Positive and Negative Congruency Effects in Masked and Unmasked Priming: Match of representation strength, Attention, and Consciousness

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Your file Votre référence
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To Shahin and our parents

ABSTRACT

In this thesis different data were analyzed, including behavioural performance (speed and accuracy), fMRI brain activation, and modelling simulation, to investigate the underlying processes in perceptual and symbolic, masked and unmasked magnitude priming. The perceptual stimuli were either simple or Müller-Lyer lines and the symbolic stimuli were either Arabic numerals or arbitrary symbols memorized and treated as numbers. These factors and contextual information affecting attention and conflict (and factors investigated in previous studies) were all supposed to fit in the match of representation strength as the main factor. The manipulation of this factor changed the performance in decision on the magnitude in the behavioural performance measured as the congruency (priming) effects i.e., performance in the congruent compared to incongruent trials. Stimuli with high strength caused a positive congruency effect and stimuli with low strength caused a negative congruency effect, especially when both prime and target had low strength of representation. Cueing the target made these effects disappear.

With regard to the difference in the masked and unmasked conditions, it will be argued that in the unmasked priming attention is drawn to the relevant, and is withdrawn from the irrelevant prime, increasing and decreasing the match of representation strength, respectively (based on the task context). The fMRI brain activations and behavioural data showed the difference between masked and unmasked and illusory and non-illusory conditions.

The model illustrated the role of major factors in the match of representation strength, including the attentional modulatory effects on those factors. The model simulated both types of congruency effects in the experimental data and accounted for main factors in masked and unmasked priming including, but not limited to, the prime and target strength, the role of mask, the time and length of stimulus presentation, stimulus degradation, attention, and conflict. A prime with a strong representation caused high activations, including attentional responses, and caused a positive congruency effect when the target came early, but when the target came late or both prime and target had low strength the congruency effect was negative.

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Chapter 1: Introduction

In the current study, the size and direction of priming (see below) are measured to show how it is affected in terms of speed and accuracy by different factors such as masking, type (here, illusory and non-illusory lines and symbols and numerals), distance from a reference (here, the distance of a single digit number from *five*), and cueing. A functional Magnetic Resonance Imaging (fMRI) experiment was conducted to reveal the effect of masking and illusion on brain activations. A model was then developed to investigate the role of the main factors and their interactions with attentional and other cognitive resources in a unified way based on the match of representation strength framework.

Most cognitive tasks, including those in the current thesis, are two-alternative forced choice task. In the experiments employing these kinds of tasks, if evidence for one of the two alternatives exceeds a threshold, a response indicating that alternative is triggered. Evidence for one or the other alternative is supposed to be affected by the target stimuli and all relevant stimuli in the task, as well as the attention. As will be further discussed after reviewing the literature, match of representation strength refers to the overall neural activation caused by the prime, target and contextual information that favours a given representation over its alternative(s).

The usual way in the literature to describe the difference made by masking is to say that without a mask, participants are conscious of the stimulus, but with a mask they are not. However, this is a questionable way of describing the difference. Who is to say that participants are not still conscious of the stimulus after it is masked? Maybe they are just not conscious of being conscious of it. In fact, all we know with real reliability is that they can no longer report on what the stimulus was. I am going to by-pass all the issues that arise here about consciousness, memory, and so on by using an entirely neutral concept, the concept of reportability. Without a mask, subjects can report what the stimulus was. With a mask, they cannot. This concept captures the crucial difference and it does so in a way that is unproblematic in itself and neutral with respect to the bigger underlying issues.

The thesis consists of five chapters. The current chapter is an introduction. Other chapters include an fMRI study (Chapter 2), three behavioural experiments (Chapter 3), a computational model (Chapter 4), and finally a discussion (Chapter 5). As will be further described shortly, the experiments use the priming paradigm with new stimulus types. The results reveal what is known as the congruency effect and the difference between masked and unmasked priming. The neuro-computational model matches the findings in this thesis and previous experimental studies, with new and/or better results compared to previous models in this area (which are fairly rare). Thus, it may simulate the underlying neuro-cognitive processes. The last chapter is a discussion of the results of the thesis and previous studies, limitations and future studies.

The main experimental findings in the thesis include a priming effect for line length comparison similar to what was found in previous studies on numbers and shapes, a priming effect for illusory line length comparison similar to that found for non-illusory lengths, higher brain activation in the unmasked compared to the masked and illusory compared to the non-illusory priming conditions, especially when the prime was unmasked, reversal of priming in the masked condition when numerals primed symbolic encoding of numbers, mainly when the distance was close, and finally the disappearance of priming effects when the target type (symbol versus numeral) was cued. The model matched the main experimental findings in this thesis and in relevant previous studies, including the role of prime and target strength, the effect of masking (the difference between the masked and unmasked conditions), the degradation effect, the relation of mask to prime and target, the prime duration effect, the prime-target interval, and other effects.

Overview of masked and unmasked priming

Priming

In priming tasks, a brief stimulus (the prime) can affect the processing of the stimulus that follows (the target). This priming can have two, opposite effects. One is positive and is called the Positive Congruency Effect (PCE), also known as the positive compatibility effect, where the prime improves the performance on the target if they are congruent and decreases the performance if they are incongruent. For example, participants were asked to press the left response button when a female face was presented and to press the right response button when a male face was presented (e.g., Enns & Oriet, 2007). When a female face was preceded by another female face, the task was performed faster than when a female face was preceded by a male face, although the task was just to respond to the second face. The other priming effect is negative and is called the Negative Congruency Effect (NCE), also known as the negative compatibility effect, where paradoxically the prime improves the performance on the target if they are incongruent and decreases the performance if they are congruent. For example, participants were asked to press the left response button when a happy face was presented and to press the right button when an angry face was presented. Under some conditions (see below), when a happy face was preceded by an angry face, the response was paradoxically faster than when a happy face was preceded by a happy face (Bennett, Lleras, Orient, & Enns, 2007). The change in priming directions is caused by a variety of different factors (see below) but it has been mainly attributed to the prime visibility (i.e., reportability) by some researchers (e.g., Eimer & Schleghecken, 2002; Breitmeyer, Ogmen, Ramon, & Chen, 2005), although this is argued to be irrelevant by others (e.g., Verleger, Jaśkowski, Aydemir, van der Lubbe, & Groen, 2004; Lleras & Enns, 2004, 2005, 2006).

Masking

Several studies have shown changes in cognitive processing by manipulating the visibility of stimuli. Some of these researchers have argued for a fundamental difference between unconscious and conscious states (e.g., Marcel, 1983; Dehaene et al., 1998, Dehaene, Artiges, Naccache, Martelli, Viard, Schürhoff, et al., 2003; Klapp & Hinkley, 2002; Eimer & Schleghecken, 2002; Breitmeyer et al., 2005; but see Verleger et al., 2004; Lleras & Enns, 2004, 2005, 2006; Klapp, 2005).

To find changes in cognitive processes related to consciousness, scientists usually render stimuli unreportable using a variety of experimental methods. A widely used method to make stimuli unreportable is masking (for reviews see Enns & Di Lillo, 2000; Kim & Blake, 2005). In the masking paradigm, the perception of a target stimulus is usually attenuated by a subsequent stimulus, called a backward mask or a preceding stimulus, called a forward mask.

The masking phenomenon is generally thought to occur by its competition, interruption, or substitution effects. According to the competition hypothesis of masking (Keysers & Perrett, 2002; Kim & Blake, 2005), in forward and backward masking, where a target stimulus is preceded and followed by masks, the masked stimulus competes with the forward mask and the backward mask competes with the masked stimulus. The new stimulus generally wins but it is also affected by the earlier stimulus. The superiority of the mask over the masked stimulus produces the masking phenomenon, i.e., the reportability of the mask instead of the masked stimulus.

In the interruption hypothesis of masking, the mask interrupts the perception of the masked stimulus (Kahneman, 1968; Enns & Di Lillo, 2000, Lamme, 2000). For example, for backward masking, Lamme (2000) argues that the interruption abolishes "re-entrant signals" that are required for the reportability of the target. For forward masking it has been argued that the target's invisibility is caused by reduced target contrast at peripheral stages of processing (Kim & Blake, 2005).

Similar to the hypotheses mentioned above, the object substitution/updating hypothesis proposes that the newer stimulus substitutes for or overrides the older one (e.g., Enns & Di Lillo, 2000; Lleras & Enns, 2004). The difference between this theory and previous ones is that it proposes a more active role for the mask. The re-entrant processes play an important role in stimulus identification in this hypothesis. The re-entrant processes evoked by the masked stimulus are affected by the mask. If the identification of the masked stimulus, through re-entrant and attentional processes, is incomplete when the mask arrives, those processes will be taken over by the mask and consequently will serve its identification. Some evidence for this hypothesis comes from experimental studies (see below) where a stream of targets and masks are presented and participants are asked to report the target(s) and ignore the distractors (masks). For example, it has been shown that participants report the mask instead of the target, showing that the mask can play the role of the target by replacing or updating it (Enns & Di Lillo, 2000).

In terms of using masking to manipulate the reportable and unreportable (the so called conscious and unconscious perception of a stimulus), Kim and Blake (2005) have argued that backward masking (without forward masking) has some limitations. For example, in a way similar to stimulus degradation (e.g., by adding random dots to the background), it makes abnormal changes to physical stimuli. They suggest dealing with these limitations by using techniques such as looking at the results in terms of hits (correct responses) and misses (no responses until response deadline) under identical masking conditions or both forward and backward masking. They also mention that sometimes a masked target may be unidentifiable (the participant cannot report its identity), though detectable.

Therefore, it seems that the presented stimuli compete for attention and if the masking stimulus is set up right, it will render the masked stimulus unavailable for conscious reporting and also can affect the performance on, or visibility of, the subsequent stimulus. Although a masked stimulus usually cannot be reported, it can create a priming effect. However, the effect of the mask heavily depends on the type of mask (see below).

Masked priming

In the masked priming paradigm, a masked prime is followed by an unmasked target and participants are asked to respond to the target. Prime and target are either congruent or incongruent regarding the required response. Although the task is to respond only to the target, it has been shown that participants apply the task instruction to the prime as well (Dehaene et al., 1998).

In the following sections, I will review previous studies that have investigated some of the main factors in the priming effect. As will be discussed in detail, these factors include the role of the mask, the timing of stimulus presentation (onsets and durations), stimuli (physical) degradation, semantic features (e.g., magnitude), and attention, to name but a few. Physical features other than duration, such as low degradation, brightness, and other salient features, and similarly, semantic features, such as notation (e.g., Arabic numeral vs. number word) and numerical magnitude, all have been shown to affect the priming patterns. Learning to the level of automatic stimulus-response mapping is another main factor in priming, especially with brief primes. Among these factors, a crucial factor is the time of stimulus presentations. Mask and target need to be presented at specific temporal points with regard to the prime. These timing factors, especially the prime-target Stimulus Onset Asynchrony (SOA), prime-mask Inter-Stimulus Interval (ISI), and mask-target ISI, interact with other factors in a dynamic way that has not been fully explained. We will now review some priming studies that have employed visual masking and look at the results of different patterns of priming, the role of the mask, and other relevant phenomena.

Positive effect in priming

Studies on priming have long shown reliable positive effects of the congruent prime on target processing, i.e., PCE. An early study, in the age of using tachistoscopes, was one conducted by Marcel (1983), consisting of a word naming experiment and a colour naming experiment. In his word priming experiment, he found the usual masked priming, i.e., a PCE, by words: the target words (e.g., tree) were named faster when they were preceded (primed) by relevant (congruent) masked words (e.g., wood) than when they were preceded by irrelevant (incongruent) masked words (e.g., glass). An interesting finding in Marcel's experiment was an effect related to the conflict notion used in this thesis (it will be introduced later). It was that a greater priming effect was found in a group of participants who engaged in the task passively, i.e., they tended to select target words which "felt right", in Marcel's words, than actively.

Marcel's (1983) colour naming experiment was a modified Stroop task. In the classic Stroop task (Stroop, 1935, for a review see MacLeod, 1991), colour words, e.g., the word "blue", are presented and participants are asked to name the colour of the colour word and ignore the word, or read the colour word and ignore its colour. The colour word and its colour can be either congruent or incongruent, e.g., the word "red" written in red and the word "red" written in blue, respectively. It has been shown that Reaction Times (RTs) increase in the incongruent compared to the congruent trials, especially in colour naming (for more details and a model, see Appendix F, Part 2). Using his modified Stroop task, Marcel asked participants to name a colour patch as fast as possible by choosing one of the four buttons corresponding to each of the patches. In each trial, after

1s, a colour name (prime) appeared followed by a colour patch (target), either simultaneously or 400 ms later. Moreover, a random pattern mask replaced the prime either with a 400 SOA ms delay or at a predetermined prime-mask SOA (matched to each participant's threshold in detecting brief stimuli). The mask and colour patch remained until the participant's response. So, either the onsets of the word and colour patch were simultaneous (i.e., 0 ms prime-target SOA) or the word onset was 400 ms before that of the colour patch (i.e., 400 ms prime-target SOA), forming two conditions in terms of word-colour SOA. Likewise, either the mask followed the word after 400 ms or after 30-80 ms depending on each participant's threshold, forming the two conditions in terms of word-mask SOA. Participants could not report the masked words (colour names). The result showed a PCE with differences between the masked and unmasked conditions. Participants were slower in the incongruent trials, especially in the unmasked condition and more specifically in 0 SOA. They were faster and more accurate in the congruent compared to the incongruent conditions, especially in the masked condition with 0 ms SOA and in the unmasked condition with 400 ms SOA condition. The effect was PCE, i.e., a regular congruency effect. A possible confound in this experiment was the use of a longer prime duration in the unmasked condition that can account for main differences in masked and unmasked conditions; however, the effect of masked priming showed that masked stimuli are indeed processed to the level of response. Later studies using equal prime durations for primes in both unmasked and masked conditions showed similar results, i.e., PCE-type masked priming effect (e.g., Neumann & Klotz, 1994; Dehaene et al., 1998; Eimer & Schleghecken, 2002; Reynvoet & Brysbaert, 2004) and masked and unmasked differences (e.g., Cheesman & Merikle, 1986; Dehaene, Artiges, et al., 2003; Schleghecken & Eimer, 2002, see below).

In the numerical priming paradigm (e.g., Dehaene et al., 1998), participants are asked to compare numbers to *five.* A small prime (e.g., 1) is congruent with a small target (e.g., 4) and similarly a large prime (e.g., 6) is congruent with a large target (e.g., 9). In contrast, small and a large numbers are incongruent. Dehaene et al. briefly presented a prime (e.g., 4) that was masked by being sandwiched between two flashed random patterns, followed by a target (e.g., 3). Participants had to decide whether the target was larger or smaller than *five* in magnitude. The prime and target numbers could be larger or smaller than *five,* encoded in Arabic numerals or words (spelled-out), and incongruent or congruent conditions. They found a significant positive priming for numbers in both Arabic and verbal encodings. Dehaene et al. attributed the numerical priming, especially with different notations and non-repeated priming (e.g., 1 priming 3), to semantic processes. The involvement of semantic processes has been challenged by some studies (e.g., Kunde, Kiesel, & Hoffmann, 2003). Kunde et al. argued that these types of priming happen as a result of stimulus-response mapping without the involvement of semantic processes. However, a study by Naccache and Dehaene (2001) supported the semantic interpretation. They included new primes that had not been used as targets at all and found that new primes could cause a priming effect similar to old primes that had been used as targets. For example, when the numerals 2 and 3 (smaller than *five*) or 7 and 8 (larger than *five*) were used as the prime and target, the numerals that have not been used at all did produce a priming effect.

In the masked priming studies mentioned above, there were at least three stimuli, the prime, the mask, and the target. Another technique to render stimuli unreportable is called metacontrast masking, which can have only two stimuli, either congruent or incongruent. The second stimulus plays the role of target and the metacontrast mask at once. If the mask comes early enough, it can render the first one (prime) unreportable. Using this method, Neumann and Klotz (1994) found faster RTs in the congruent trials where a square was followed by another square (with different form) than in the incongruent trials where a square was followed by a diamond. They attributed such effects to direct "perceptuo-motor links" that enable direct stimulus-response processing in these types of shape stimuli.

Negative effect in priming

In priming studies, including those mentioned so far, the prime usually facilitates the processing of the target, i.e., creates a positive priming effect or PCE. Paradoxically, a negative priming effect, i.e., NCE, has also been found, showing faster and more accurate responses in the incongruent compared to the congruent trials (e.g., Schleghecken & Eimer, 2000, 2002, 2006; Eimer, 1999; Eimer & Schleghecken, 1998; 2001, 2002; Lleras & Enns, 2004, 2006; Verleger et al., 2004; Jaśkowski & Ślósarek, 2006). This NCE pattern of priming is the opposite of PCE. The PCE has been found usually with verbal and shape stimuli and a short mask (e.g., 71 ms, as in Dehaene et al., 1998) and no or a small interval between stimuli. In contrast, the NCE has been shown mainly with arrow stimuli and a longer mask (e.g., 100 ms). Recently, it has been replicated with other stimuli, for example shapes (Jaśkowski & Ślósarek, 2006) and faces (Bennett, Lleras, Orient, & Enns, 2007). This effect has been found by using a long mask (about 100 ms) and a long mask-target SOA (>80 ms) or a long (> 30 ms) prime-mask ISI or mask-target ISI (e.g., Eimer & Schleghecken, 1998, 2002; Jaśkowski & Ślósarek, 2006). These manipulations all increase the prime-target SOA.

To explain these results, Schleghecken and Eimer (2000), especially based on Event Related Potential (ERP) measurements, argued that when SOA is short, response selection can already take place during the initial response activation phase (shown by an early increase in ERP), and this should result in the congruency effects in the form of a PCE. When SOA is longer, responses have to be selected during the subsequent inhibitory phase (shown by a decrease in ERP for congruent compared to incongruent trials), and this should be reflected as a negative priming effect (NCE). They attributed the reduction in ERP activity to a motor self-inhibition, causing the NCE effect (see below).

In another study, Schleghecken and Eimer (2002) systematically added random-dots to the stimuli and their background to degrade the perception. They showed that degradation of the stimuli can change NCE into PCE. While undegraded stimuli created an NCE, degraded stimuli turned it into a small PCE. Moreover, Eimer and Schleghecken (2002) manipulated the duration of the prime and the density of the mask in separate experiments. Increasing the prime duration from 16 ms to 32 ms increased the NCE, and from 32 ms to 48 ms decreased the NCE, and further increase turned NCE to PCE. Increasing mask density (the number of lines in the mask) from 0% to 5% decreased PCE and from 5% to 10% turned PCE into NCE; more increase made no more difference. As mentioned above, Eimer and colleagues attributed the NCE to an automatic inhibition of the response to the prime (e.g., Eimer & Schleghecken, 1998; Klapp & Hinkley, 2002; Schleghecken & Eimer, 2002; Seiss & Praamstra, 2004; Praamstra & Seiss, 2005). Their computational model (Bowman, Schleghecken, & Eimer, 2006) uses an inhibitory activation from a layer that inhibits the preceding layer, based on previous neurocomputational models of self-inhibition (e.g. Arbuthnott, 1995; Houghton, Tipper, Weaver, & Shore, 1996).

However, Eimer and colleagues' motor self-inhibition hypothesis has been challenged recently. Before reviewing the evidence against their hypothesis, two neuroscientific studies of their own could be mentioned because they are not consistent with mere motor self-inhibition. Firstly, Haggard and Eimer (1999) measured the ERP (both the readiness potential, RP and lateralized readiness potential, LRP) in a Libet task.[1] The LRP, but not RP, differentiated the early and late reportability of movement initiation. They concluded that the process that underlies the LRP is involved in the reportability of movement initiation (i.e., voluntary action initiation, which is pre-motor). At least this being pre-motor may indicate the involvement of a pre-response process of some kind, rather than motor inhibition, in NCE, as LRP also has been shown to be involved in NCE (e.g., Eimer & Schleghecken, 1998; 2000; Verleger, Ewers, & Jaśkowski, forthcoming paper cited in Jaśkowski & Ślósarek, 2006). More evidence for

[1] Libet, Gleason, and Wright (1983) asked subjects to perform a simple action, e.g., flexing their wrists, whenever they liked in a given period of time. At the same time, they had to memorize the exact time of being able to report the urge to move while looking at a special clock. Libet et al. used ERP and found that the RP component emerges about 350 ms before the willingness to move and the willingness occurs about 150 ms before the actual movement. They concluded that human voluntary movements (related to free will) are initiated unconsciously.

the involvement of a pre-response (non-motor) process in NCE is a study that used Transcranial Magnetic Stimulation (TMS). Schleghecken, Münchau, Bloem, Rothwell, & Eimer (2003) showed that stimulating the motor area by TMS has no effect on PCE and NCE.

Taking into account the similarity of the mask and the prime (e.g., Lleras & Enns, 2004; Verleger et al., 2004), recent studies have argued that a prime with a mask similar to it or to the target can activate a response opposite to the response indicated by the prime itself. Lleras and Enns (2004) attributed the NCE they found with masked arrows to the perceptual interaction between the arrow prime and its similar mask. They argued that the mask has some features in common with the prime, but the opposite features also exist that can activate the opposite response by itself, because it "updates" the initial response (in an opposite way). The similarity between mask and prime is obvious in the arrow priming experiments where masks are superimposed arrows, but Lleras and Enns (2006) have argued for feature similarities between arrow primes and other random patterns as well. Verleger et al. (2004) and Lleras and Enns (2004) hypothesized that the NCE is not caused by self-inhibition but results from two consecutive positive priming processes with opposite directions. Lleras and Enns's hypothesis is called "object-updating" and argues that stimuli are searched for task-relevant features to be used in directing behaviour. Only new elements need updating. A mask that is similar to the prime stops the prime and/or evokes the opposite response, because the new parts need updating but not the repeated parts. Similarly, Verleger et al.'s "active-mask" hypothesis is also based on the interactions between prime and mask. In their "dialectics" hypothesis, Verleger et al. (forthcoming paper cited in Jaśkowski and Ślósarek, 2006) argued that "object updating" accounts only for similarity, not type (letters versus arrows) of mask, prime, and target. They argued that behavioural data and ERP evidence indicate that an interruption of the prime arrow causes activation opposite to the arrow direction, and it is because arrows form natural pairs that they can cause NCE.

