavita's simple and choice RT tasks within the extended contention scheduling system it is also necessary to specify appropriate schema networks. We assume that the difference between the simple and choice tasks lies purely in the schemas installed in these networks, and that all numeric parameters of the complete system are fixed across the tasks. We further assume that all parameters governing flow of activation within the contention scheduling system have domain-independent values. We therefore fix these parameters to the values used in the coffee preparation task (Cooper & Shallice, 1997).

Simple Reaction Time

Although qualitative similarities between the behaviour of the model and that of Colavita's subjects may be established without difficulty, the establishment of quantitative equivalences is less straightforward. We begin with the simple RT task and a fixed update equation. We assume that the task requires four schemas: one which detects when a stimulus is present, one which detects when a stimulus is not present, one which corresponds to a key press, and one which corresponds to abstinence of a key press.[1] The hierarchical network structure of these schemas is shown in figure 2, where italic font is used to indicate schema names and bold font is used to indicate goals.

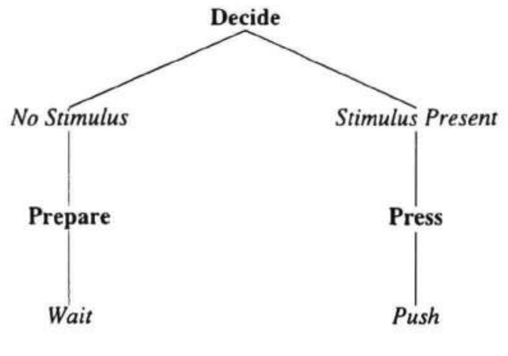

Figure 2: Simple RT Schema Hierarchy

Note that the schema hierarchy of figure 2 is independent of modality. As the difference between visual and auditory channels is assumed to result from their different parameter values, it is possible to adopt a modality-free approach to the exploration of the relation between these parameter values and reaction time. In what follows, we use the parameters s and l to refer to modality-free channel strength and lag.

The schema hierarchy of figure 2 does indeed yield a system capable of simulating simple RT behaviour. Qualitatively normal reaction time behaviour (i.e., pressing of the appropriate key shortly after the appearance of a stimulus) occurs over a wide range of parameter values, but the number of processing cycles required of contention scheduling before an action is effected is highly dependent upon the channel strength (as would be expected). This relation is shown graphical in figure 3 (where channel lag is set to zero). The effect of increasing channel lag is to add a constant time to total reaction time. As noted above, the effect of modifying cycle time is to multiply reaction time by a constant.

The results plotted in figure 3 are derived from the simulation of 100 trials at each of 51 values of s ranging from 0.00 to 1.00. A non-linear regression suggests an exponential relation between number of cycles and the square of channel strength:

$$\#\,\text{cycles} = 39.3 + 23.8 \times e^{-5.1 \times s^2} \quad (5)$$

This provides a good fit to the data, with an RMS error of 0.48 cycles over the 51 data points.

For any value of s_v and c_t, equation 5 may be used in conjunction with equations 2 and 4, and the simple reaction times reported by Colavita and reproduced in table 1, to determine a value of l_v which will yield a simple visual reaction time near to that of subjects. Similarly for any value of s_a an appropriate value of l_a may be determined. The equations effectively allow the isolation of lines of fixed RT (geodesics) within [Strength × Lag] space. Figure 4 shows two such lines, corresponding to the observed simple auditory and visual reaction times (with t_c = 2 milli-seconds per cycle).