Jaśkowski and Ślósarek (2006) provided more evidence for the dialectics model. They showed that NCE occurs with non-arrow stimuli but it is stronger with arrows than with other shapes, consistent with Verleger et al.'s (2006) dialectics hypothesis. They also found that negative priming can be found with reversed hand-arrow assignments (i.e., responding with the left hand to the right pointing arrows and vice versa), showing that negative priming is not due to the ''natural'' meaning of arrows, but due to "natural" pairing, consistent with the dialectics and object updating hypotheses. In both Lleras and Enns's and Verleger et al.'s hypotheses, the mask plays a role by providing evidence for the primed response, not by removing the evidence, as is argued by Eimer and colleagues.

Evidence provided by Verleger et al. (2004) and Lleras and Enns (2004) comes from experiments that have shown no or small NCE for non-arrow masks, masks with horizontal and vertical lines, and randomly arranged squares. In a reply, Schleghecken and Eimer (2006) claimed that these counter-arguments do not provide a complete explanation of NCEs for all conditions. They found NCEs using random pattern masks (lines as in Lleras & Enns, 2004 and checkerboards as in Verleger et al., 2004) that apparently had no similarities to arrow primes.

In response to the findings showing NCEs for random masks, Lleras and Enns (2005) argued that when prime and target appear at the same location, attentional or perceptual processes are triggered, not a low-level motor inhibition. But NCE has also been found for primes and targets presented at different locations (Eimer, 1999; Praamstra & Seiss, 2005; Schleghecken & Eimer, 2000; Seiss & Praamstra, 2004; Jaśkowski & Ślósarek, 2006). In a recent reply especially to Schleghecken and Eimer (2006), Lleras and Enns (2006) showed the effect of the prime and mask relationship using geometrical similarity. They found that NCE is increased if prime and mask have more features in common (geometrical, spatial, and temporal, and in relation to the target). In contrast, priming becomes positive when they lack these features. Therefore, Lleras and Enns (2004) proposed that the distinct physical events of prime and mask can be interpreted as an evolving instantiation of a single object.

As mentioned above, in another experiment, Eimer and Schleghecken (2002) found that the number of lines in a mask (i.e., mask density) affects the direction of priming (turning it from positive into negative) as well as the prime visibility (see below). They argued that NCE relates to a threshold level of prime strength that is decreased by high density masks (see also, Eimer & Schleghecken, 2003). As mentioned by Lleras and Enns (2005, 2006), in Eimer and Schleghecken (2002) increasing mask density more than a specific amount did not change the size of the NCE. Lleras and Enns interpreted Eimer and Schleghecken's finding in this way. Increasing the number of lines in the mask increases the possibility of creating arrow-like patterns. A given level of density is enough to create an NCE of a certain magnitude, but more does not increase it more than that.

Recently Kiesel, Berner, & Kunde (2007) showed that a very brief (10 ms) arrow prime can cause NCE in their metacontrast masking task using an arrow prime and target with long SOA. In one experiment they employed the same design but used a numeral as the prime and first let participants completely learn to map the numerals (4 and 6) to left and right responses. This over-learned numeral did not cause an NCE when random letter masks were used. However, they were able to show an NCE using a metacontrast mask for digit primes and arrow targets with long SOAs. As they noted, finding an NCE with such a brief prime duration is not consistent with Eimer and colleagues' inhibition hypothesis. A brief prime is not able to initiate inhibition according to their motor self-inhibition hypothesis. Rather, Kiesel et al. argued that their findings support the role of a mask-induced activity of some kind, a possibility introduced above (Lleras & Enns, 2004; Verleger et al., 2004).

Reportability of stimuli

Unmasked priming

In Eimer and Schleghecken's (2002) aforementioned experiments on the role of prime duration and mask density, participants who were better at detecting the prime showed a later change from positive to negative, and conversely those who were not good in reporting the prime showed an earlier change from positive to negative, showing that there is a close relationship between prime reportability and the direction of priming. Schleghecken and Eimer (2000) and Eimer and Schleghecken (2002, see also 2003) found that when there is no mask or the mask is peripheral (i.e., it does not make the prime unreportable), the result is PCE, unlike the situation with masked priming. Again using their motor self-inhibition hypothesis, they argued that the inhibition is initiated (as an automatic or evolved process) when visual input disappears, otherwise is blocked by visual input. Therefore, they claimed that an NCE, being a result of this self-inhibition, occurs only in the masked condition because prime input is stopped by the mask. They added that with the reportable prime, motor self-inhibition is prevented by the prime, so a PCE occurs. However, recently Lleras and Enns (2006), by comparing different studies, showed that prime visibility has no linear relationship with NCE, meaning that NCE is not necessarily caused by prime invisibility (see below).

To investigate whether there is any difference between masked and unmasked priming, Cheesman and Merikle (1986) employed Marcel's colour priming task with modifications. They changed the ratio of congruent to incongruent trials, so that in one condition this ratio was 25:75 and in the other one it was 75:25. In the unmasked condition, they found that when the number of congruent trials was high (i.e., the 75:25 condition), the congruency effect was higher than when this number was low (i.e., the 25:75 condition). In other words, when an incongruent trial was frequently preceded by a congruent trial, the congruency effect increased, and conversely, when an incongruent trial was frequently preceded by an incongruent trial, the congruency effect decreased. This difference was not found in the masked condition. They argued that participants can use a strategy based on context only in the unmasked condition.

Jaśkowski (2007) combined Eimer and Schleghecken's paradigm and Merikle and colleagues' (Cheesman & Merikle, 1984, 1986; Merikle & Joordens, 1997) to study the difference between the masked and unmasked conditions. In a congruent to incongruent ratio of 20:80, a PCE was found in the unmasked condition with both medium (100 ms) and long (800 ms) prime-target ISI. While in the congruent to incongruent ratio of 80:20, a PCE was found in medium (100 ms) ISI but an NCE was found, interestingly enough, in long ISI condition. In another experiment, while Jaśkowski found an NCE in the masked condition with a prime-target ISI of 100 ms, he found only a non-significant NCE with a long ISI. Therefore, surprisingly, with the long ISI the NCE for the unmasked condition was larger than it was for the masked condition, ruling out the necessity of the mask and invisibility of the prime in NCE. A similar result had already been found with a Stroop task (Merikle & Joordens, 1997).

Looking only for the PCE, regardless of the masked and unmasked difference, Koechlin, Naccache, Block, & Dehaene (1999) conducted a priming study on numerical magnitude with a variety of different encodings (Arabic numeral, word, and dot patterns). They found a PCE in the masked conditions in all cases. In the unmasked conditions, participants had to respond first to a stimulus (a 200 ms prime), then to the second one (a 200 ms target) presented immediately after the first one. In this condition, the results they reported were a NCE when the prime and target were in different encodings but only when the prime was Arabic numeral or dot, not when it was a spelled-out number. Their result, NCE for the unmasked condition, and Jaśkowski's result share one feature: in both cases, paying attention to the prime was required to do the task. This makes them similar to the attentional blink paradigm (see below).

In a study on normal and schizophrenic groups, Dehaene, Artiges, et al. (2003) used their aforementioned paradigm and found a PCE in the masked condition in both groups and in the unmasked condition only in the former group (and an NCE in the latter without further description). Using fMRI, they found that in the unmasked condition, compared to the masked, conflict (incongruency) activates a distributed network including the Anterior Cingulate Cortex (ACC) and its adjacent area, medial Pre-Frontal Cortex (PFC), in normal participants. But they found no conflict effect (i.e., difference between incongruent and congruent trials) in activating those areas in schizophrenics, even with the unmasked priming. They argued that in the masked condition, the conflict resulted from incongruent sensory-motor functions that can be processed without the involvement of the ACC and PFC. Therefore, these researchers claimed that the ACC and PFC are involved in conflict monitoring mainly in the unmasked condition. However, even in the masked condition, incongruent trials caused more activation in those areas compared to the congruent trials, though the effect was less than the unmasked condition.

Breitmeyer et al. (2005) employed a metacontrast masked priming approach and compared RTs in trials with reportable targets and with unreportable targets by presenting them at short (53.3 ms) and long (200 ms) SOAs, respectively. They presented shape stimuli (e.g., squares and diamonds) consisting of either the whole form or their parts (sides or corners) and followed by the mask with the SOAs just mentioned. They found an opposite effect for short and long SOAs priming with whole or partial forms. In the short SOA condition (unreportable), there was a greater congruency effect for complete form priming, but in the long SOA condition (reportable) there was a greater congruency effect for partial form priming. While they left the explanation open (they suggested that visibility played a role), it seems that in the long SOA condition, compared to the short, participants were able to process incomplete information more easily than complete information. However, the researchers used different SOAs to change the stimuli visibility. This is a possible confound and leaves open the possibility that the difference was caused by an effect relevant to different SOAs and prime duration (discussed above in connection with Eimer et al.'s studies). The effect may also be caused by the lower strength of parts compared to whole forms, rather than the effect of consciousness *per se*. We will return to this question when we discuss the model in Chapter 4.

Attentional blink (AB)

The AB paradigm is similar to masked and unmasked priming. While in the priming paradigm the strength of the representation of the stimulus affects the priming effects and direction, in the AB paradigm it affects the reportability of the stimuli. Because of this similarity, we should consider it briefly. The effect of a masked (but otherwise reportable) prime, here called Target 1 (T1), on the visibility of a second target (T2) has been studied especially with a task called Rapid Serial Visual Presentation (RSVP) containing a stream of masks and targets (usually 5 to 15 stimuli), with a brief blank interval (e.g., Luck, Vogel, & Shapiro, 1996). For example, two numbers (T1 and T2) are presented, each is preceded and followed by one or more letters (masks) and the task is to report T2 and/or T1. An AB resulting in an inability to report the T2 usually occurs when participants are asked to pay attention to both T1 and T2 so that they can report them at the end of each trial. Participants often miss T2 if it falls in a time window of about half a second after T1, except right after the T1 (by less than 100 ms). This is called lag 1 sparing (e.g., Luck et al., 1996; Feinstein, Stein, Castillo, & Paulus, 2004). In the case of blink, the T2 stimuli do not activate the P300 component of ERP measurement, which is supposed to be correlated to global accessibility of conscious experience, but they do activate P1, N1, and N400, which are involved in visual and semantic processing (Vogel, Luck, & Shapiro, 1998).

Sergent and Dehaene (2004) employed an AB paradigm, similar to masked priming, with no forward mask but one backward mask for T1 and two for T2, and a varying T1-T2 SOA. They asked if the AB reflects an increased probability of an all-or-none loss of reportable perception or a gradual increase in visibility. They had participants rank the visibility of T2 on a scale with 21 positions (0 and 1-20). Although the subjective visibility scale was designed to be sensitive to continuous changes in perception, participants used it in an all-or-none fashion. The AB did not result in a gradual reduction of T2 visibility, but rather resulted in an increase in the probability of missing T2. This result supports the hypothesis that AB consists of an all-or-none loss of conscious access to T2, but distributed randomly.

Binocular rivalry

Another interesting phenomenon relevant to conscious reportability is a visual phenomenon that occurs when two different images are presented to the corresponding fields of the two eyes, simultaneously or with a brief interval. In this situation it is hard, if not impossible, to see both images at once, so each time usually only the dominant one is seen (reported consciously). This phenomenon has been termed binocular rivalry and has long been known (e.g., Wheatstone, 1838).

According to Williams, Bush, Rauch, Cosgrove, & Eskandar (2004), binocular rivalry is related to having two visual pathways, a subcortical pathway that conveys crude but rapid signals before conscious report and facilitates early detection of threat, and a geniculo-striate pathway that conveys detailed but slower information, allowing fine-grained visual processing of the input (LeDoux, 2000). Sheinberg and Logothetis (1997) recorded activity from individual neurons in a monkey's superior temporal sulcus and inferior temporal cortex. They found correlations between neural activities in those areas and the perceptual performance of the monkeys. These neural activities follow the perceptual processing rather than the stimuli on the retina. Many of these neurons respond in an all-or-none way, firing for one percept, not for an alternative one. Williams et al. (2004) found that, under conditions of binocular suppression, when visual inputs are restricted to non-cortical pathways, the amygdala responds non-selectively to both threatening and non-threatening facial expressions, showing that the suppressed processing of faces does not involve detailed information. This shows that the representation of a stimulus is attenuated by a competing one.

Magnitude and representation

In addition to the timing of the prime and target, the experiments in this dissertation using the masked priming paradigm also focused on manipulating the strength of the mental representation of both the prime and the target. For instance, numbers with different distances from *five* were studied, based on their numerical magnitudes, or numbers were encoded in different formats (words, numerals). It is proposed that a framework consisting of four elements can be used to understand strength of representations. These are: *representation type, representation of magnitude, representation strength, and match of representation strength.*

Representation Type

As noted above, representations can take many different forms. However, the most fundamental difference is that representations can be either symbolic or perceptual. For example, the concept "bigger" can be conveyed by a number that is bigger than another number (symbolic) or a line that is longer than another line (perceptual). Masked priming experiments differ in terms of their use of perceptual and symbolic stimuli.

Representation of magnitude

Representation of magnitude refers to the content or meaning of representations that convey information about magnitudes, including both symbolic and neural codes that represent magnitude. For example, the symbol "7" represents a magnitude that is greater than 3. However, it is important to note that representations of magnitude are not always symbolic and/or consciously reportable. To throw a dart at a dart-board, the weight of the dart, the distance to the board, and the angle of the throw must all be represented in some way because representations of all these things are needed to throw the dart. Likewise, with numbers, in addition to our knowledge of the symbolic meaning of a numeral or number word, we must also have a sense of the magnitude that is represented (e.g., Dehaene et al., 1993). In the masked priming paradigm, stimuli are sometimes presented to the subject in the form of representations of magnitude.

Strength of Representation

Strength of representation refers directly to the strength of a representation within the brain. At a neural level, this would in some way be related to the rate and/or extent of neural firing. One of the assumptions behind the model to be developed in Chapter 4 is that representation of magnitudes is related to strength of representation. Specifically, we represent larger magnitudes through larger amounts of neural firing. This is discussed further in the next section. However, in this thesis strength of representation does not refer to the magnitude *per se* (i.e., the numerical size), but to the extent that the type and distance factors change the priming effect. Changes in both type and distance factors are assumed to cause changes in neural firing and, therefore, in the strength of representation. For example, a number far from *five,* compared to a close one, causes more increases in the neural firing and, similarly, an Arabic numeral, compared to a spelled-out number or an arbitrary symbol mapped to a number, causes more increases in the neural firing. Therefore, for instance, 1 and 9 are assumed to make similar priming effects, because they are far from *five*, with an equal distance, but 1 and 4 are assumed to produce different priming effects. Similarly, a number written in Arabic format and the one encoded by an arbitrary symbol are assumed to produce different priming effects.

The effects of these two factors are assumed to be added together and cause a strong change in priming effects.

Match of representation strength as neural firing rates

In masked priming experiments, it is often the case that the prime and/or the target convey information about magnitude. For example, numerals or spelled-out numbers could be used to convey information about magnitude. Manipulating representations of magnitude in this way (i.e., changing the type or distance factors) often has an effect on processing speed, just as changing the perceptual magnitude (e.g., by changing perceptual clarity) has been shown to affect processing speed. For example, a numeral is processed faster than a spelled-out number and a number distant from the reference number *five* is processed faster than one close to it. This is interesting because if the representation of magnitude is just informational, and there is no sense of urgency attached to the information, it is hard to see why it would affect the processing speed. In forced choice tasks, used in priming paradigms, participants have to decide on a response quickly. Therefore, it is important how strongly or easily a representation supports a response alternative. If the task is to respond with left and right hands to numbers smaller and larger than five, respectively, the reaction time for a number far from *five* is faster than for a number close to *five.*

Since, at the neural level, the most direct way to represent magnitude (e.g., five dots) is through neural firing, representations of magnitude (e.g., 5) may also be represented in this way. This would make magnitude representation similar to magnitude strength, that is, a direct reflection of neural activity. Taking the literature as a whole, many of the different manipulations can be conceptualized as manipulating *match of representation strength* for the prime and the target. What I mean is this: How meaningful the information provided by the prime and the target is within the context of performing the experiment. The meaningfulness is increased by strong representations and contextual information such as cueing. The match of representation strength refers to the overall neural activation caused by the prime and target (and contextual information) that tends to a given representation versus its alternative(s). A prime with a strong representation (e.g., an Arabic numeral) may have a weak representational match if participants know that it is followed by an incongruent target, so they will ignore it. While strength of representation refers to the strength of the prime and target, regardless of the effect of attention and task context, the match of representation strength refers to the overall strength of the representation of the prime and target after being affected by attention and the context of the task. Therefore, a stimulus that has high strength of representation need not have a strong representational match, for example when it is irrelevant to the task or goal.

In this thesis, it is proposed that the strength of representational match can be represented by a change in neural firing rate. Specifically, it is proposed that a prime is accessed in terms of its significance as a cue for the set of possible targets and that this assessment is weighted according to factors that affect the level of confidence (or, conversely, uncertainty). So, for example, a visually degraded prime would have the same significance but would be weighted less than the same prime not degraded, because the uncertainty about the degraded prime would be higher. Likewise, targets are assessed in terms of their significance as related to the set of primes in the same way. It is proposed that this can be represented neurally by encoding the prime, the target and their strength of representation, in a way that affects the level of neural firing associated with the prime and the target. This section reviews some of the findings indicating that neural firing rates can be used in this way.

A mental number line

In the number comparison task, two numbers are presented and participants are asked to compare them, for instance they have to choose the larger one. It has long been known that number comparison is faster when the distance between the two numbers is larger than when it is small (Moyer & Landauer, 1967). For example, comparing 6 and 7 takes longer than comparing 5 and 8. Similarly, in another paradigm, as mentioned in connection with the previous studies on numerical priming, participants are asked to compare each digit that is presented to the reference number *five* (not presented). It has been shown that if the number is distant from *five* (e.g., 1 or 9) compared to one close to *five* (e.g., 4 or 6), participants are faster and more accurate (e.g., Gallistel & Gelman, 1992; Dehaene et al., 1993).

Some researchers (e.g., Buckley & Gillman, 1974; Dehaene et al., 1993; Dehaene & Cohen, 1997) have proposed that the magnitude of a number is represented on a "mental number line" automatically, located from left to right (i.e., larger numbers are spatially located on the right, mentally). Therefore, when the required response and the number to be recognized are at the same side, responses are faster than when they are at different sides. The SNARC (Spatial-Numerical Association of Response Codes) effect

(Dehaene et al., 1993) refers to this automatic association between the response side (e.g., left or right hand) and the semantic magnitude of a given number. For example, in numerical comparison tasks, it is easier for participants to respond to smaller numbers with the left hand and to larger numbers with the right hand than vice versa. The SNARC effect in numerical processing indicates a close relationship between representation of space and representation of number. This effect may involve well-learned connections that automatically activate semantic processing or spatial attention, leading to motor preparation. A shared representation of space, number, and time has been proposed previously (e.g., Meck & Church, 1983; Walsh, 2003).

The effect of a "mental number line" has been found in a similar numerical task where a string of numerals (e.g., 6668666) are presented and participants are asked to compare the target numeral in the middle (here, 8) to the reference number *five* and ignore other numerals that are just distractors (Nuerk, Bauer, Krummenacher, Heller, & Willmes, 2005). If the target and the distractors are all smaller or all larger than *five* the trial is congruent. But if the target is smaller than *five* and the distractors are larger than five or vice versa the trial is incongruent. This task is a numerical version of Eriksen's flanker task (Eriksen & Eriksen, 1974; and especially Eriksen & Schultz, 1979) where participants indicate the direction of a target arrow that is in the middle with their corresponding hand (and ignore the distractor). For instance, >>>>> is congruent and >><>> is incongruent. Usually the RTs are faster in the congruent compared to the incongruent trials. With their numerical version, Nuerk et al., in addition to showing this congruency effect, showed that the incongruent trials are faster when the distance between the target and the distractors is large than when the distance between them is small. Conversely, they found that within congruent trials, when the target was farther from the distractors, RTs were slower than when the target was closer to the distractors. They also showed another effect within congruent trials that they named the "second order congruency effect". When the target was smaller or larger than the reference number and the distractors (e.g., 4442444 or 6668666), the trial was called second order congruent. When the target was smaller or larger than the reference number but not than the distractors (e.g., 1112111 or 9998999), the trial was called second order incongruent. Participants were faster in the second order congruent trials than the second order incongruent trials. However, it seems that the distance of the target to the reference produced the main effect in all conditions.

In some studies, the numerical comparison has been combined with a physical size comparison to make a Stroop task where two numerically or physically different numbers are to be compared, but only one dimension is task-relevant each time. Participants are informed early each time if they are going to be doing a physical or a numerical comparison. A congruency effect occurs if the two numerals are consistent or inconsistent in magnitude and physical size, even though one aspect is always irrelevant to the task. For example, 3 4 are congruent because here 4 is larger both numerically and physically, and 3 4 are incongruent because each one is larger in one aspect. In this paradigm both numerical distance and distance in physical size (based on the size difference of the two numerals) have an effect. Usually numbers with a small distance from each other are compared more slowly than those with a larger distance, as mentioned before. However, within the incongruent trials a reversed effect has been found when physical size and numerical magnitude were incongruent in the physical size comparison (e.g., Girelli, Girelli, Lucangeli, & Butterworth, 2000; Tang, Critchley, Glaser, Dolan, & Butterworth, 2006) and numerical magnitude comparison (Tang et al., 2006). The reversed effect depended on the physical or numerical distance between the two numbers. For example, Tang et al. (2006) looked at RTs in the incongruent trials in a task where the physical size and the numerical magnitude of the two numbers were manipulated and again only one of them was task-relevant each time. They found that greater distance between the two numbers in the relevant dimension made the comparison faster but greater distance in the irrelevant dimension made the comparison slower. The distance factor that causes this effect is based on strength of representation, because the smaller distance interfered less, due to the weaker representation of it, and conversely the larger distance had facilitating effect, due to its stronger representation.

Neural correlates of magnitude

Stimuli are different in their representational strength. The difference has been shown in terms of activation in the brain, in neural response, in addition to speed of behavioural response. Faces are among stimuli that can be processed very quickly, due to their very strong activation in the brain. In an fMRI study by Whalen, Rauch, Etcoff, McInerney, Lee, and Jenike (1998), the amygdala was activated by masked face stimuli. In another study, Delorme, Richard, & Fabre-Thorpe (1999) presented natural images (animals and foods) to humans and monkeys for a very short time, about 30 ms. Delmore et al. found that the images could be categorized in this brief exposure. They argued that such quick performances in humans and monkeys cannot depend on time-consuming iterative processing through feedback. These findings show that stronger stimuli take a shorter time to be processed compared to weaker stimuli. In priming task usually stimuli with strong representations are used (for example, arrows, faces, words, or numerals), to take effect in a brief time.

Similar to the strength of faces, neuroimaging studies have shown the effect of distance (i.e., magnitude difference) by measuring activations in specific brain areas in numerical priming. Although magnitude judgment takes longer when distance is short as compared to long, brain activation is higher for short distances compare to long. However, when the task does not involve judgment and is to look at numbers passively, opposite results can be found. Recent studies using an adaptation method (e.g., a new stimulus, 50, is presented in a series of similar stimuli, 17, 18, and 19) have found that parietal activation is increased with numerical distance, independent of notation (e.g., Piazza, Pinel, Le Bihan, & Dehaene, 2007; for difference in notations see Cohen Kadosh, Cohen Kadosh, Kaas, Henik, & Goebel, 2007). In these studies, participants were asked to look at numerals passively. For example, in Piazza et al. (2007), while participants were looking at a series of subsequent numerals, a deviant numeral appeared that was either close to or far from the numeral series. They found higher activation for the deviant numeral, the one that was distant from the previous numerals in the series.

However, in number comparison and numerical priming (which also involves comparison to a reference), other neuroimaging studies have shown higher activations for close compared to distant distances in the inter parietal sulcus (IPS) for number magnitude (Cohen Kadosh, Henik, Rubinsten, Mohr, Dori, Van de Ven, Zorzi, et al., 2005; Kaufman, Koppelstaetter, Delazer, Siedentopf, Rhomberg, Golaszewski, et al., 2005) and to a lesser extent, for physical size judgment (Kaufman et al., 2005). Similar to the results of these numerical comparison studies, previous numerical priming studies have shown the effect of distance in causing activations in the same brain areas (e.g., Schwarz & Heinze, 1998; Naccache & Dehaene, 2001). Naccache and Dehaene found a higher activation for close compared to distant primes especially in IPS. However, their result may in fact show a higher activation in response to the target because the closer the prime, the less attentional resources are activated, leaving more resources for the target (the modelling results support this claim, see Chapter 4).

In a study with both fMRI and ERP, Pinel, Dehaene, Riviere, & LeBihan (2001) showed that comparing two numbers close to one another takes longer than comparing two numbers distant from one another. They further found that the encoding of the numbers (Arabic numerals vs. words) added to the effect of distance, i.e., responses to numbers encoded in words were slower than to those encoded in Arabic numerals both at close and far distances while the RTs increased for both notations at close compared to far distances. When they looked at brain activations using fMRI, they found higher activations especially in the parietal area with numbers close together compared to numbers farther apart. Therefore, opposite to the RT effects, especially for Arabic compared to word encoding, close distance caused higher activation and far distance caused lower activation. They also measured brain activation using the ERP method in the same study. This measurement was also not closely correlated to the behavioural results in general, but one can notice an additive effect of notation and distance by considering the temporal changes in the activations related to prime and target, as word encoding caused higher activation, especially later in time. It may reveal that responses in priming are more time-locked to brain activities measurable by ERP, which has better temporal resolution than fMRI.

Major issues in masked priming

There are three major issues in masked priming. The first is about whether the priming is a matter of semantic or low level associations. However, it is difficult to show that something that can be interpreted as an association is not an association. In the case of vision, degrading stimuli affects masked priming but it can be interpreted as affecting the association or affecting the confidence in the information. In the case of semantic information, there is evidence that at least some of the time semantic information is involved in masked priming, but it has been suggested that priming works better in well-learned domains (e.g., Arabic numerals) than in less well-learned domains (e.g., numbers encoded in words). The second issue is understanding why there are negative effects. Why do incongruent primes and targets sometime confer a benefit? The main factors in creating negative effects are masking and a long interval between prime and target. The third issue is creating a model that can deal with all of the different experimental manipulations and produce negative and positive effects in the right places.

Current approach

I will approach these issues in the following way. First, I will create a low level, non-semantic way to manipulate vision to see the effect on priming. Second, I will test the extent of semantic priming by examining recently learned semantic mappings. Third, I will look for positive and negative effects in the experiments and simulate them by the model.

Overview of the experiments

Experiment 1

In experiment 1, simple target lines with two parts were primed by similar lines that were either masked (with random shapes) or unmasked. Prime lines had arrowheads and had two parts with either non-illusory or illusory lengths. Participants had to choose the longer part of the target line. Short and long parts were at the left and right randomly. An effect of masking, congruency, and illusion on the priming effect was shown in this line length comparison task with real and illusory lengths. This experiment has never been done before.

As described above, Dehaene, Artiges, et al. (2003) found an effect for incongruent priming especially in the unmasked condition. However, they included repeated numbers as prime and target (e.g., 1 priming 1) and non-repeated priming (e.g., 1 priming 3) while Experiment 1 only included non-repeated priming using prime and target lines with different lengths. Moreover, in Dehaene et al.'s paradigm, participants had to hold a reference number (*five*) in memory to compare it with the target number but in Experiment 1, participants only compared one part of the target line with the other part, both available perceptually (see the experiment for more details).

Use of fMRI

In Experiment 1, in addition to the speed and accuracy of decision-making as the main behavioural measurements, fMRI was employed to measure brain activity. To my knowledge, no previous studies have used illusory line length for priming and looked at brain activation to check the difference between illusory and real perception. The fMRI study also examined differences between the masked and unmasked conditions.

Brain activations are subject to changes through time and from one area to another, making it hard to track by neuroimaging, especially by the block design fMRI used in this study. For example, some brain areas are more activated at the early sessions of a task compared to the latter sessions. However, using blocking or grouping for each factor increases the statistical power even with a small number of trials, especially by having repeated blocks (here repeated three times).

Experiment 2

In experiment 2, a numeral or a symbol (arbitrary symbols mapped to numbers) primed a numeral target, or a numeral primed a symbol, all with different magnitudes and with masked or unmasked primes. The use of different formats or notations in these experiments was mainly intended to control a confounding variable, namely repetition in (perceptual) priming (e.g., Mayr et al., 2003), by forcing semantic priming that requires more attentional and other cognitive resources than priming over and over with stimuli of a single type.

Experiment 3

Experiment 3 was a complement to Experiment 2. This experiment investigated the magnitude factor further by controlling the role of numerical distance. It aimed to reveal the interaction between target type (symbols and numerals) and the distance of prime and target from *five,* by assuming an additive effect of the two factors on priming direction (i.e., PCE or NCE) and size.

Experiment 4

This experiment was identical to Experiment 3 but the predictability of the target was considered as another factor in the match of representation strength and hence in changing the priming effects. Here, the target type (numerals or symbols) could be predicted by a cue that was presented before the prime.

Modelling

To simulate the results of these experiments a dynamic, neuro-cognitive model of masked priming was developed. In addition to replicating the results of the experiments in this thesis, we designed the model to produce results that match many other relevant findings in the literature. The main feature of the model is that its output matches the effects of the various different stimuli by manipulating a single parameter. The match of representation strength is assumed to be embodied in an analogue form through neural activity. It is assumed to have an analogue form because it reflect the firing rates of a group of neurons that changes through time by decay, attention, and interactive effects of stimuli. Both symbolic and perceptual representations are assumed to operate this way. This aspect of the model is unique and makes it possible to generalize the model across a wide variety of experiments in this domain. The model also simulates the effects of timing such as prime-target SOA and other important factors in priming. Changes in attention mode for the prime in the model simulated the difference between relevant and irrelevant primes (in the unmasked condition) by higher and lower attentional responses to the prime, respectively. Prime duration and degradation and mask properties changed the direction of priming. The reversal of priming happened when a relatively weak prime and a weak target were used. In addition, a stronger prime (e.g., using higher weights, less degradation, relatively higher excitation from the mask, higher spatial cue) caused a strong priming initially, but inverted the priming direction when the target came later in time. Further work could be done to find if the effects that found here in the masked condition could be also found in the unmasked condition, to reveal the precise role of cueing in removing the priming effect and to improve the model's match to human data.

The distinction between symbolic and neural

Cognitive modelling has been approached in many ways, with a number of levels of abstraction. While neural modelling provides more biologically plausible details (although it still has some critiques), symbolic modelling has been more successful in modelling high level cognition such as problem solving and reasoning (e.g., Anderson, 1983; Anderson & Lebiere, 1998). Explaining the PCE is straightforward and can be understood at the symbolic level. The prime provides information about the target identity therefore it can cause facilitation or interference when prime and target are congruent or incongruent, respectively. However, the NCE phenomenon is hard to explain at the symbolic level. Specifically, it is hard to see why changing the timing of the prime and the target could cause a congruent prime to slow down responses and an incongruent prime to speed up responses. This effect seems to result from the dynamic effect of the stimuli on each other and especially their demand on attentional resources.

In contrast a neural model might be able to simulate both PCE and NCE in human subjects through various mechanisms related to timing and the match of representation strength. The model was developed to simulate priming patterns but other phenomena arising from the experiments we did include the role of conflict or incongruency, the difference between masked and unmasked priming, the involvement of different types of attention.

The model

When the prime in the model is activated, the mask can cause an interruption in the activation caused by the prime. Some factors such as longer prime duration, less or no degradations, relevant mask, and cueing, can increase the prime activation. The higher activation of the prime causes stronger attentional responses. This, in turn, increases the prime activation even more, i.e., strengthening its representation. A prime with a strong representation causes a large priming effect but if the target comes late, the priming direction will be inverted. A reversal of the priming can also be found if both prime and target have weaker representation, even if the target comes relatively early in time. The model simulates representation strength by using excitatory weights or connections. A recently learned representation, compared to a well-learned one, is represented by lower excitatory weights. Similarly, a number that is close to the reference number, as opposed to distant from it, is represented by lower excitatory weights. As will be discussed in detail in Chapter 4, the prime and target representations interact with attentional resources, simulated by a dynamic component. The activation caused by the stimuli and affected by the attentional resources results in an activation that increases the match of representation strength. The dynamic response of the model's units and especially the attentional resource and its refractory period play an important role in priming effects shown by the model. Moreover, the attentional response is driven by a conflict or incongruency measurement that is crucial in changing the priming direction. While attentional response to the target is directed by conflict monitoring, the attentional response to the prime is fixed to high activational response in the masked condition. In the unmasked condition, this activational response is decreased only when the prime is irrelevant for the decision on the target (see Chapter 4 for details).

Model evaluation

Parsimony

Our model simulates a wide variety of results with a single, relatively straight-forward model. The model has a one-parameter feature (i.e., only one parameter is manipulated and all parameters are fixed in different conditions, such as strong stimuli versus weak stimuli and masked versus unmasked. Therefore, the present model is able to simulate all the main processes and results involved in priming research with minimal changes in the parameters for at least the main results such as changes in priming effect by the change in the strength of representation, masking, and cueing.

Falsifiability

The model's parsimony and parameterization make it falsifiable. Its main factors are representation strength, attention, and conflict. Thus the role of these factors can be assessed in future studies. There are a few previous models of priming. These models have not simulated attention and therefore, as will be discussed further in the last two chapters, they do not display some of the phenomena displayed in our and other experimental studies. The model we developed does display these phenomena.

Summary

In summary, the dissertation reports four experiments (including an fMRI study) and a model. The first experiment tested the effect of masking, illusion, and congruency. The fMRI part of this experiment looked at what happens to activation levels in the brain when subjects are engaged in masked versus unmasked and illusory versus non-illusory conditions. The second experiment tested the effect of recently learned representation versus well-learned, the third experiment tested the distance factor, and finally the forth experiment tested the effect of cueing. The model simulated the priming process and produced results very similar to how human subjects behaved in our experiments and other studies.

Chapter 2: Perceptual representation

Experiment 1: An fMRI study of masked and unmasked geometrical magnitude priming

Introduction

As noted above, the role of perception in masked priming studies has been examined by degrading the prime stimulus and/or the target stimulus (Schlaghecken & Eimer, 2002). In terms of the way things are framed in this thesis, degrading a stimulus changes the priming effect by affecting the match of representation strength. Specifically, it is hypothesized that degrading the stimulus makes it look less like a meaningful cue and this increases the level of uncertainty attached to the interpretation of the prime. That is, the prime is identified as having a particular meaning within the context of the experiment, but there is some level of uncertainty attached to it, making its representation weaker. Alternatively, the effects associated with prime degradation could be directly due to differences in visual processing related to the degrading of the prime. More generally this implies that changes in the visual experience can directly alter the effect of the prime. This explanation is consistent with an S-R interpretation of the task, where the vision system communicates directly with the motor system to produce the effect.

In this experiment an alternative avenue for manipulating the perception of the prime was explored. Specifically, the effect of using illusions as primes was explored. Unlike degraded stimuli, which are more difficult to recognize, an illusion is a misinterpretation of the stimulus by the visual system. To examine this, the Müller-Lyer illusion was used to generate a prime. The Müller-Lyer illusion was chosen because it produces a very strong, unambiguous perception that one line is longer than another (when they are, in fact, the same length) and because there is evidence that Müller-Lyer illusion is an adaptive process (e.g., Howe & Purves, 2005) and it works in brief presentations (e.g., Moore & Egeth, 1997). A strong illusion was used to avoid the problem of the illusion producing something that is difficult to see and is thus similar in this way to a degraded stimuli. According to the model put forward in this thesis, how the visual system produces the image should not matter, instead it is the meaning of the resulting image that produces the priming effect. More specifically, the Müller-Lyer illusion works because the line length is interpreted within the context of the converging and diverging lines at the end. Thus, for the Müller-Lyer illusion to have an effect the prime would need to be interpreted within the visual context of the converging and diverging lines. Two questions can be asked about this: (1) Will it work? i.e., is the visual context an important part of interpreting the prime? (2) How will it work compared to using real line length differences? i.e., is an illusion less compelling than the real thing?

This experiment focused on magnitude of line lengths (lines with two different parts) and length type (non-illusory vs. illusory lines). For this purpose, I adopted Dehaene et al.'s (e.g., 1998) numerical (symbolic) priming paradigm for a perceptual domain. The magnitude was introduced with real as well as illusory line length. A line length comparison task was employed to see if illusion of magnitude could make any difference in both behavioural and fMRI measurements. I further assumed that line length comparison is a perceptual decision that is easier than numerical comparison because it has stronger representations. Specifically, I was interested in the size and the direction of priming effects and their relationships to the factors relevant to the strength of stimulus representation such as masking factor and type factor (real and illusory length).

The task was to select the longer part of a two-part target line which was preceded by a two-part prime line. One of the two parts was longer both in prime and target lines, making the trials congruent or incongruent. If the longer parts of prime and target were at the same side, the trial was congruent. Conversely, if the longer parts of prime and target were at opposite sides, the trial was incongruent. The differences between the length of the two parts of the prime was either real or illusory but no illusory lines were used as target. However, the prime and target were not the same even if the prime had no illusory length because the length of the longer part in the prime line was slightly different from the length of the longer part in the target line. This was especially intended to control repetition priming, as for example shown by Dehaene et al. (1998) and Dehaene, Artiges, et al., (2003), repeating the prime as target (e.g., 2 and 2) has a stronger effect than a target physically different from the prime (e.g., 2 and 3). Dehaene et al. found an effect for numerals and spelled-out numbers which are symbols, so in this study I looked at whether magnitude (line length) would produce the same result. Müller-Lyer illusory length was supposed to be processed automatically and to make priming effects like real line length.

As discussed in Chapter 1, recently fMRI has brought interesting findings (e.g., Marois, Chun, & Gore, 2000; Dehaene et al., 1998; Dehaene, Artiges, et al., 2003; Feinstein et al., 2004) in the area of consciousness and cognition. In the current experiment, the fMRI was employed to study the neuro-cognitive processes using a geometrical (line) task to see the effect of illusion. The current task had less working memory load compared to Dehaene et al.'s numerical task (1998, see below); thus the effect could not be attributed only to the memory load factor. It also was meant to assess the role of masked and unmasked priming, as well as illusion, that has not been looked at before.

I investigated the differences between representational maps of magnitude in a real line length and illusory lines representing real line length. Masked brief stimuli, despite being unreportable, can be processed up to the semantic level (Dehaene et al., 1998). In the unmasked condition, participants were supposed to be able to report the illusion, so some brain areas were assumed to light up compared to masked condition. For both types of prime, arrowheads were used to create an illusory line length (i.e., Müller-Lyer) in illusory primes that were supposed to invoke extra or different cognitive processes (e. g., correction and inhibition) and to make the task a bit harder in non-illusory lines as well, to decrease prime representation and especially to prevent strategy use, such as letting participants just look for motion-like changes.

As discussed before, usually in priming tasks, as with the current study, a flashed prime is rendered unreportable by sandwiching it between two brief masks. Then a target is presented that requires a response from the participants. Although the task is to respond only to the target, it has been shown that participants also apply the task instruction to the prime (e.g., a left or right key press). Even when the prime is unreportable, it results in an activation that can affect the final response to the target. As will be described in the method section, the prime is either congruent or incongruent with the target, and is unreportable or reportable, usually called unconscious and conscious conditions (e.g., Dehaene, Artiges, et al., 2003) or, as here, masked and unmasked conditions, respectively.

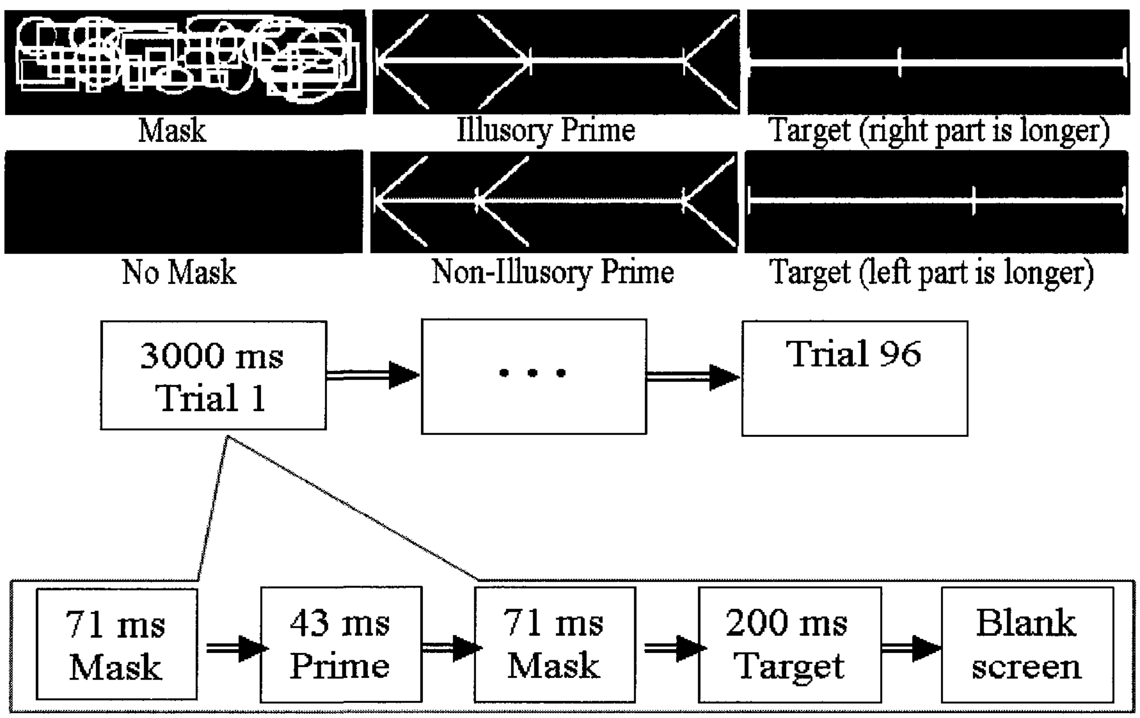


Figure 2.1. The experimental design and stimuli. Top: This shows some examples of the stimuli used in the task. The prime line was masked or unmasked and also was illusory (Müller-Lyer line with equal parts) or non-illusory (line with arrows in one direction, toward left or right, in which the ratio of the long to short part was 2 times (called 4:2 as shown) or 1.5 times (called 3:2, not shown). The target line had no arrows with ratios 3:2 (as shown) or 4:2 (not shown). Bottom: As shown in this diagram, each trial consisted of a prime presented briefly for 43 ms and was either unmasked or masked by inserting it between two flashed (71 ms) masks of random shapes. Then it was followed by a briefly (200 ms) presented target line. A 3:2 prime was followed by a 4:2 target, and conversely a 4:2 prime was followed by a 3:2 target.