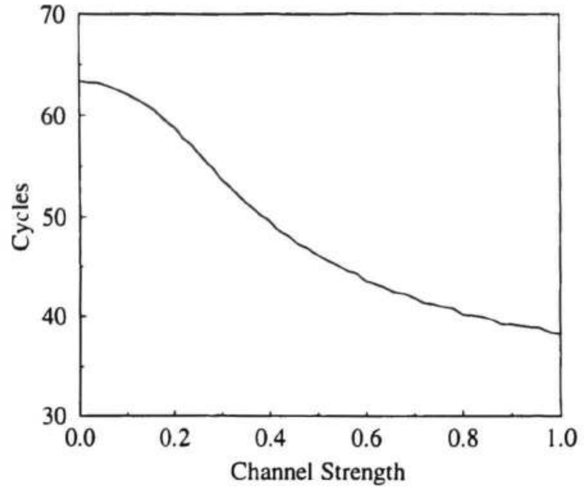

Figure 3: RT (in Cycles) as a Function of Channel Strength

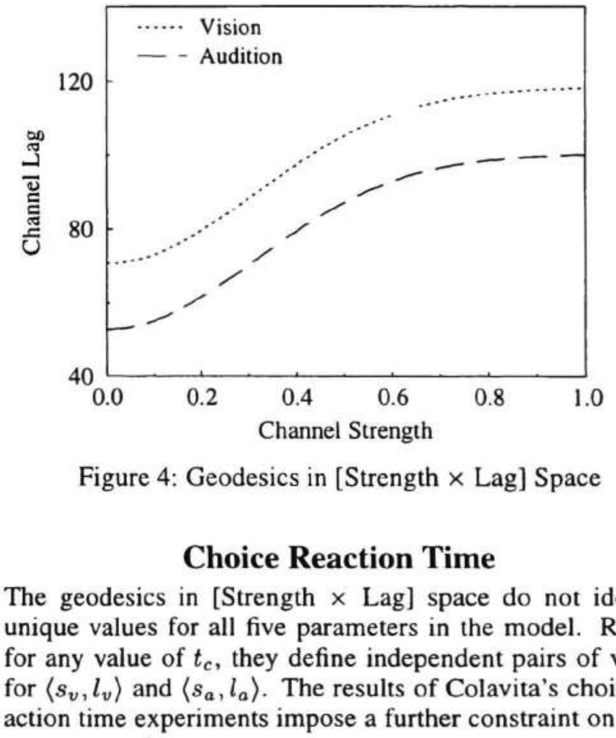

Figure 4: Geodesics in [Strength × Lag] Space

Choice Reaction Time

The geodesics in [Strength × Lag] space do not identify unique values for all five parameters in the model. Rather, for any value of t_c, they define independent pairs of values for $\langle s_v, l_v \rangle$ and $\langle s_a, l_a \rangle$. The results of Colavita's choice reaction time experiments impose a further constraint on these parameter values.

A further set of simulations aimed at reproducing choice reaction time behaviour was therefore performed. In these simulations, the schema hierarchy given in figure 5 was employed. It is assumed that this corresponds to the schema hierarchy that a subject would employ when s/he was not warned of the stimulus modality before presentation of the stimulus (as in Colavita's choice RT experiments). All other aspects of the model remained as in the simple reaction time simulations.

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[1] The competitive mechanisms within contention scheduling require that all schemas have at least one competitor. Hence, schemas are required for both situations in which a stimulus is present and those in which no stimulus is present.