The participants' task was to select the longer part of a horizontal target line that had two fragments (parts). This new stimuli format thought to make less interference compared to the numerical version (e.g., Dehaene, Artiges, et al., 2003; see also the next chapter) in which participants had to hold a reference number (*five*) in memory to compare it with the target number. In the current study, participants had to compare one part of the target line to its other part, not with a separate reference in their memory. As mentioned by Dehaene, Artiges, et al. (2003), holding a reference in memory could increase the response interference and working memory load especially in the unmasked priming condition where participants may compare the target with the prime instead of the reference number. The geometrical format also can allow to see if the numerical priming in Dehaene et al.'s studies are generalizable to the current stimuli and procedure. Specifically, using prime lines with arrows (wings) made it possible to look at the role of illusory priming (Müller-Lyer) and its interaction with masking.

Method

Participants

Participants were eight right-handed healthy volunteers (4 females, 4 males, age 23-31) with normal or corrected-to-normal vision (using contact lenses). Each participant gave a written informed consent and signed an MRI safety and ethics form provided by the Ottawa Hospital MRI research unit. Participants were given a printed MRI picture of their brain (and an electronic version upon request).

Material and procedure

The prime and target stimuli were lines with two parts (Figure 2.1). The parts of the prime lines had arrows (wings) that were pointing to the same direction in the line with real length (henceforth, Non-Illusory) or to different directions making illusory length (Müller-Lyer) in the line with illusory length (henceforth, Illusory). One part of the lines was always longer than the other one in the Non-Illusory, or seemed longer, as in the Illusory.

As shown in Figure 2.1, the non-illusory lines (both prime and target) had two different ratios of the long compared to the short part, 4:2 or 3:2. In the illusory condition, targets (that were non-illusory with no arrows) had one of these ratios each time, randomly. In the non-illusory condition a 4:2 prime was followed by a 3:2 target, and conversely a 3:2 prime was followed by a 4:2 target, randomly. Therefore, no trials with identical prime and target were included, to exclude repetition priming effect. In each trial, the prime was presented very briefly (43 ms) and participants had to select the longer part of a briefly (200 ms) presented target line (see Figure 2.1). The prime line either was unmasked or was masked by being inserted between two flashed (71 ms) pattern masks composed of random shapes (fixed for all trials). The long and short parts of the target lines appeared on the left and right sides, randomly. In the congruent condition the longer parts of the prime and target lines were at the same side, while in the incongruent condition they appeared on opposite sides to each other.

The presentation of the non-illusory primes with two different arrow directions and the target with two ratios was counterbalanced and randomly presented among the blocks. The target was presented for 200 ms and the participants had to make a response during an interval starting from the onset of target to the rest of the 3s of the trial, otherwise a missed trial would be recorded (although no trial was missed during this experiment).

Before the experiment, in the instruction session outside the scanner, participants performed four trials of each masked prime type without target. They could not verbally report the nature of the prime, when they were asked after each trial. No examples of the unmasked primes were shown but they were told that the presented patterns were some examples of the stimuli in the real experiment. They also were naïve to the psychological aspect of the illusion in the unmasked condition when they were asked after the experiment, except one participant whose data did not cause any significant change in the result.

The task was programmed in Microsoft Visual Basic 6 (Microsoft Corp.) with millisecond time precision using Class and Thread Priority procedure (e.g., Chambers & Brown, 2003) and was run on a Pentium III laptop. The stimuli were back projected (using an SVGA projector) onto a screen to be viewed through a mirror attached to the standard coil of the MRI machine. Participants responded by the index or middle finger of their right hand using a fiber optic response device.

The fMRI design

The imaging was performed using a 1.5-T Siemens Magnetom Symphony MR scanner with the quantum gradient set. Participants lay supine with their head secured in a standard head holder. Whole brain echo planar fMRI, based on the BOLD signal, was performed using a gradient echo pulse sequence (TR/TE 3000/40 ms, flip angle 90, slice thickness 5 mm, 27 axial slices).

The fMRI data were analyzed with Statistical Parametric Mapping analytic package (SPM2, Wellcome Department of Cognitive Neurology). For each participant, the images were realigned (with re-slicing and co-registering), normalized, and finally spatially smoothed with 10 mm FWHM isotropic Gaussian kernel. Then, all data were analyzed (except the first four images of the initial extra trials included for hemodynamic T1 equilibration purpose), taking into account the hemodynamic response and the global effect using a block design.

The experiment had 96 trials. The main blocks were masking and illusion, repeated three times. Other factors including congruency, the side of the longer part, and the two types of long to short ratio, were counterbalanced among the blocks. The direction of arrows in the non-illusory prime lines correlated with ratio factor. In the 4:2 ratio prime, the arrows pointed to the left and in the 3:2 ratio the arrows pointed to the right. The blocks were repeated three times in a random order, with the constraint that unmasked illusory blocks were presented after unmasked non-illusory to minimize the effects of the unmasked illusory trials on the other trials.

For analyzing the behavioural data, the mean RTs and percentages of error of all participants were analyzed using repeated measure ANOVA (2 x 2 x 2) on the three factors: Masking (i.e., prime visibility, with two levels, Masked and Unmasked), Incongruency (i.e., conflict, with two levels, Congruent and Incongruent), and Illusion (with two levels, Illusory and Non-illusory).

For statistical analysis of images, a second level analysis (i.e., random effect; RFX), based on the results of the first level analyses (i.e., fixed effect; FFX), was performed on the contrasts of interest relevant to Masking, Conflict (i.e., Congruency), and Illusion, with at least *p* 0.005 (uncorrected) and the cluster size of at least 4 voxels (with at least *p .05,* uncorrected, at cluster level). The coordinates were converted from MNI atlas (Cocosco, Kollokian, Kwan, & Evans, 1997) to Talairach atlas (Talairach & Tournoux, 1988) using an algorithm proposed by Brett, Johnsrude, and Owen (2002), for labeling the brain areas.

Results

Behavioural results

The RTs and percentages of error were averaged for eight possible conditions with three factors: Masking (Masked vs. Unmasked) by Illusion (Non-Illusory vs. Illusory) by Congruency (Congruent vs. Incongruent). These results showed that participants had understood the instructions and were able to do the task properly. The correlation between the two scales was positive, though not significant ($r = .549$, $p=.159$). Therefore no trade-off between RTs and percentages of error were found. A regression curve shows this relationship (Figure 2.2).

A three-way repeated measure ANOVA (2 x 2 x 2) was run on the mean RTs from all participants on three factors: Masking (Masked vs. Unmasked), Illusion (Non-Illusory vs. Illusory), and Congruency (Congruent vs. Incongruent). The main effect of Congruency was significant, $F(1, 7) = 10.522$, $p = .014$. As shown in Figure 2.3, a significant interaction was found for Masking by Congruency, $F(1, 7) = 7.764$, $p = .027$.

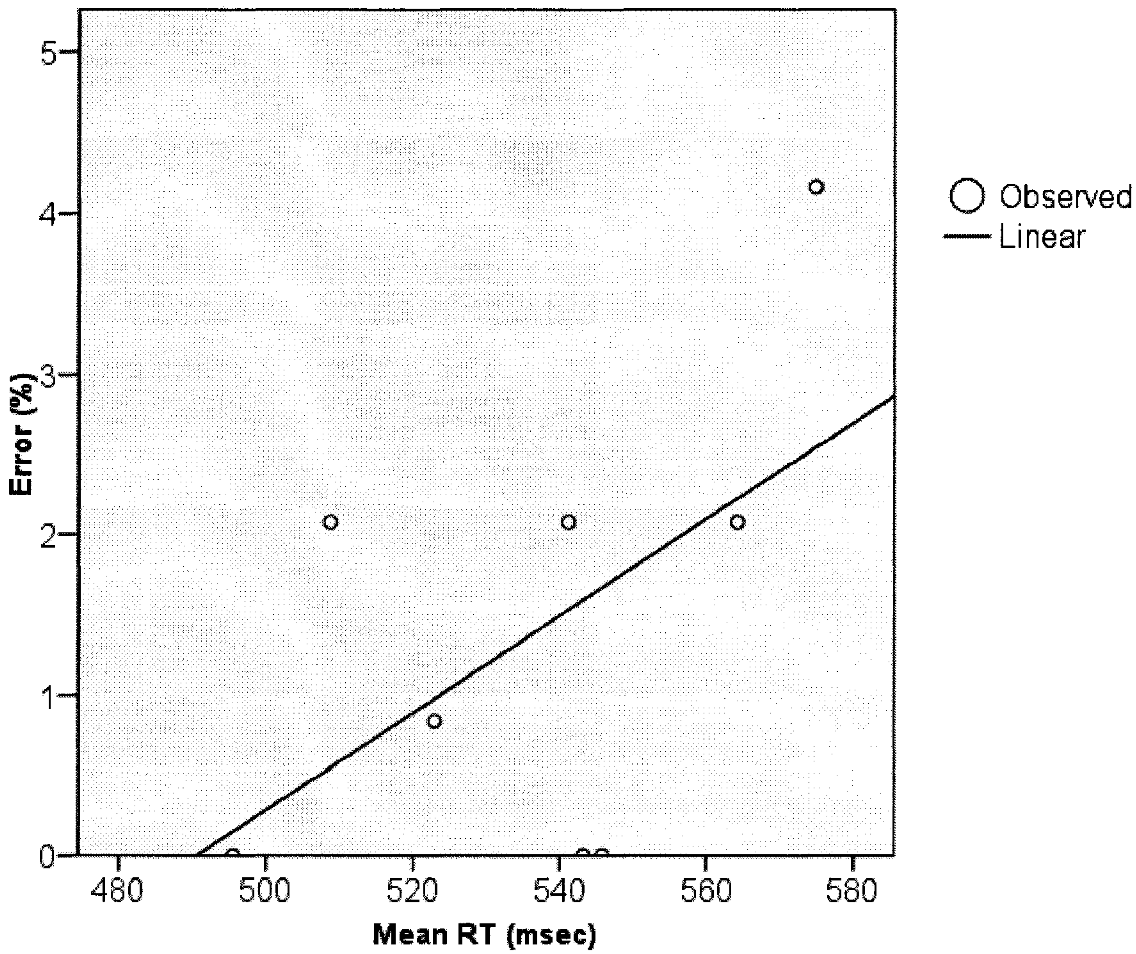


Figure 2.2. Correlation between RT and Error.

Further analysis by t-tests revealed significant difference between Masked Congruent condition compared to Masked Incongruent condition, $t(7) = 6.612$, $p <. 001$ ($p <. 002$, adjusted for multiple comparisons with Bonferroni method), but not between Unmasked Congruent and Unmasked Incongruent, $t(7) = .395$, $p = .704$. The difference between Congruent and Incongruent was significant in both Masked Non-Illusory, $t(7) = 4.087$, $p = .005$ ($p <. 02$, adjusted for multiple comparisons with Bonferroni method), and Masked Illusory, $t(7) = 7.628$, $p < .001$ ($p <. 004$, adjusted for multiple comparisons with Bonferroni method), but not in the Unmasked Non-Illusory, $t(7) = .166$, $p = .873$, and Unmasked Illusory, $t(7) = .821$, $p = .439$, as shown in Figures 2.4 and 2.5, respectively. An ANOVA was performed on error percentages but showed no significant effects (see figures in Appendix C).

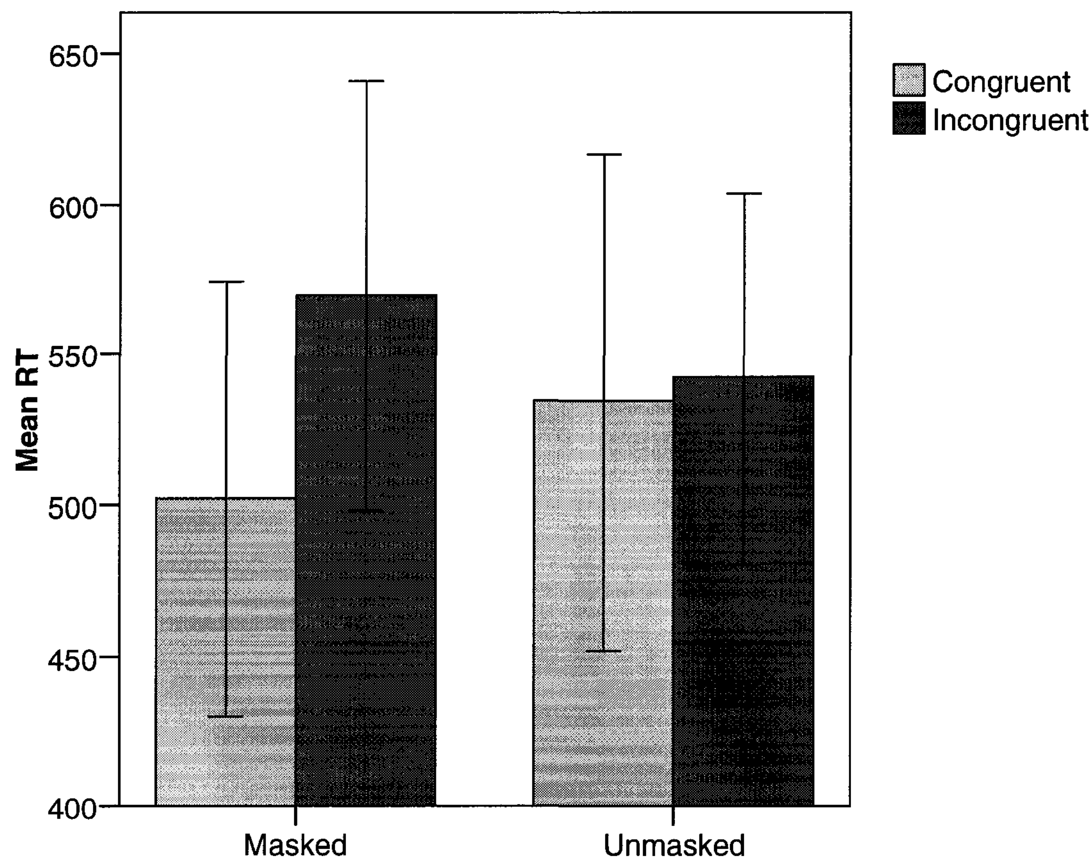


Figure 2.3. Interaction between Masking and Congruency.

Imaging results

As mentioned above, the two blocked factors in the fMRI design each with two levels, Masking (Masked vs. Unmasked) and Illusion (Illusory vs. Non-Illusory), were considered for the t-test contrasts (subtraction method, shown by – sign) at the first (FFX) and second (RFX) level group-analyses. Based on the levels of the two factors, relevant terms with initial capital letters are used to refer to all possible conditions or blocks including Masked Non-Illusory, Masked Illusory, Unmasked Non-Illusory, Unmasked Illusory).

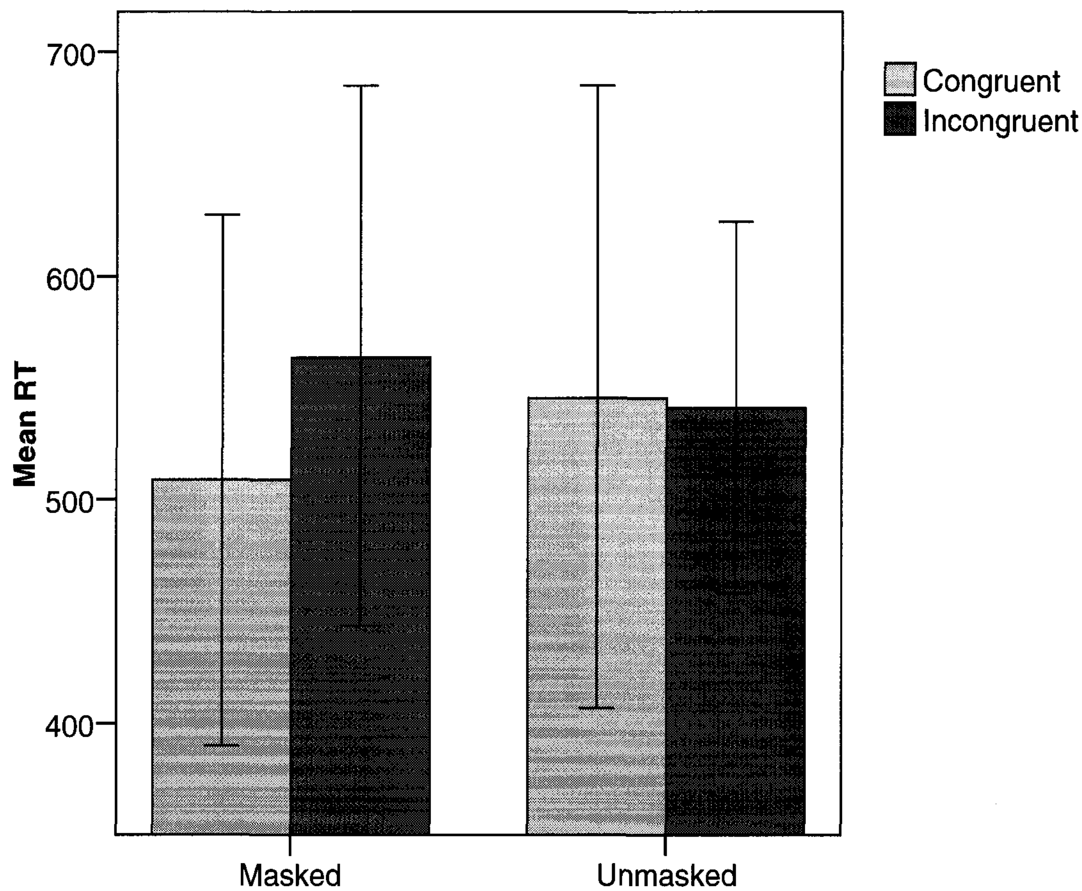


Figure 2.4. Interaction between Masking and Congruency in Non-Illusory condition.

The FFX is not generalizable and reliable as much as the RFX, therefore I focused on RFX result. The activations of the brain areas related to these significant contrasts are shown in Figures 2.6-2.9, superimposed on the gloss brain (which reveals activations around the whole brain, not just the surface) and the standard anatomical brain template provided with SPM2.

The result of Unmasked – Masked and Illusory – Non-Illusory and their opposite contrasts are shown in Figure 2.6 and 2.7. The Unmasked – Masked was significant at $p \leq .005$ (uncorrected) with at least four voxels in clusters significant at $p \leq .05$, uncorrected

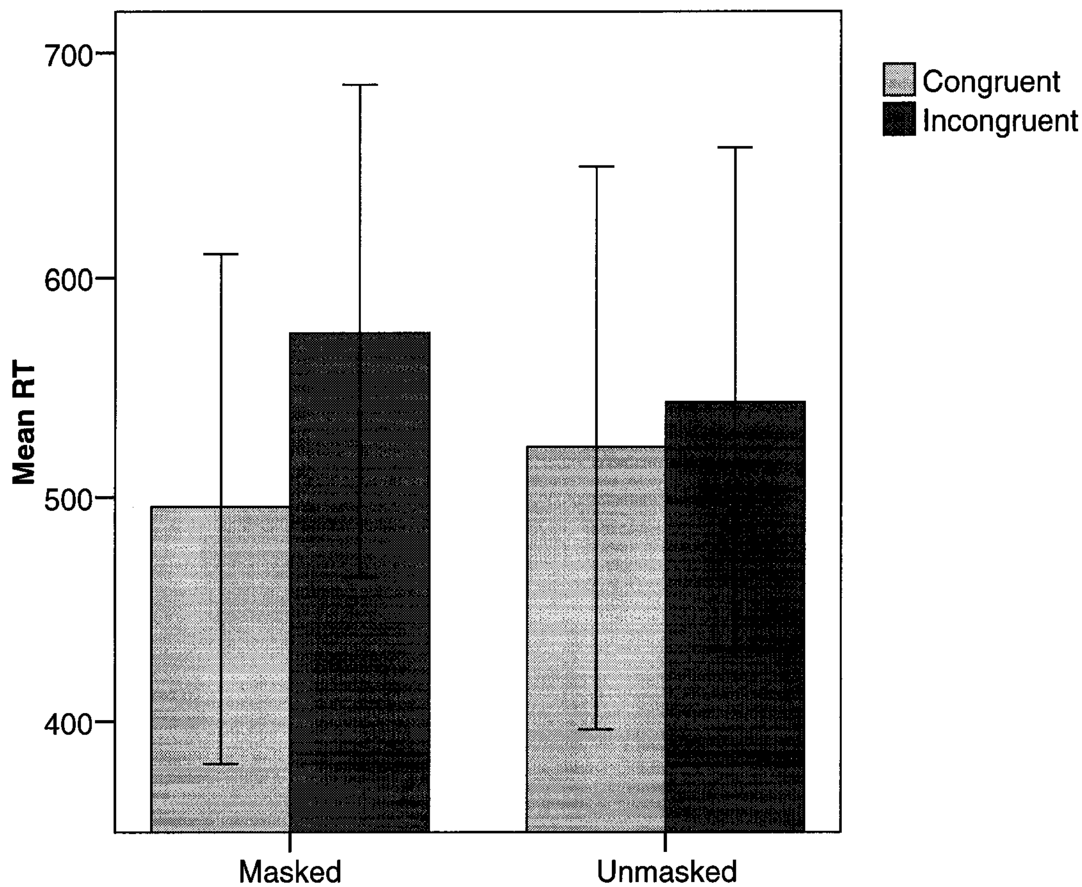


Figure 2.5. Interaction between Masking and Congruency in Illusory condition.

(cluster level). This contrast showed a widely spread activations around the whole brain, from Occipital to prefrontal cortex. Its opposite contrast, Masked Unmasked at this level

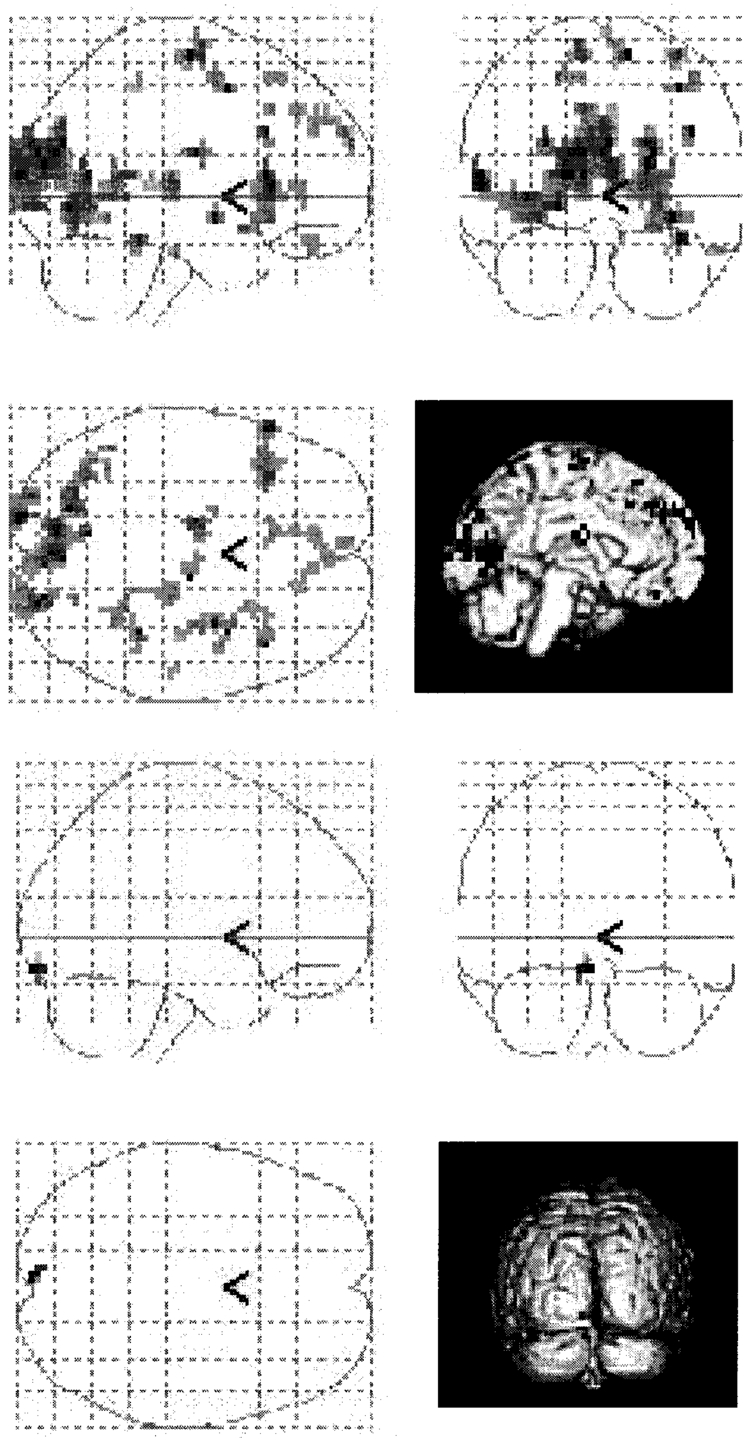


Figure 2.6. Activation results of the contrast Unmasked – Masked (top) and its opposite, Masked – Unmasked (bottom).

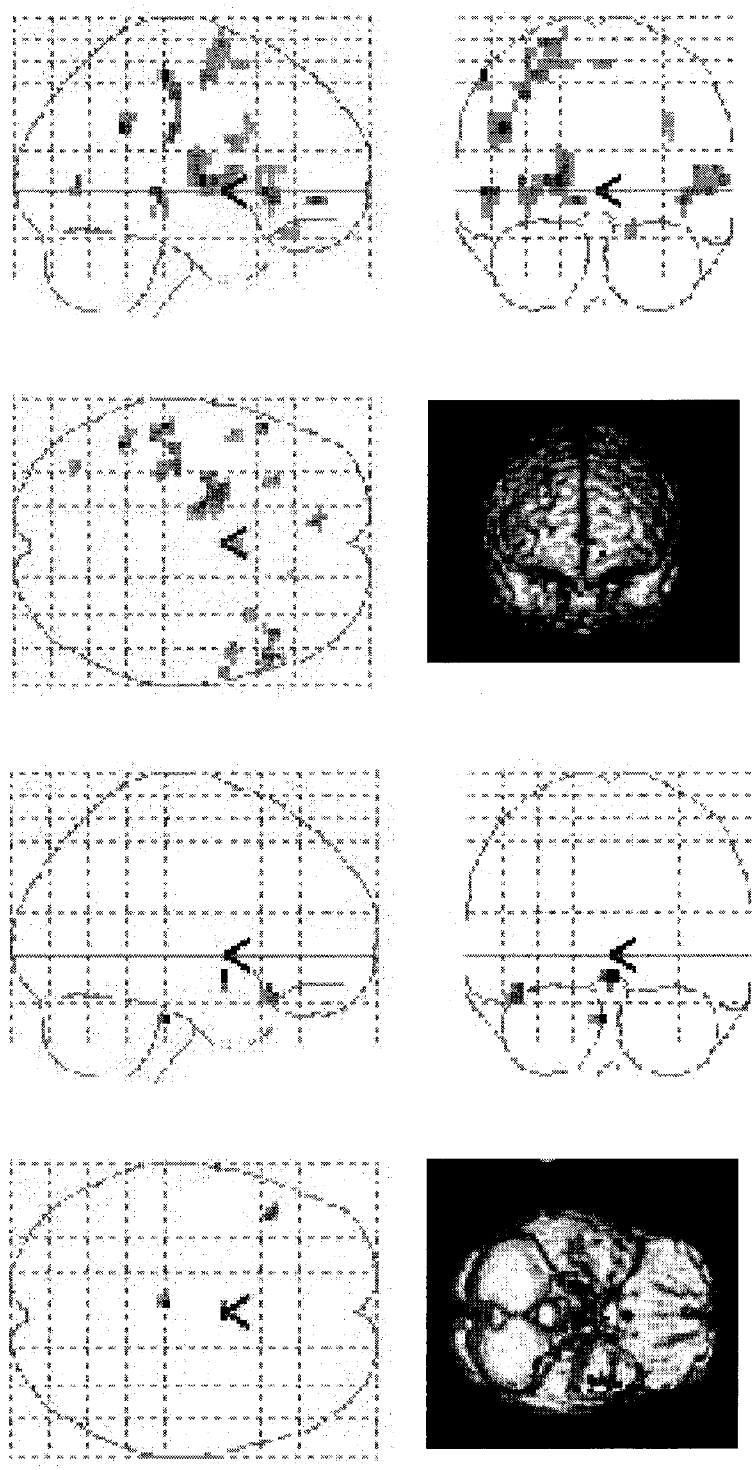


Figure 2.7. Activation results of the contrast Illusory – Non-Illusory (top) and its opposite, Non-Illusory – Illusory (bottom).

Table 2.1. *The areas, coordinates, and the statistical parameters of the activations in the contrasts related to Illusion and Masking (Unmasked Illusory – Unmasked Non-Illusory).*

Area	*k* (cluster)	*t* (peak)	x, y, z (mm)	Side	BA
IFG & dl-PFC	9	5.61	-59 15 18	Left	44 & 45

Table 2.2. *The areas, coordinates, and the statistical parameters of the activations in the contrasts related to Illusion and Masking (Unmasked Illusory – Masked Illusory).*

Area	*k* (cluster)	*t* (peak)	x, y, z (mm)	Side	BA
IFG & dl-PFC	33	6.43	-59 15 18	Left	44, 45, & 9
PFC: sub-gyral (white)	22	5.51	-24 19 27	Left	N/A
IFG	20	4.96	-39 23 -1	Left	47

of significance or threshold showed only a small activation in visual cortex. The widely spread activations for unmasked condition is similar to the activation found in seen compared to unseen trials in attentional bilk (e.g., Feinstein et al., 2004). The Illusory – Non-Illusory was significant at $p \leq .005$ (uncorrected) with at least four voxels in clusters significant at $p \leq .05$, uncorrected (cluster level). This contrast showed high activations around the brain, especially in prefrontal cortex. Its opposite contrast, Non-Illusory – Illusory at this level of significance or threshold showed only a small activation in temporal cortex and brain stem. Therefore, illusory lines caused higher activations compared to non-illusory lines (for structure coordinates and statistical parameters of these main effects see Appendix E).

To reveal the effects of different levels of main factors, I looked at all possible contrasts made of those levels. To assess the effect of Unmasked Illusion, two contrasts

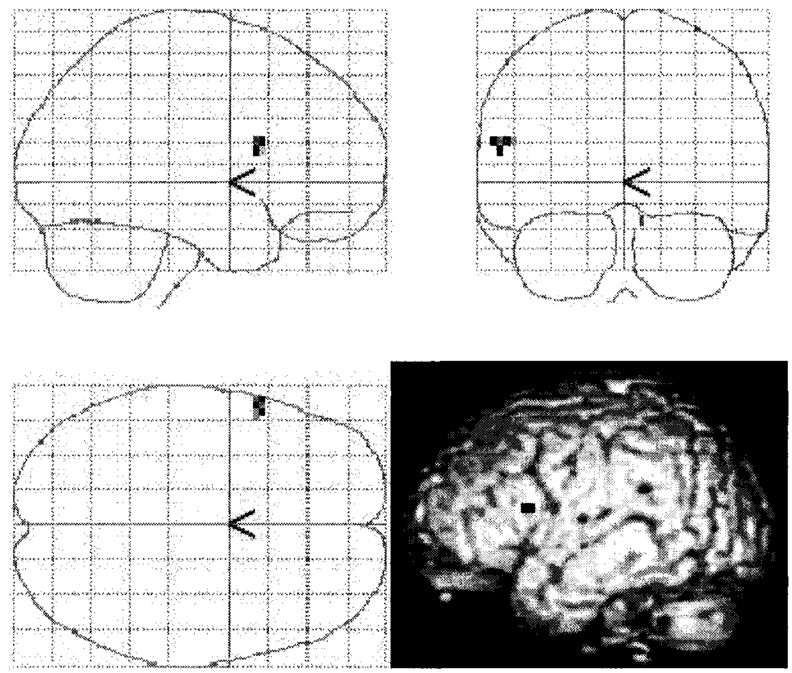


Figure 2.8. Activation results (mainly in the left IFG and dl-PFC) of the contrast Unmasked Illusory – Masked Illusory.

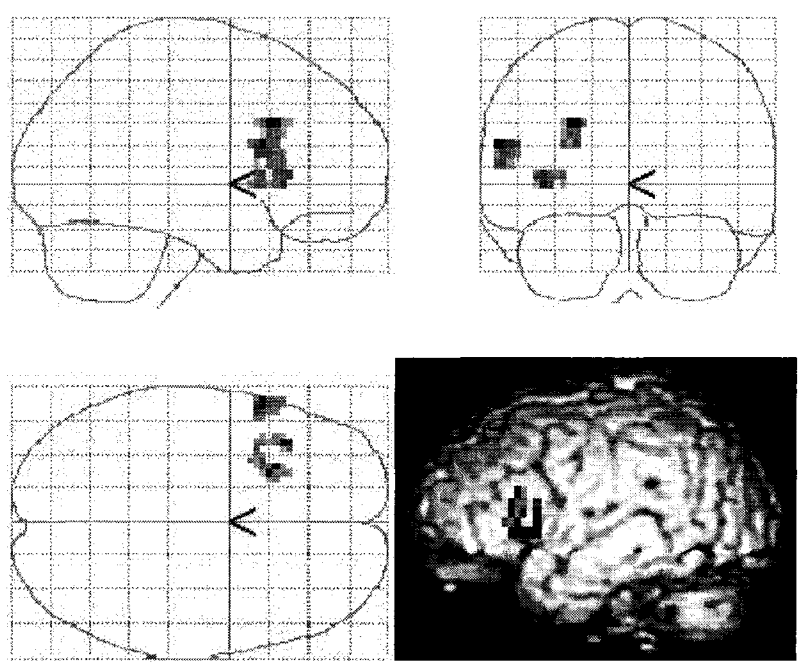


Figure 2.9. Activation results (mainly in the left IFG and dl-PFC) of the contrast Unmasked Illusory – Unmasked Non-Illusory.

were used: Unmasked Illusory – Unmasked Non-Illusory and Unmasked Illusory – Masked Illusory. These contrasts were significant at $p \leq .001$ (uncorrected) with at least four voxels in clusters significant at $p \leq .05$, uncorrected (cluster level). The structure labels with their Talairach coordinates, BAs (i.e., Brodmann Areas), and statistical parameters are shown in Tables 2.1 and 2.2. The Unmasked Illusory – Unmasked Non-Illusory (see Figure 2.8 and Table 2.1) showed a significant activation in the Inferior Frontal Gyrus (IFG) and dorso-lateral PFC (dl-PFC). Similar activation was also lit up by the contrast Unmasked Illusory – Masked Illusory (Figure 2.9 and Table 2.2). But their opposite contrasts, Unmasked Non-Illusory – Unmasked Illusory and Masked Illusory – Unmasked Illusory were not significant. Moreover, the effect of the Masked Illusion, using the contrast Masked Illusory – Masked Non-Illusory, was not significant. The activated brain areas (the IFG and dl-PFC) have been proposed to be involved in higher cognitive responses, presumably as a signature of inhibition (Aron, Robbins, & Poldrack, 2004) and cognitive control (Brass, Derrfuss, Forstmann, & von Cramon, 2005).

Discussion

The fMRI data did not reveal results for the priming effect, because the congruency factor was not controlled (but see Dehaene, Artiges, et al., 2003). Regarding other factors, the main fMRI results were a widely spread activation for unmasked condition compared to masked. Similar results have been found for reportable and unreportable stimuli in attentional blink (e.g., Feinstein et al., 2004; Kranczioch, Debener, Schwarzbach, Goebel, & Engel, 2005). Also, a higher activation was found in the illusory compared to non-illusory condition, especially in PFC. The high activation of the

PFC (especially, dl-PFC and IFG) in the illusory condition was tracked to the unmasked condition, not the masked.

The experimental data, however, indicated a clear priming effect, in the masked priming, for both illusory and non-illusory conditions. Participants were faster in the congruent trials compared to the incongruent ones, showing a PCE pattern. In the unmasked condition no effects were significant. The fact that no difference was found between the illusory line conditions and the real line conditions suggests that, at least in this case, the illusion was as compelling as the real lines. Since degraded primes cause an effect (as mentioned in Chapter 1), illusion does not act in this way. The results also suggest that the prime is interpreted within its visual context before the priming effect occurs. Of course the failure to find a significant difference does not mean there was not one. However, the overall pattern of results is consistent with this interpretation. But in the unmasked condition, Müller-Lyer probably involved in some higher-order cognitive processes that led to more inhibition or control compared to real line length, as revealed by the fMRI results. At least, Müller-Lyer could have led to depth of edges processing that the "real" display did not.

Chapter 3: Symbolic representation

Introduction

The previous study examined the effects of using a more indirect representation for the prime within the perceptual domain. Specifically, it was shown that an illusion of line length can produce a priming effect similar to actual line lengths. The present study looked at using more indirect representations within the semantic domain. The idea that semantic stimuli could create masked priming effects has been doubted by those who saw masked priming in terms of the vision system priming the motor system directly (e.g., Kunde et al., 2003). However, it has been clearly established that the semantic meaning of the stimulus can be involved in priming effects (e.g., Reynvoet, Gevers, & Caessens, 2005). However, this does not mean that any semantically meaningful prime or target will work. So far the semantic information used for primes and targets have been mainly "well-learned" stimuli (e.g., numbers or words). Dehane et al. (1998) have shown that how well-learned something is will effect how well it functions as a prime. Specifically, they found that Arabic numerals prime better than written numbers, as we are more familiar with the Arabic form. If this is the case then something that has just been learned (e.g., x = 5 and y = 7) might not be expected to work very well in a priming task, either as primes or targets.

It is important to be clear about what "well-learned" or "less well-learned" or "just learned" might mean. Although there is a lot of disagreement about what working memory means and its relationship to long term memory, there is general agreement that some pieces of information are forgotten after or even during the task where they are needed, while other pieces of information persist in memory for our entire life. Thus, well-learned (and slightly less-well-learned) could refer to items in long term memory while just-learned would refer to items in working memory. In this case, something that is just-learned might not function in the same way as something well-learned because it is subject to rapid decay and also takes longer to retrieve. However, other theorists postulate that just-learned and well-learned items exist in the same system but behave differently. Specifically, just-learned items are thought to have a low level of activation, meaning they will decay away quickly if not used and that it takes longer to retrieve them (Anderson, 1983). In either case different masked priming effects could result from different lengths of time taken to retrieve the stimulus meaning for the prime and for the target. Thus the actual interval between prime and target would be (target onset + target retrieval time) – (prime onset + prime retrieval time). This leads to several questions regarding using recently learned symbolic mappings as prime and/or as target: (1) if working memory is a separate system will its contents be relevant for priming, (2) what will the effect of a longer retrieval time be if a recently learned symbolic mapping is used for the prime, (3) what will the effect of a longer retrieval time be if a recently learned symbolic mapping is used for the target?

The experiments in this chapter focused on the type (symbols that are well-learned vs. recently learned symbols) and the magnitude (numerical size and distance) of stimuli. A new masked priming task was employed to investigate the effect of numbers and symbols, and their joint effects with the distance factor. As described in Chapter 1, since these two manipulations involve processes that have been investigated using fMRI in previous studies, fMRI was not employed in this experiment.

I sought to determine if there is any positive or negative priming when symbols, representing numbers, are held (temporarily) in memory, knowing that numbers are well-learned (and therefore have strong representation) while recently learned symbols have weaker representation. For this purpose, I used Dehaene et al.'s (1998) paradigm, but employed Arabic numerals and symbols associated with numbers to be held in memory, instead of their paradigm using Arabic numerals and spelled-out numbers.

Experiment 2: Masked and unmasked priming using symbols and numbers

Introduction

In the current experiment, single digit numbers were assigned to arbitrary symbols with enough training. For this purpose, I used symbols and numerals in the same priming paradigm as Experiment 1, by adding symbols to a number comparison paradigm (e.g., Dehaene et al., 1998). Therefore, Arabic numerals and symbols representing numbers were used as stimuli (Figure 3.1). Here participants compared a target number to a reference number (*five*) while it was preceded by a masked or unmasked prime. Before the task they saw the four single numerals used in the task as well as four symbols to map each numeral to a specific symbol within a short time (see Appendix A).

Two conditions were used: symbols priming numerals and numerals priming symbols. Masked and unmasked conditions were included to see their effects on the priming pattern. Moreover, perhaps Dehaene, Artiges, et al.'s (2003) consciousness manipulation was confusing because prime and target had the same colour. Therefore, participants might have been confused about which stimulus they had to respond to. This was controlled in this study by using different colours for prime and target (see also Jaśkowski, 2007, whose solution was to present the target with the same colour but at a different location compared to the prime).