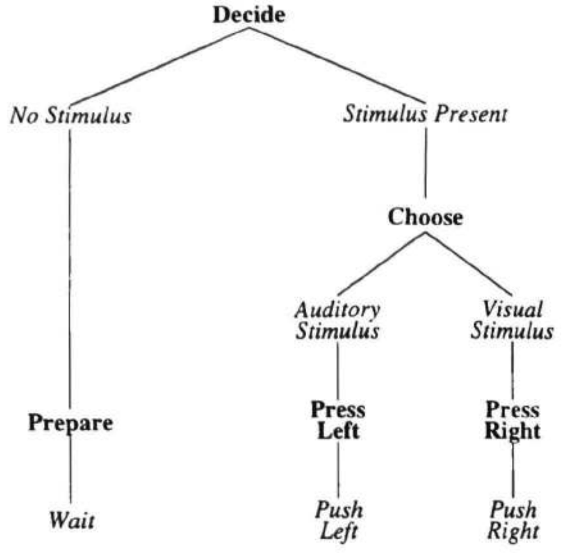

Figure 5: Choice RT Schema Hierarchy

Comparison of the schema hierarchies of figures 2 and 5 shows that choice reaction time requires selection of an additional schema identifying the modality of the stimulus. When a single stimulus is presented (as in Colavita's standard choice RT trials), this additional step allows more time for differences in channel strength to play a role, and the greater strength of the visual channel cancels out that channel's greater lag.

The schema hierarchy of figure 5 was found to yield the observed choice reaction times when, for example, $t_{cs} = 1$, $\langle s_v, l_v \rangle = \langle 0.141, 136 \rangle$, and $\langle s_a, l_a \rangle = \langle 0.128, 117 \rangle$. These $\langle s, l \rangle$ pairs lie on the appropriate geodesics, and so are guaranteed to also yield appropriate simple reaction times.

Further Results

As noted above, merely showing that the model can reproduce the Colavita data with *one* appropriate configuration of parameters is, methodologically, a poor test of the model. Firstly, it may be argued to be little more than parameter fitting. Secondly, it may lead to the results being interpreted too strictly (by implying that the true value of each parameter has been determined). We therefore adopt a strategy of providing multiple parameter configurations, with two activation update equations, which give rise to the data reported by Colavita. Table 2 presents a series of such parameter/equation combinations arrived at by the method described in the preceding sections. All equation/parameter combinations in this table lead to reaction times within 5 milli-seconds (i.e., less than 1 standard error) of those in table 1.

In this table, equation refers to the function used to calculate change in activation in terms of current activation and net input. The "tanh" function is that used by Cooper & Shallice (1997). This function specifies that the activation of a schema node at any time t is the hyperbolic tangent of the sum of the net input at that time plus 0.80 times the net input at time $t-1$ plus 0.80^2 times the net input at time $t-2$ plus 0.80^3 times the net input at time $t-3$ and so on. 0.80 is a parameter, the persistence of previous input, which serves a role similar to that of decay in other interactive activation work. The "sigmoid" equation is similar to tanh, except that the sigmoid or logistic function is used in place of the hyperbolic tangent and a persistence parameter of 0.90 is used.

Table 2: Parameter Values

Equation	t_c	s_v	l_v	s_a	l_a
tanh	1	0.141	136	0.128	117
tanh	2	0.210	80	0.191	60
tanh	3	0.262	28	0.237	7
sigmoid	0.5	0.140	136	0.130	118
sigmoid	1	0.210	81	0.192	61
sigmoid	1.5	0.260	29	0.241	9

Conflict Reaction Time

We assume that in Colavita's conflict trials — when visual and auditory stimuli are presented simultaneously but when the subject is expecting only one stimulus to occur — the supervisory system deploys the same schema hierarchy as is used in standard choice trials. In the vast majority of such situations Colavita found that subjects responded first to the visual stimulus, and frequently appeared totally unaware of the presence of the auditory input. Mean reaction time in these situations was 303 milli-seconds, which, though greater than choice reaction time for stimuli in either modalities, was not significantly so.

When simultaneous visual and auditory stimuli are presented to the model qualitatively similar behaviour is observed: the visual response dominates, with a slowed reaction time. Because auditory lag is less than visual lag, the schemas corresponding to the detection of an auditory stimulus initially react more quickly than those corresponding to detection of a visual stimulus. The activation of auditory related schemas begins to rise. Once the input from the visual stimulus arrives at the schema network, however, the strength of the visual input causes the activation of visual-related schemas to quickly exceed that of auditory-related schemas, despite the lateral inhibitory competition between the two. When the visual schemas are more active than the auditory schemas, the visual schemas quickly inhibit the auditory schemas, causing the activation of auditory schemas to fall back to near rest. Once a visual response is given, the visual schemas are inhibited. If the auditory stimulus is still present, this allows the auditory schemas to reactivate and become selected. The basic effect is illustrated in figure 6, which shows the salience of each stimulus throughout a typical conflict trial.