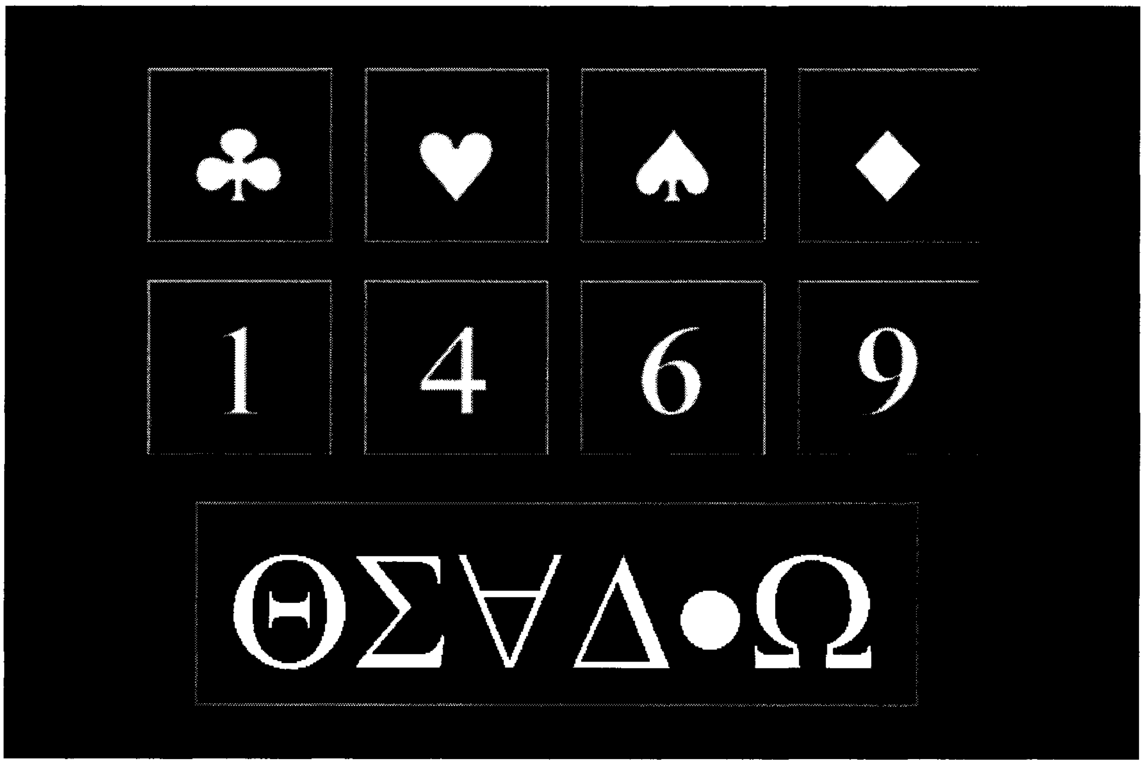


Figure 3.1. The stimuli used in the experiment. The task was to map each symbol (top) to its corresponding numeral (middle) and to use them in the priming of numerals and symbols both as prime and target. The mask consisted of six symbols (bottom) in random order for each trial. The assignment of symbols to numbers were randomized between participants to control confounds as much as possible. For example, there is an order of value for the card suits in several games, e.g., bridge: Spades, Hearts, Diamonds and then Clubs.

Method

Participants

Participants were ten healthy graduate students (3 females; age 25-46) with normal or corrected to normal vision. The study was approved by the Carleton University Ethics Committee for Psychological Research.

Procedure

The stimuli were four single digit numerals (1, 4, 6, and 9) and four symbols used in playing cards: Heart, Club, Diamond, and Spade (Figure 3.1). The task was to map each symbol to a numeral and then to use the mappings in a priming task by deciding if the target is larger or smaller than *five,* using the right and left button press on the response device, respectively (i.e., SNARC compatible, see Chapter 1). First, participants were shown the numerals and their corresponding symbols while the instructions were given to them. Before the priming task, participants were tested to determine if they had memorized the correct mappings between numerals and symbols, by giving eight blocks of the four symbol-numeral pairs, presented randomly in each block. Feedback on accuracy and the correct response were provided after each trial. The mappings for each participant were randomized and all were counterbalanced between participants.

In the priming phase, numerals and symbols were presented both as prime and target, making two main conditions: In one condition, the prime was symbol and the target was numeral (henceforth, Symbol-Number). In the other condition, the prime was numeral and the target was symbol (henceforth, Number-Symbol). Similar to Dehaene et al.'s (1998) paradigm used in Experiment 1 (here, after presenting a white frame for one second), the prime was presented very briefly (43 ms). Then participants had to respond to a briefly presented target (200 ms). The prime was either unmasked (reportable) or masked (unreportable) by being presented between two flashed patterns (71 ms each), composed of six symbols (appeared at once as a string but with a random order each time) that differed from the four symbols used in the task (see Figures 3.1 and 3.2). In the congruent condition, the prime and target both were either smaller or larger than *five*, while in the incongruent condition, one was smaller and the other one was larger than *five*.

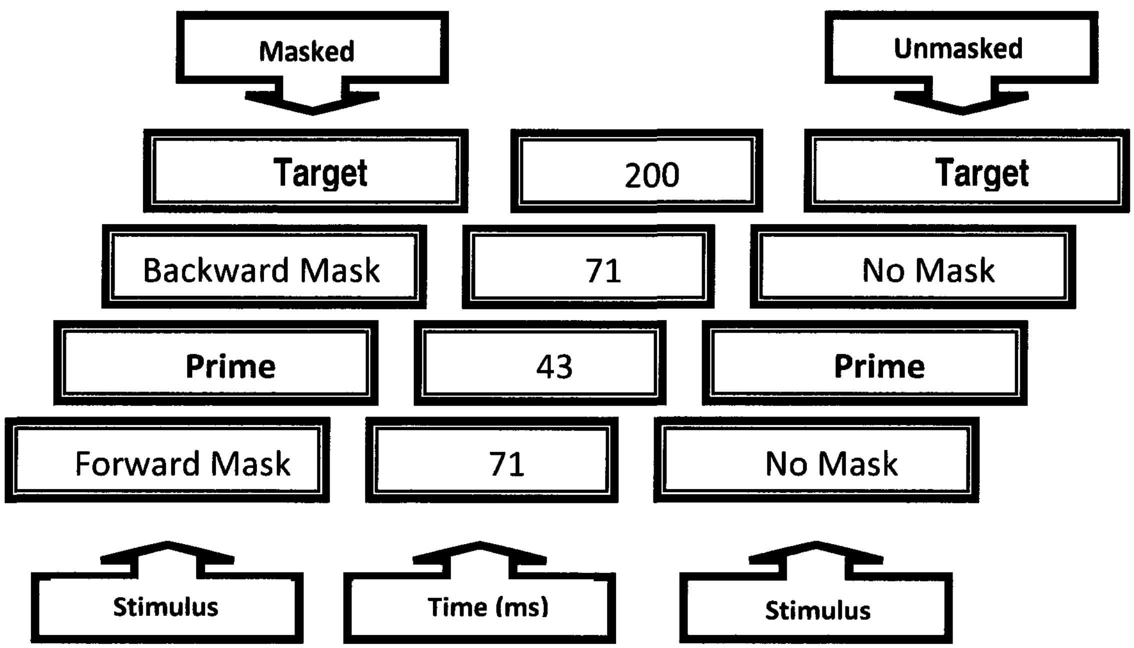


Figure 3.2. Masked and unmasked priming design in Experiment 2.

Stimuli were presented with 75 Hz refresh rates on a 14" Sony 1024 by 768, colour monitor. The stimuli were chosen from the standard Symbol font with size 90 points in Microsoft Windows XP presented at the centre with an approximate distance of

60 cm. Responses were made using a joystick - R and L button presses by the index finger of the right or left hand - and were recorded with the same software used in Experiment 1. All trials, including masked and unmasked, were presented randomly. The participants had to respond during the target presentation or within the remainder of the 3s of the trial; otherwise a missed trial would be recorded. The Inter Trial Interval (ITI) was a 1s white frame as mentioned, not considered in the 3s deadline.

The trials were random and consisted of 16 combinations of four symbols and four numerals for Symbol-Number and 16 combinations for Number-Symbol as well as masked and unmasked, each repeated twice during the task. Therefore, the priming session consisted of 128 trials. Before the experiment, participants performed four trials of each masked prime without target. They could not verbally report the nature of the prime when they were asked after each trial to report if they had seen a specific stimulus other than the mask.

Results

The results of training phase showed that participants had learned the relationships between symbols and numbers. The mean RTs and percent errors of all participants showed that they had learned the task. By the end of the eight blocks of the four numeral-symbol maps, both errors and RTs decreased substantially (but not completely, for more details see, Appendix A).

The RTs and percentages of error were averaged for eight possible conditions with three factors: Type (Number-Symbol vs. Symbol-Number), Masking (Masked vs. Unmasked), and Congruency (Congruent vs. Incongruent). These results showed that participants had understood the instructions and were able to do the task properly. The correlation between the two scales was positive and significant (r=.885, p=.003). Therefore no trade-off between RTs and percentages of error were found. A regression curve shows this relationship (Figure 3.3).

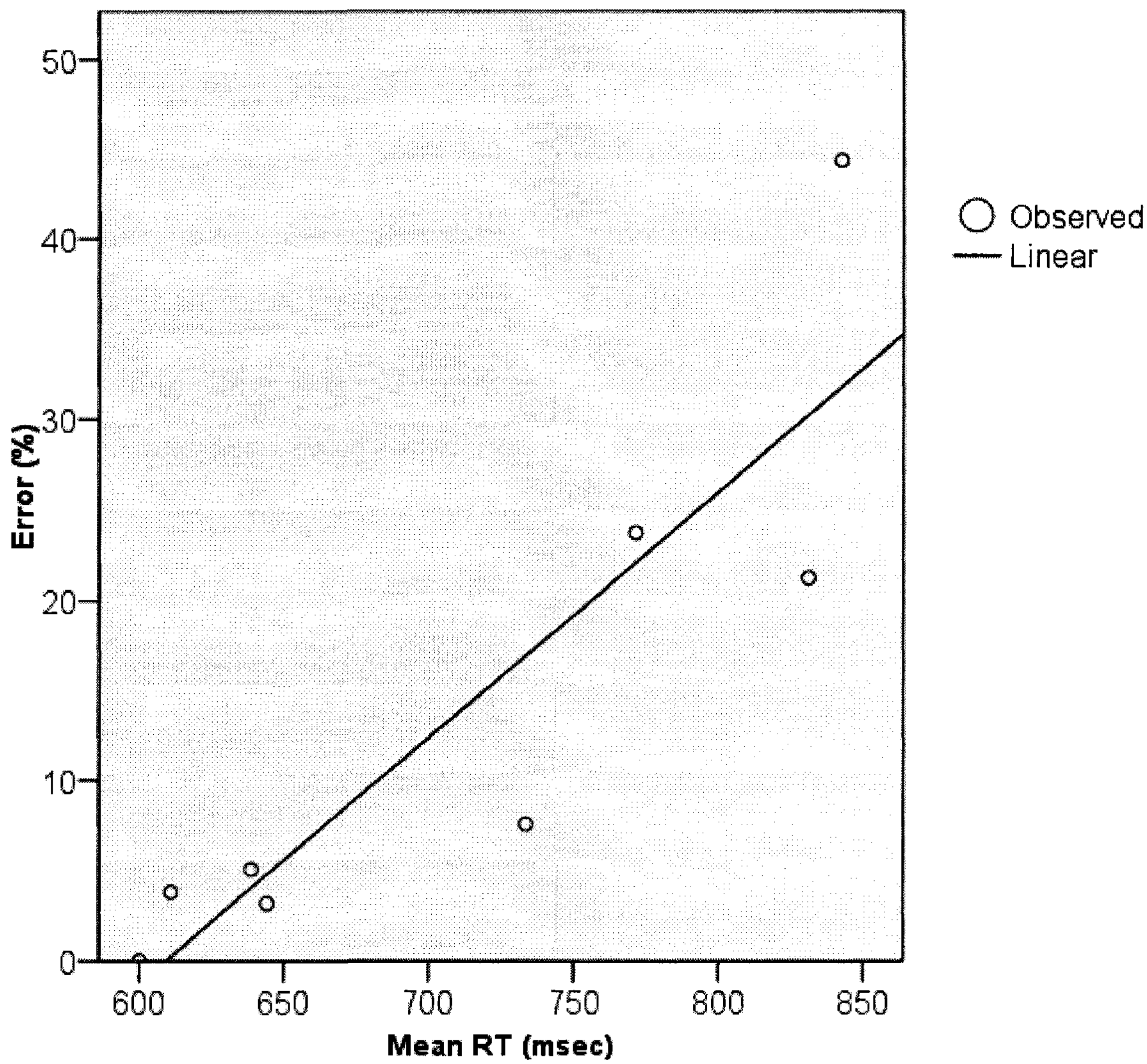


Figure 3.3. Correlation between RT and Error.

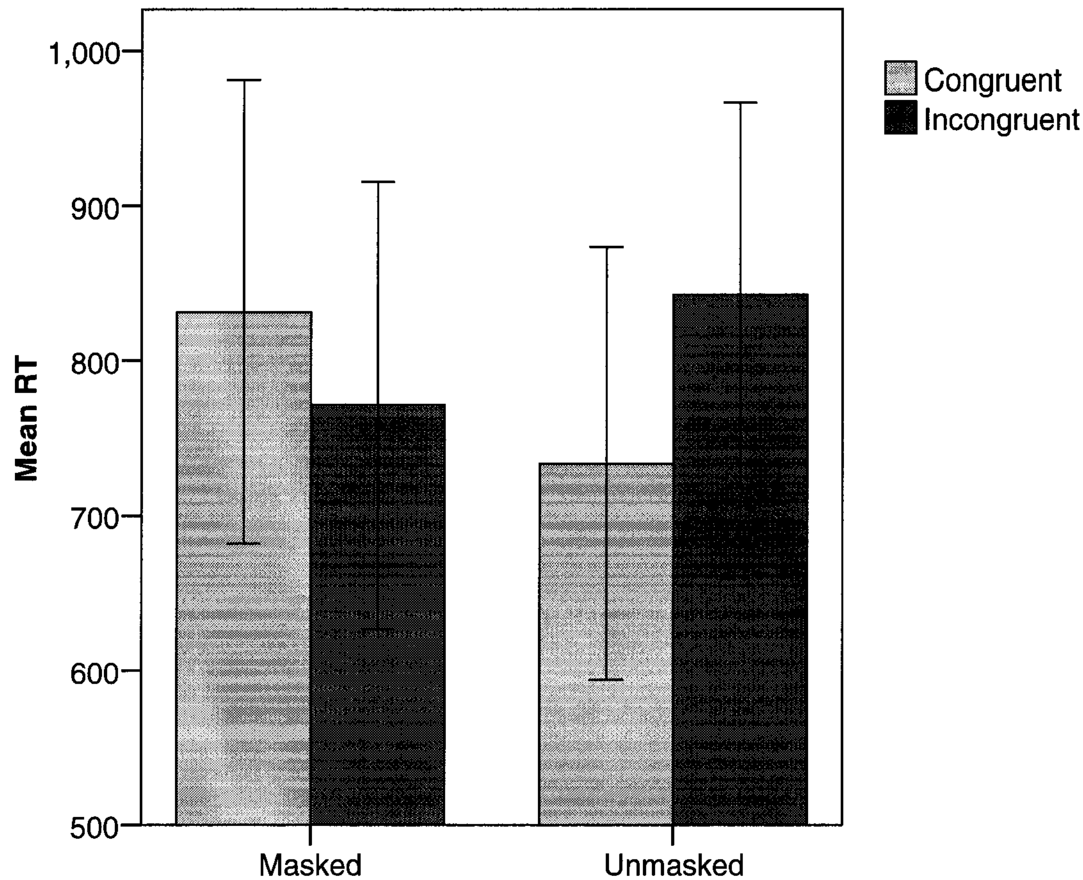


Figure 3.4. Masking by Congruency interaction (RTs).

To analyze the priming data, a repeated measures ANOVA (2 x 2 x 2) was run on mean RTs of all participants. Three factors were included in the analysis: Type (Number-Symbol vs. Symbol-Number), Masking (Masked vs. Unmasked), and Congruency (Congruent vs. Incongruent). One participant showed errors for all Masked, Number-Symbol, Incongruent trials, so her mean RT in this condition was missing. The main effect of Type (Number-Symbol vs. Symbol-Number) was significant, $F(1, 8) = 15.349$, $p=.004$, showing that participants were faster in Symbol-Number compared to the

Number-Symbol condition. A significant interaction was found for Masking by Congruency, F(1, 8) = 6.119, p = .038, (Figure 3.4). T-test on RTs in Number-Symbol was significant for Masked condition, showing an NCE pattern, $t(9)$=2.519, p=.033 *(non-significant when adjusted for multiple comparisons with Bonferroni method, p <. 132),* but not for Unmasked condition, showing a non-significant PCE pattern, $t(8)$ = 1.826, p = .105). However, in Symbol-Number, no significant congruency effects were found both in Masked, $t(9)$= 1.038, p = .326) and Unmasked, $t(9)$ = .487, p = .638) conditions (Figure 3.5).

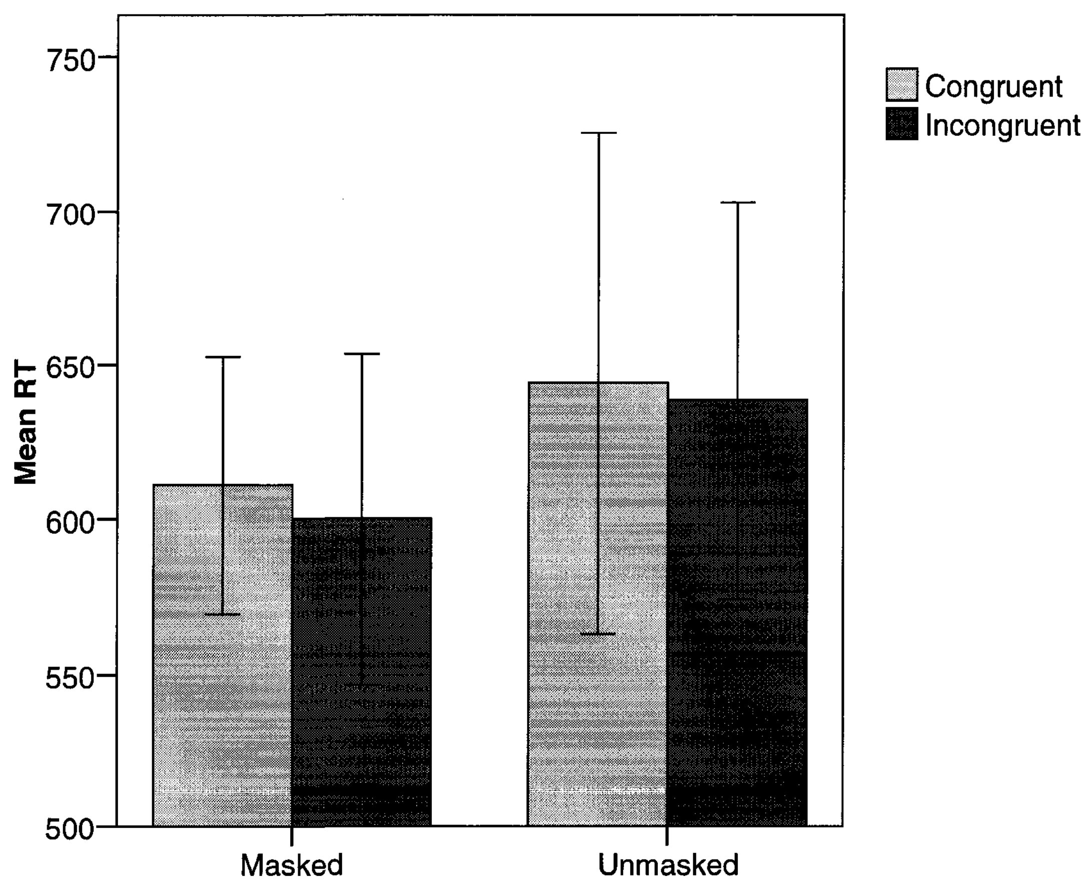


Figure 3.5. Symbol priming Number (RTs).

To analyze the error percentages in priming data, a repeated measures ANOVA (2 x 2 x 2) was run on mean error percentages. Three factors were included in the analysis: Type (Number-Symbol vs. Symbol-Number), Masking (Masked vs. Unmasked), and Congruency (Congruent vs. Incongruent). The main effects of Type, $F(1, 9) = 12.456$, $p = .006$ and Congruency, $F(1, 9) = 5.311$, $p = .047$, were significant, showing that participants were more accurate in Symbol-Number compared to the Number-Symbol and Congruent compared to Incongruent conditions. Significant interactions were found for Masking by Congruency, $F(1, 9) = 10.461$, $p = .01$, Type by Congruency, $F(1, 9) = 5.712$, $p = .041$, and Type by Masking by Congruency, $F(1, 9) = 8.563$, $p = .017$. The t-test on errors was significant only for Unmasked Number-Symbol, showing a PCE pattern, $t(9)=2.988$, $p= .015$ (marginally significant when adjusted for multiple comparisons with Bonferroni method, $p= .06$) (see figures in Appendix C).

Discussion

In the unmasked condition the variability was very high, suggesting that subjects were consciously applying strategies to the task with variable success. So overall the unmasked conditions were uninformative. In the masked condition the recently learned symbol failed to work as a prime and produced no effect. However, as a target, the recently learned symbol produced an NCE. Because this general experimental set up has previously produced positive priming effects (Dehaene et al., 1998) and because the mask-prime SOA in this experiment has not been associated with NCE, this suggests that the extra time taken to retrieve the meaning of the target significantly extended the SOA from when the target was presented until when the target was meaning was retrieved.

This longer SOA could account for the NCE, which is associated with long SOAs.

Experiments 3: Distance effect.

Introduction

In the previous experiment a potential confound existed. Specifically, it was possible to predict the form the target would take (number or symbol) based on the prime (i.e., number always primed symbol and symbol always primed number). Given the unusual result, Experiment 3 was designed to rule out the possibility that this predictability factor was involved in the result. Therefore in this study the prime was always a numeral and the target was either a numeral or a symbol associated with a number (as in the last experiment). Also, to further investigate this effect the distances between the numbers was included as a factor. Here, 1 and 9 were used as numbers with far distance from *five* and 4 and 6 were used as numbers with close distance from *five*. This was done as studies (e.g., Gallistel & Gelman, 1992; Dehaene et al., 1993) have found that numbers with close distance from *five* are processed slower than those with larger distances from *five*.

Method

The same procedure in Experiment 2 was used with some modification. A fresh group of ten participants (4 females, age 22-43) were tested. The same instruction in Experiment 2 was given. However, here participants had 45s to look at the symbols and their corresponding numerals after the instruction. The numerals and symbols were presented in two separate rows at the centre of the screen. During this time, the numerals moved away from the symbols downward, in three 15s steps, until they disappeared from the bottom of the screen (for more details see Appendix A). Then similar to the previous experiment, the participants were tested and received feedback to completely master the mapping. However, here instead of eight blocks only four blocks of the four number-symbol pairs were presented, because the 45s presentation of the mapping prepared them to learn the relationships very quickly.

In this experiment, the initial blank frame in Experiment 2 was replaced with a 500 msec fixation cue (# or * with the same font size and at the same position as the other stimuli) and 300 msec blank screen. In the first session, both cues were presented randomly for both target types (symbol and number) with the same likelihood and the participants were told that the signs are just for fixation (but see next experiment).

In half of the trials prime and target were numeral (henceforth, Number-Number) while in the other half prime was a numeral and target was a symbol (henceforth, Number-Symbol, as in Experiment 2). Moreover, the distance factor was considered in this experiment. While in Experiment 2 the aim was to look at the congruency between prime and target, no data was recorded for the magnitude of the numbers (i.e., if a small number was preceded or followed by a large number) as well as how small or big they were (i.e., the distance of the number from the reference number, *five).* Here, the distance factor was recorded and included in the analysis as another factor (henceforth, Distance). There were sixteen types of trials based on all possible conditions with three factors: Type (Number-Number vs. Number-Symbol), Congruency (Congruent vs. Incongruent), and Distance (Close-Close, Far-Close, Close-Far, and Far-Far). Each trial type was repeated three times, therefore the total number of trials was 96.

Results

Similar to Experiment 2, the results of training phase showed that participants had learned the number-symbol mapping. The mean RTs and percent errors of participants showed that they had learned the task successfully. By the fourth blocks of the four number-symbol maps, RTs decreased substantially and no errors occurred (for more details see, Appendix A).

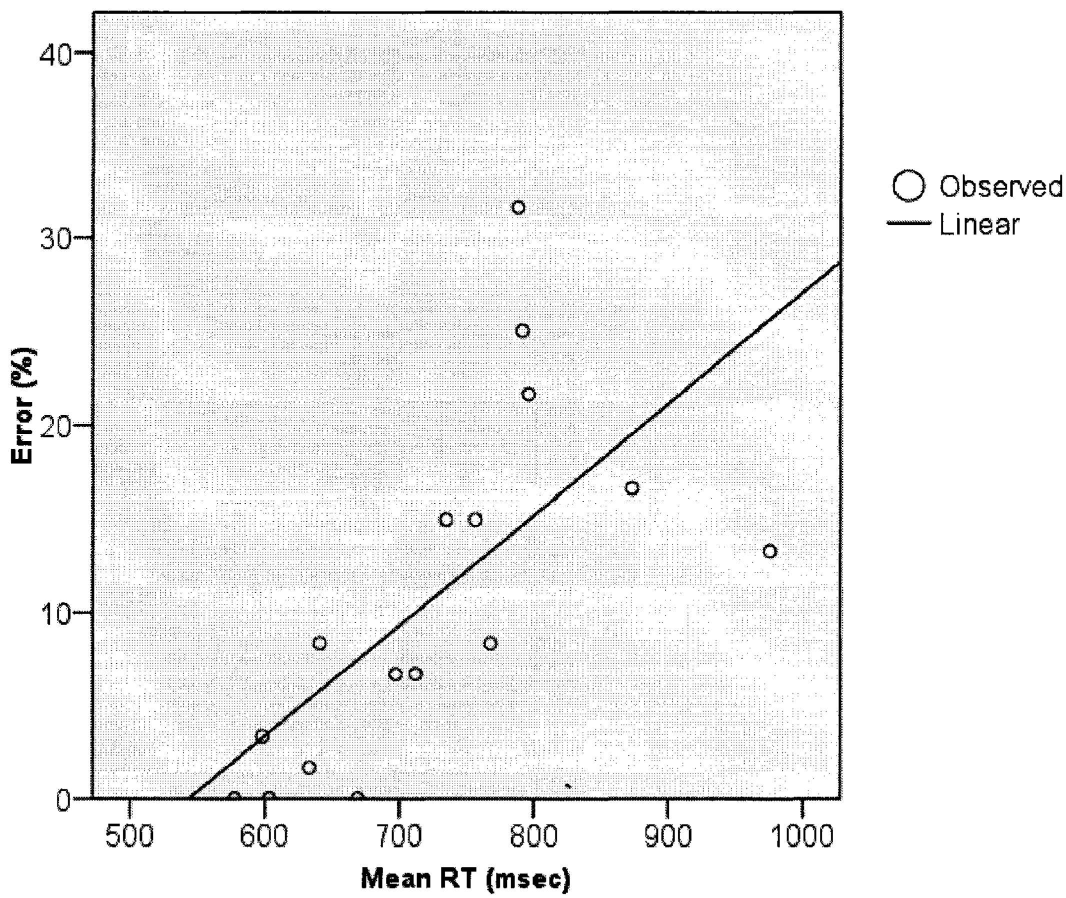


Figure 3.6. Correlation between RT and Error.

The RTs and percentages of error in the priming phase were averaged for sixteen possible conditions with three factors: Type (Number-Number vs. Number-Symbol), Congruency (Congruent vs. Incongruent), and Distance (Close-Close, Far-Close, Close-Far, and Far-Far). These results showed that participants had understood the instructions and were able to do the task properly. The correlation between the two scales was positive and significant (r=.668, p=.005). Therefore no trade-off between RTs and percentages of error was found. A regression curve shows this relationship (Figure 3.6).

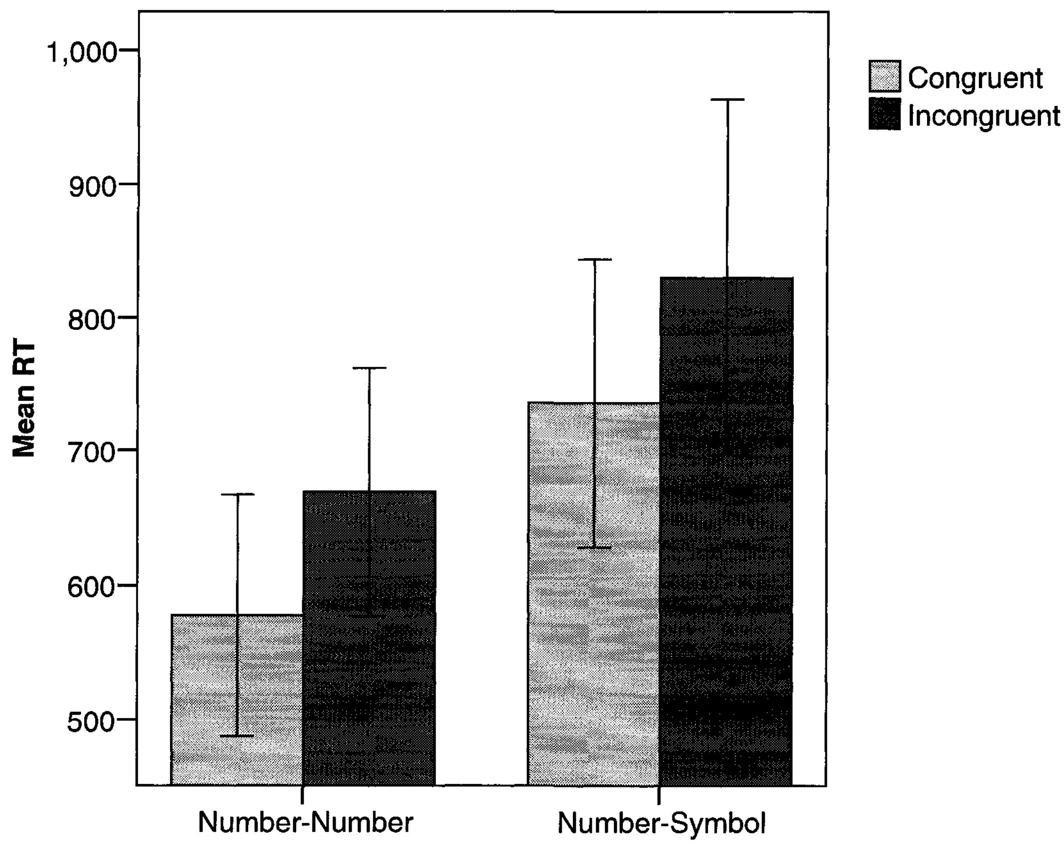


Figure 3.7. Significant PCE in Number–Number and marginally significant PCE for Number–Symbol both at Far Prime-Far Target distance.

For analyzing the data from the main part, the priming phase, a three-way (2 x 2 x 4) repeated measure ANOVA on RT was run with three factors: Type (Number-Number vs. Number-Symbol), Congruency (Congruent vs. Incongruent), and Distance (Close-Close, Far-Close, Close-Far, and Far-Far). The results revealed significant main effects of Type, F (1, 9) = 131.001, *p* = .001, Congruency, F(1, 9) = 6.519, *p* = .031, and Distance, F(3, 27) = 4.581, *p* = .01. Thus in this experiment, Number-Number trials were faster than Number-Symbol trials. This showed a specific effect of symbol target, showing the difference between numbers and symbols, presumably because of a delay in retrieving the symbols. Congruent trials were faster than Incongruent trials, and the trials with Far target were faster than those with Close target. The RTs were faster in trials with Far compared to Close target, regardless of the prime distance (see Appendix B, for more details about distance effect).

The two-way significant interactions were Type by Distance, F(3, 27) = 9.294, *p* < .001, and Congruency by Distance, F(3, 27) = 6.385, *p* = .002, and the three-way significant interaction was Type by Congruency by Distance, F(3, 27) = 5.995, *p* = .003. The analysis using t-tests revealed the role of Distance factor, showing a significant PCE at Far Prime-Far Target distance in Number-Number (Figure 3.7), *t(9)* = 4.555, *p* = .001 (*p=.008,* adjusted for multiple comparisons with Bonferroni method), a significant NCE at Close Prime-Close Target distance in Number–Symbol (Figure 3.8), *t(9)* = 3.692, *p* = .005 (*p=.04,* adjusted for multiple comparisons with Bonferroni method), and no significant priming in the other two Distance levels, Close-Far (Figure 3.9), in Number-Number, *t(9)* = .980, *p* = .352 and in Number–Symbol, *t(9)* = *.657, p* = .527, and Far-Close (Figure 3.10), in Number-Number, *t(9)* = .441, *p* = .67 and in Number–Symbol (marginally significant), *t(9)* = *2.039, p* = .072 (non-significant when adjusted for multiple comparisons with Bonferroni method, *p=.576*). By excluding Distance factor (Figure 3.11), PCE was significant in Number-Number, $t(9) = 3.737$, $p = .005$ ($p=.01$, adjusted for multiple comparisons with Bonferroni method), and non-significant in Number-Symbol, $t(9) = .665$, $p = .522$. Although a PCE was found for Number-Number regardless of Distance, it was mainly found at Far-Far. The marginally significant PCE found for Number-Symbol at Far-Close shows that Number can prime symbols, but the result for Close-Far did not show PCE. The only NCE found here was the one for Number-Symbol at Close-Close distance.

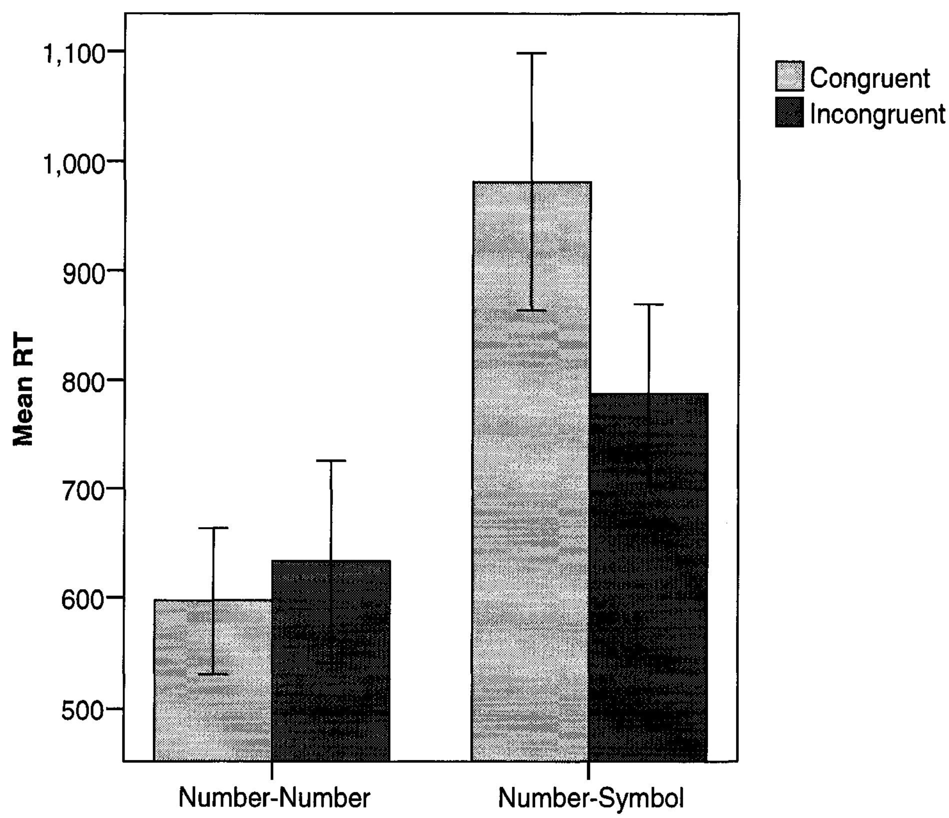


Figure 3.8. At Close Prime-Close Target, there was a non-significant PCE for Number–Number and a significant NCE for Number–Symbol.

A separate ANOVA on errors was run. The main effect of Type was significant, F(1, 9) = 12.623, *p* = .006, showing that Number-Number had fewer errors than Number-Symbol. Moreover, a Type by Congruency interaction was significant, F(1, 9) = 5.762, *p*

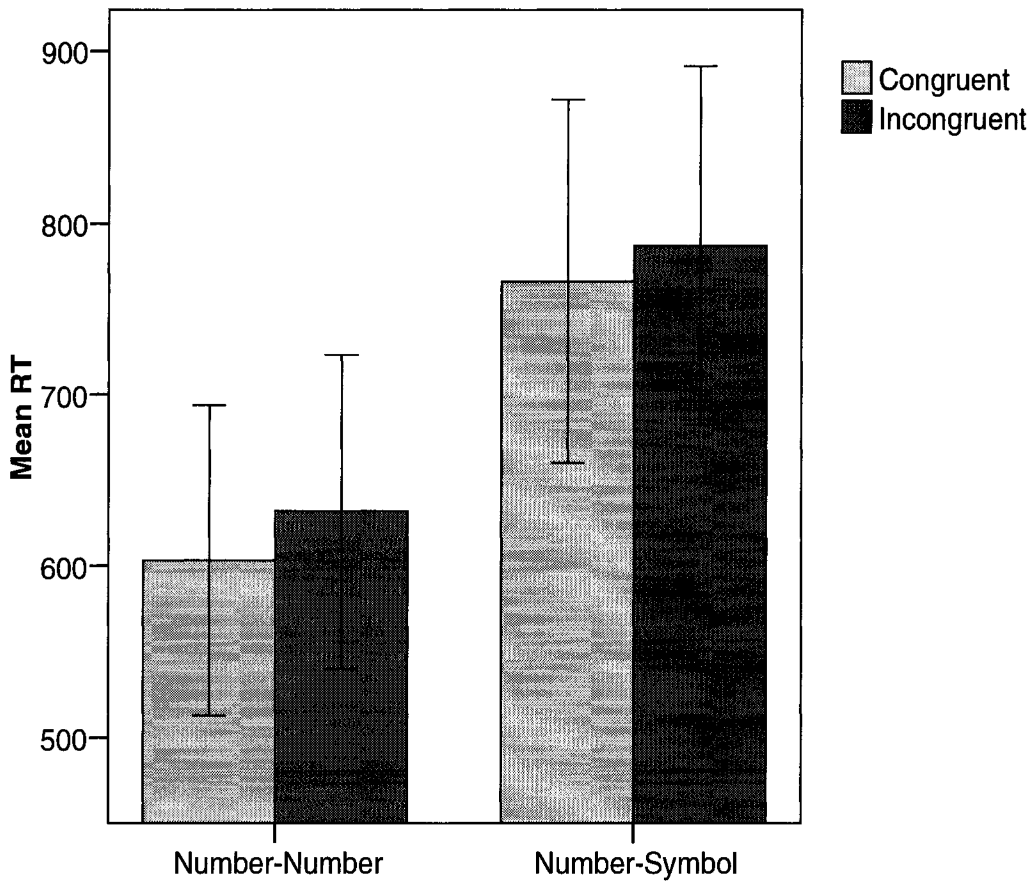


Figure 3.9. Non-significant PCE at Close Prime-Far Target distance both in Number–Number and in Number–Symbol.

= .04, showing that participants had less errors in Congruent compared to Incongruent trials, especially in Number-Symbol. T-test showed no significant PCE for Number-Number, *t(9)* = .524, *p* = .613, but a marginally significant PCE for Number-Symbol condition, $t(9) = 2.211$, $p = .054$ (non-significant when adjusted for multiple comparisons with Bonferroni method, $p=.108$) (see figures in Appendix C).

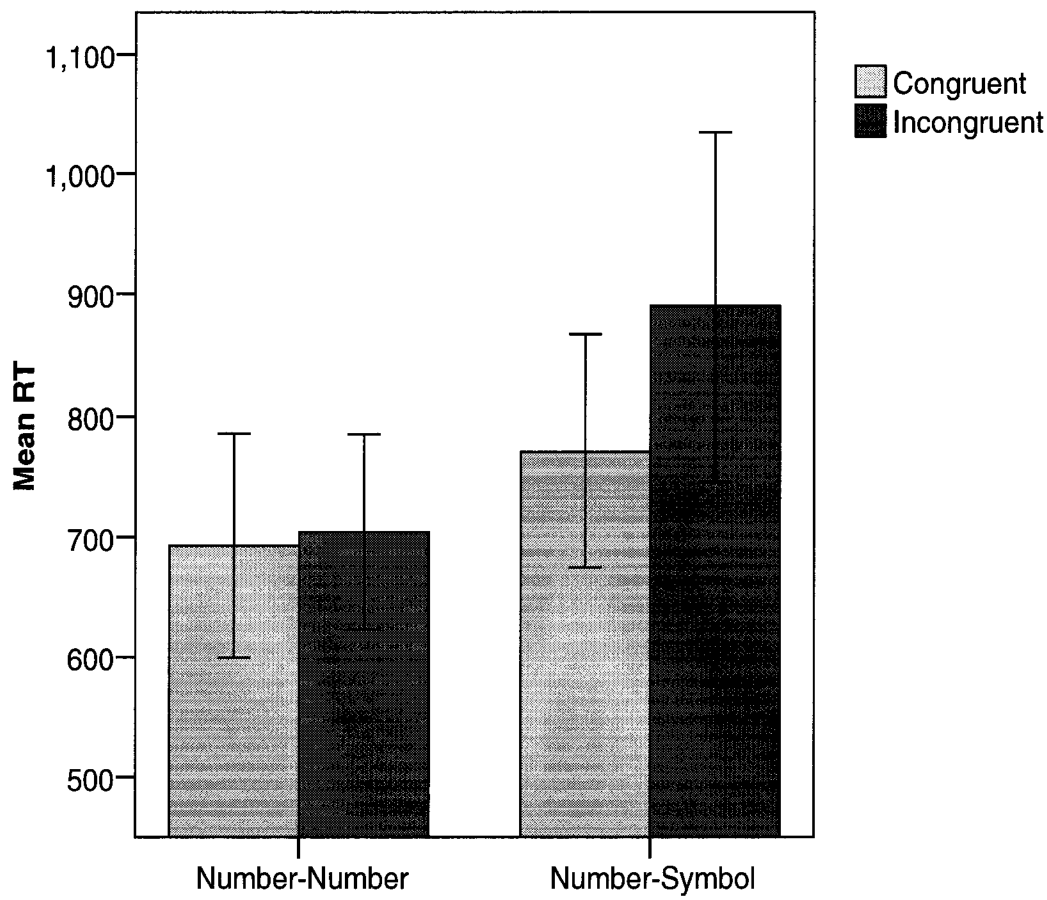


Figure 3.10. At Far Prime-Close Target distance, PCE was non-significant in Number–Number and marginally significant in Number–Symbol.