All settings of strength and lag parameters investigated in the previous section led to the visual stimulus being prepotent (i.e., an initial visual response under conflict conditions). However, the extent of slowing in the response is consistently far greater (generally by approximately 100 milli-seconds) than that observed in subjects by Colavita (1974).

General Discussion

We have developed a model of visual dominance based on parallel pre-processing of visual and auditory stimuli and subsequent competition at the level of the control of action. The model builds on Norman & Shallice's (1986) contention

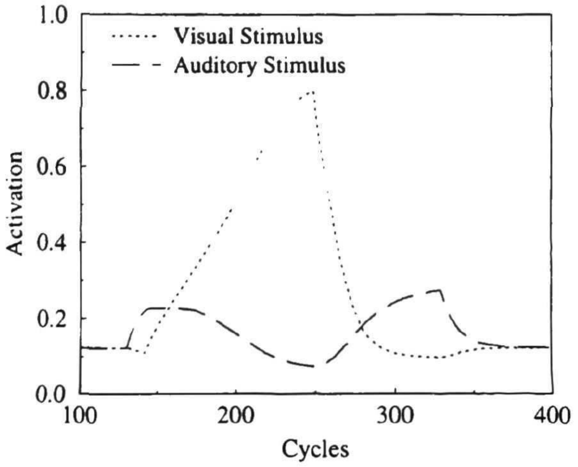

Figure 6: Object Salience During a Conflict Trial

scheduling theory of routine action selection via the addition of visual and auditory input channels. Simulations have been presented which show that the augmented action selection model is capable of producing quantitatively accurate RTs in simple and choice reaction time tasks.

Despite these successes, there are a number of caveats which must be applied to the current work. Most significantly, there are a variety of methodological difficulties which surround any attempt at quantitative modelling of reaction time data. In the current case, specific values for five parameters are necessary before quantitative results can be produced. By providing such values we do not mean to suggest that parameters with these specific values apply to the cognitive system. Rather, we have shown — by demonstrating a number of sets of suitable parameter values and two alternate activation functions — that a system of this general sort is capable of producing the qualitative *and* quantitative behaviour exhibited by normal subjects under four different task conditions. Quantitative modelling of a fifth condition, simultaneous presentation of visual and auditory stimuli, has proved elusive, although the qualitative effects seen in this condition are reproduced by the model.

The model also sheds some light on theories of visual dominance. Colavita (1974) provides a tentative explanation of his reaction time results in terms of a serial model of attention in which attention is switched between modalities. He suggests that his results would arise from such a model if the visual channel were sampled more frequently than the auditory channel. Such an explanation also requires that visual processing be inherently slower. Posner *et al.* (1976) suggest instead that visual dominance arises from the interaction of a number of properties of attention. In particular, they suggest that 1) visual signals are less alerting than signals deriving from other modalities; and 2) in an attempt to compensate there is a processing bias towards the visual modality. Our model shares much with the approach of Posner *et al.* (1976). Greater visual strength amounts to a processing bias for the visual modality. Such a bias can also be seen as a compensatory mechanism that operates to enhance visual input that would otherwise be disadvantaged by a lag which is greater for the visual modality than for other modalities. Such a visual lag, however, does not directly correspond to Posner *et al.*'s proposition that visual signals are less alerting than signals deriving from other modalities, although this proposition might follow as a result of the magnitude of visual lag.

Despite the difficulties mentioned in the preceding paragraphs, the strengths of the model (as an extension of an existing action selection model, and as providing an account of visual dominance in Colavita's simple and choice reaction time tasks) suggest that it is worthy of further investigation.

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