Discussion

This experiment produced a very interesting pattern of results. In particular the distance manipulation on the prime and the target produced a number of interesting effects. Number-Number produced a PCE, but only in the Far-Far condition, and otherwise did

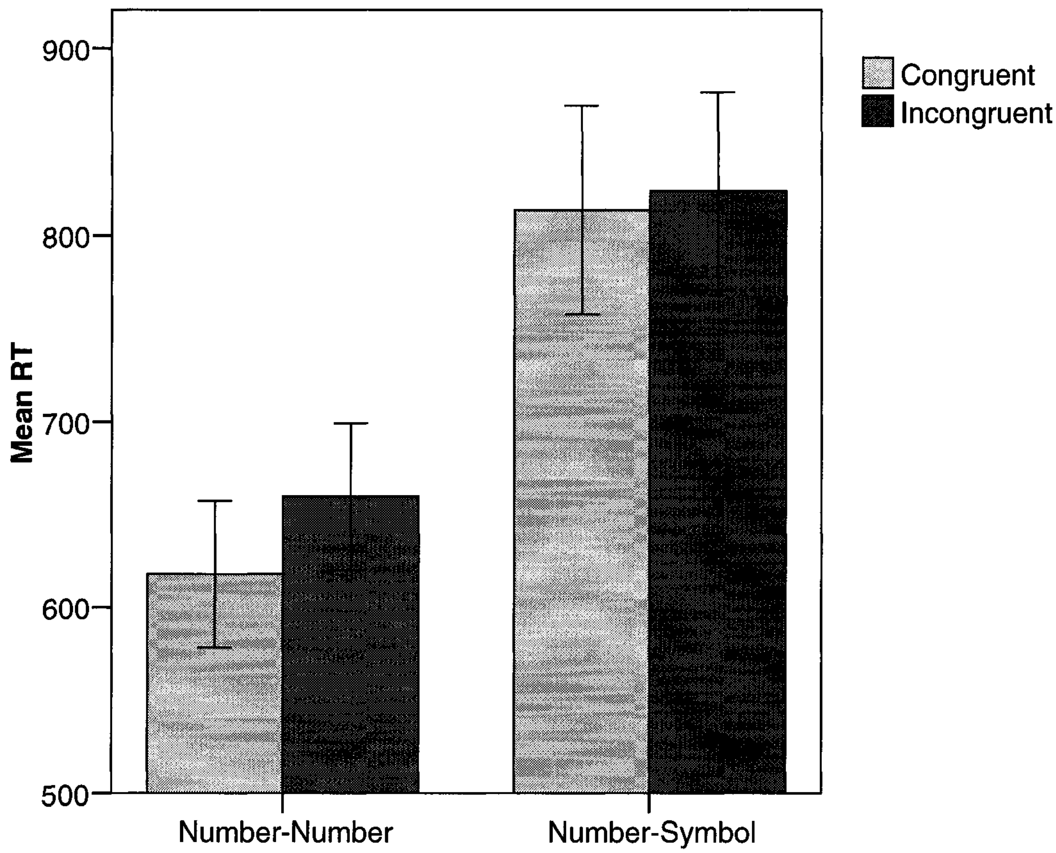


Figure 3.11. The PCE was significant in Number-Number and non-significant in Number-Symbol, regardless of Distance.

not produce any significant priming effects. In contrast, Number-Symbol produced an NCE in the Close-Close condition. As noted above, one way of understanding the results of Experiment 2 is that using a symbol as a target produces a longer SOA because the meaning of the target has to be retrieved after the target has been presented, and that the longer SOA produces the NCE. The results of this experiment indicate that that explanation is too simplistic. Experiment 2 had the same range of numbers for target and prime but the close far difference was averaged over (and not recorded by the computer).

This experiment shows that this manipulation interacts with the other factors in a complex way.

The fact that, in the Far-Far condition, both Number-Number and Number-Symbol produced a PCE (non-significant in the latter case) indicates that the two produce similar effects, except that RT is slower in the latter case. However, this is not the case for the other conditions where only the Number-Symbol condition produced priming effects (non-significant though), showing the fact that Number-Symbol was more likely to produce priming effects than Number-Number. Other interesting results are the fact that the Number-Symbol priming effect flips to a negative effect in the Close-Close condition and the asymmetry between the Close-Far and the Far-Close results. Specifically this shows that increasing the strength of stimulus operates differently in the prime and target conditions.

Experiment 4: Predictability effect

Introduction

This experiment was run right after the previous experiment, with the same participants. As noted above, in Experiment 2, it was not clear whether the different priming effects, especially the NCE in the masked condition, resulted from target type or because of predictability effect, as symbols were always followed by numbers and vice versa. Experiment 3 showed that the predictability was not a factor. However, the question of predictability was an interesting one so Experiment 4 was designed to see if predictability could have any effects on the results. For this purpose I used the same design as Experiment 3 (and masked condition in Experiment 2), but the target type was cued making it predictable. The fixation cues revealed the target's identity, because # always came in trials where the target was a numeral (henceforth, Number-Number, as in Experiment 3) while * came in trials where the target was a symbol (henceforth, Number-Symbol, as in Experiment 2 and 3). At the beginning of the experiment, the participants were told that "from now on, a new Experiment begins, similar to the previous one, only with one change, i.e., the fixation signs # and * come when the target is numeral and symbol, respectively."

Results

The RTs and percentages of error in the priming phase were averaged for sixteen possible conditions with three factors: Type (Number-Number vs. Number-Symbol), Congruency (Congruent vs. Incongruent), and Distance (Close-Close, Far-Close, Close-Far, and Far-Far). The correlation between the two scale was positive and significant (r=.908, p<.001). Therefore no trade-off between RTs and percentages of error were found. A regression curve shows this relationship (Figure 3.12).

A repeated measure ANOVA on RTs showed only a significant main effect for Type, $F(1, 9) = 136.046$, $p < .001$, showing that Number-Number trials were faster than Number-Symbol trials (Figure 3.13) as with the previous experiment. Further analysis by t-test on RTs by averaging over the Distance factor condition showed a significant positive priming for Number-Number, $t(9) = 4.063$, $p = .003$ (p=.06, adjusted for multiple comparisons with Bonferroni method),. However, since no significant interactions were found in the initial omnibus ANOVA this result has to be viewed with caution (see also Appendix B).

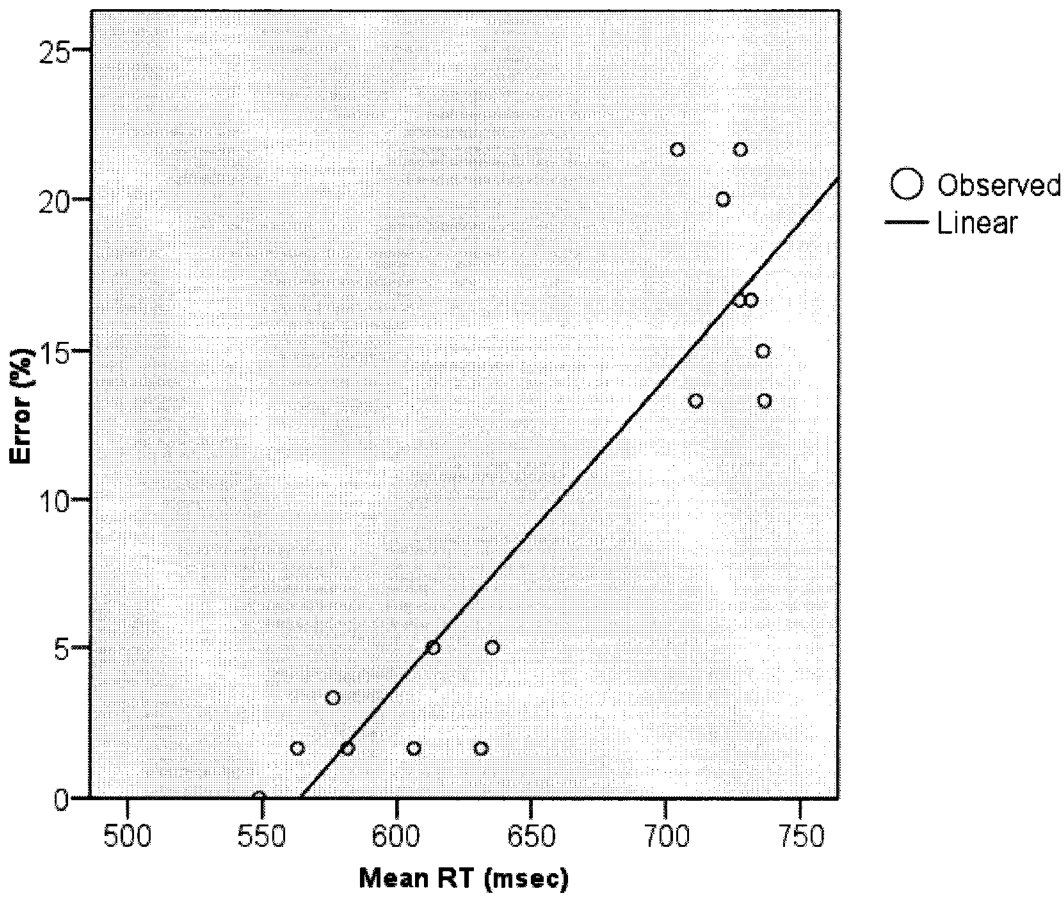


Figure 3.12. Correlation between RT and Error.

A separate ANOVA on errors was also run. The main effect of Type was significant, F(1, 9) = 6.173, *p* = .035, showing that, similar to Experiment 3, participants made fewer errors in Number-Number compared to Number-Symbol condition (see figures in Appendix C).

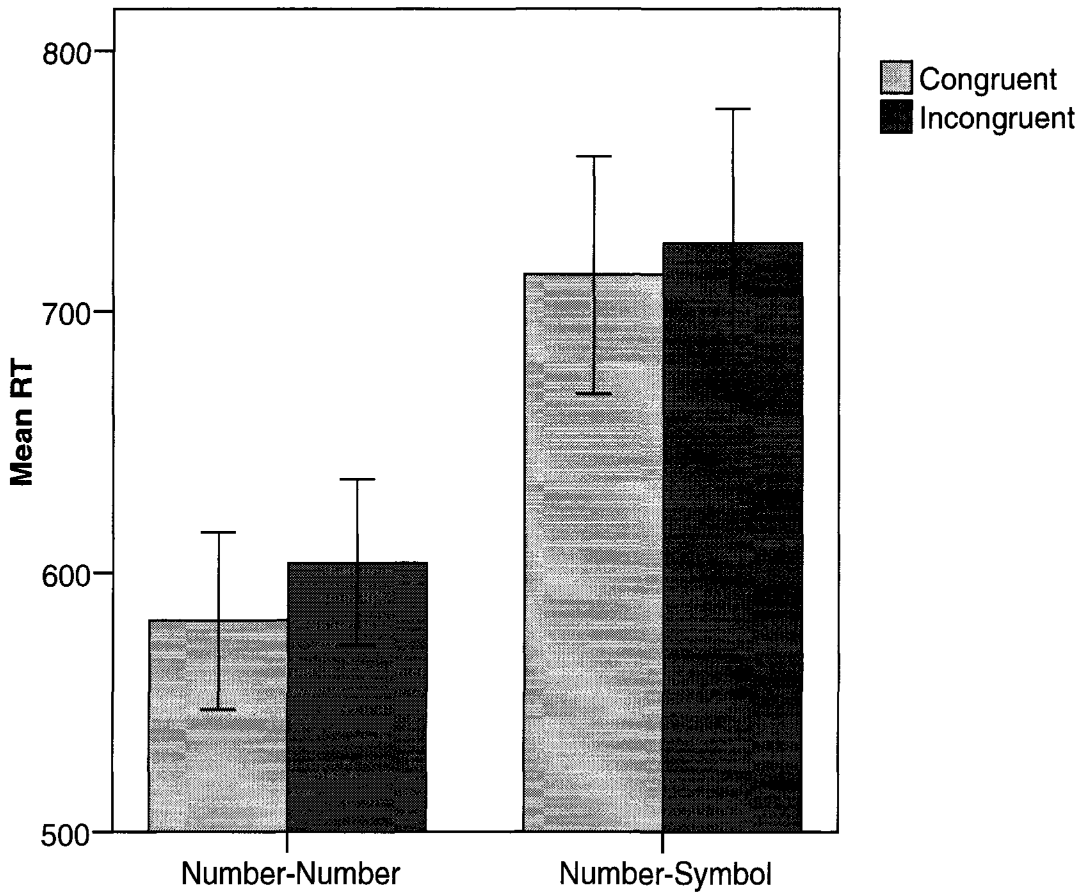


Figure 3.13. In Experiment 4, regardless of Distance, significant PCE was found for Number-Number and non-significant PCE was found for Number-Symbol.

To rule out any differences in errors in Experiment 3 and 4, a *t*-test was run on error percentages in both experiments. The result showed no significant differences, $t(9) = .509$, $p = .623$, Figure 3.14). Therefore, the differences in priming results among the two experiments were independent from the error.

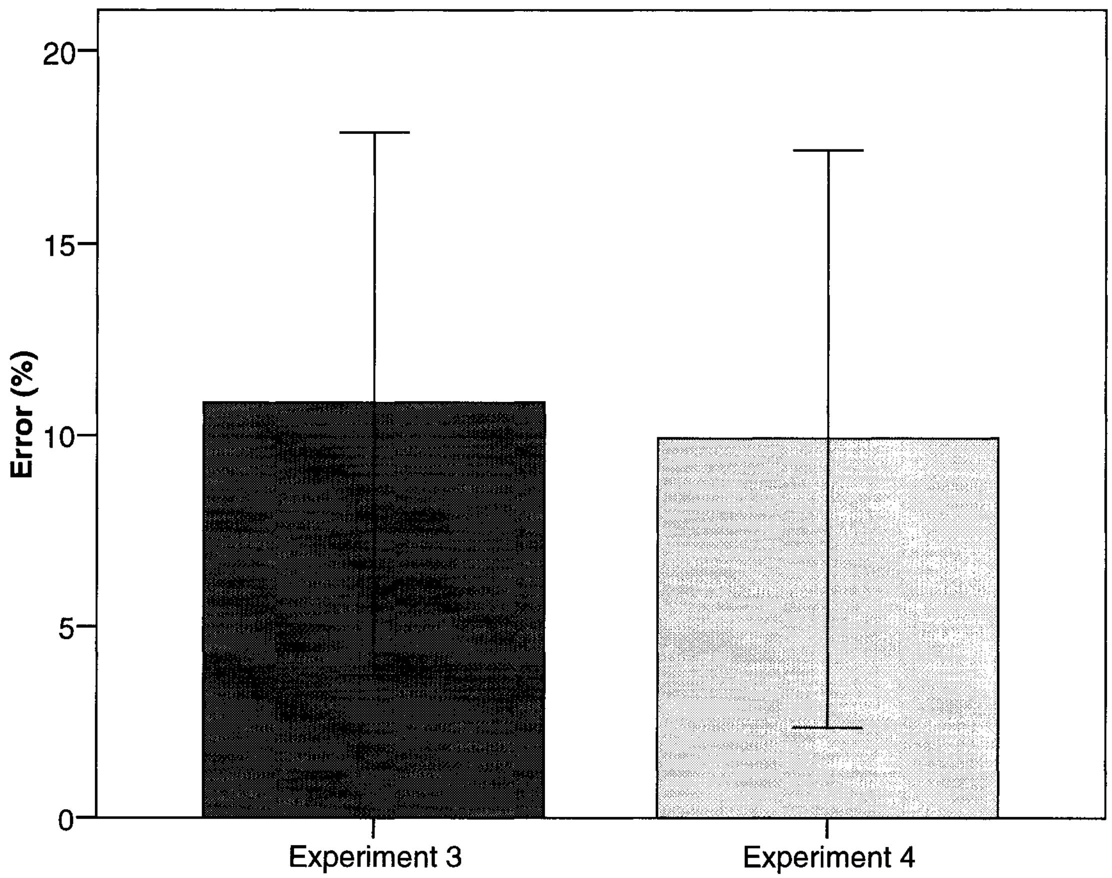


Figure 3.14. Error percentages in Experiments 3 and 4.

Discussion

Overall, providing a cue either eliminated or greatly reduced any priming effects. Since we know that the same subjects had produced multiple priming effects immediately preceding this experiment and that procedure was identical except for telling them that the fixation cue had a meaning, it would seem that it was this added bit of information that erased the effect. Since participants were faster in this version of the experiment it is likely that predictability affected the prime and target strength and washed out the priming effect.

Chapter 4: Modelling the experimental results

Review of the human data used in the modelling

The human data from the experiments showed that the NCE mainly occurred in the masked condition when symbols were used with numerals in the numerical priming task. The PCE occurred in other conditions including the line length comparison task, but it disappeared in the unmasked condition. I assume that the direction of the priming is changed either by increasing the mask-target SOA (as in previous studies) or by more direct manipulations of the strength of representation (as with the current experiments). For example, the symbols used in the current experiments seem to have lower strength compared to numerals (and lines) as they took longer time to be processed. Similarly both numerals and symbols with close, compared to far, numerical distance took longer time to be compared with the reference number *five*. The prime in the unmasked condition is not interrupted by the mask but its match of representation strength can be decreased by paying less attention to it. Based on Sternberg's (1969, see also Pinel et al., 2001) additive factors assumption, I assume that distance and stimulus type (numerals versus arbitrary symbols) contribute additively to the strength of representation. There are different combinations of these factors for prime and target (Figure 4.1 -4.3). I also assume that cueing affects the match of representation strength for prime and target. There are some other factors in the simulations of data from previous studies to be discussed later.

As shown by the experiment, an NCE is caused especially when the processing of stimuli becomes harder because of weak representation (due to low strength stimuli), for example when the effects of symbol target and close numerical distance are added together. A statistical measurement for priming effect (Incongruent – Congruent) in different conditions is the t value of a pair-wise comparison of mean RTs, as shown in Figure 4.1-4.3. The PCE and NCE have been shown by positive and negative numbers.

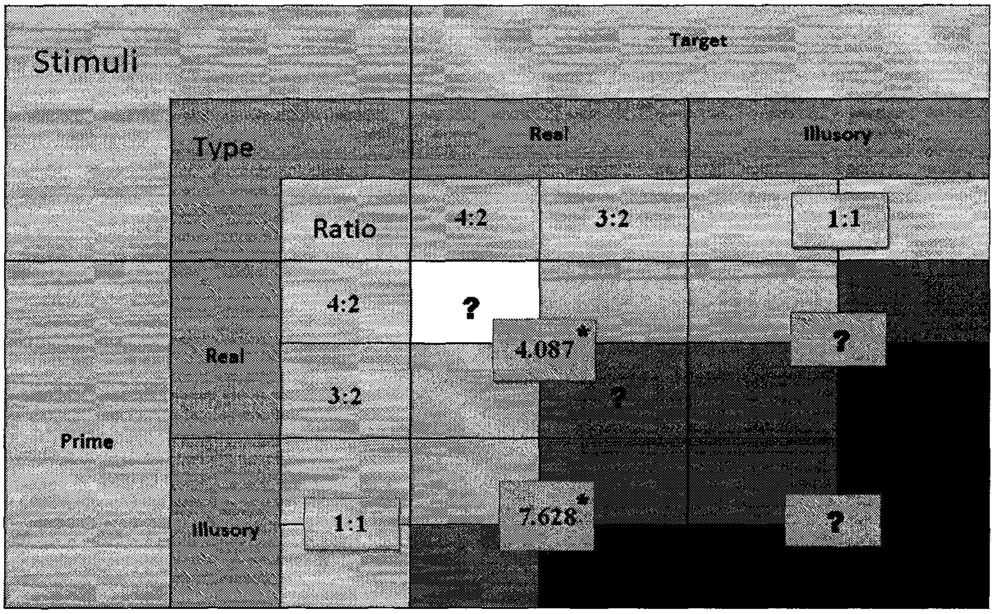


Figure 4.1. The t value of the masked priming effect in Experiment 1.

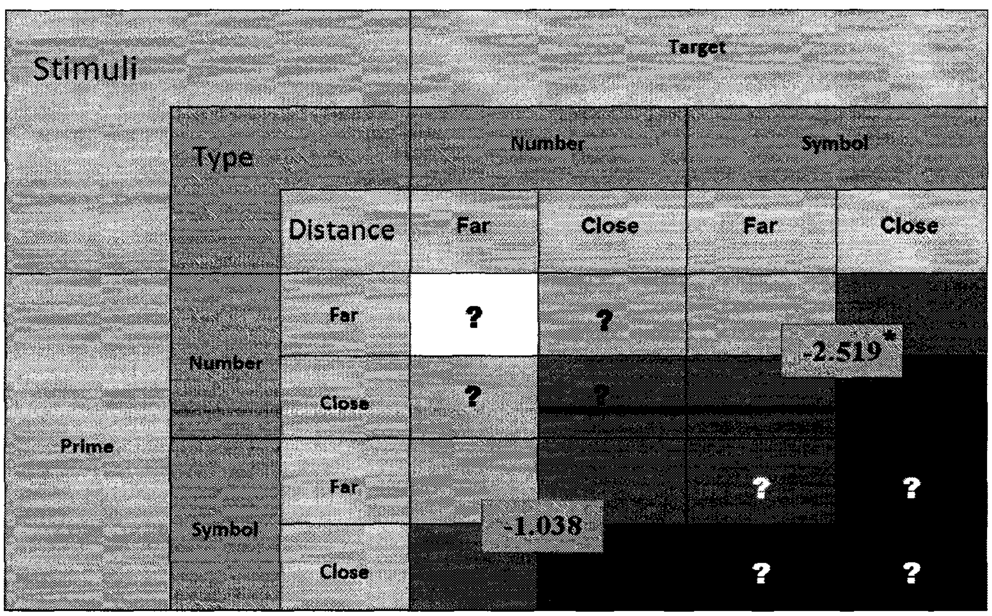


Figure 4.2. The t value of the masked priming effect in Experiment 2.

Stimuli			Target			
	Type		Number		Symbol	
		Distance	Far	Close	Far	Close
Prime	Number	Far	4.555*	.441	2.084	2.039
		Close	.980	1.545	.657	-3.692*
	Symbol	Far	?	?	?	?
		Close	?		?	?

Figure 4.3. The *t* values of the masked priming effect in Experiment 3.

Background of the current modelling approach

Attention

Attention has different forms that all affect the match of representation strength and hence priming directions. As will be discussed in the next sections, the first type of attention is assumed to be a state of arousal or alertness that has a baseline activity but its level of activation can be changed by the prime or target. The second type is executive attention, simply assumed to direct the first type by changing its activity modes. The third type is orient attention that is activated, for example, when the prime or target is cued by an external stimulus. The last two types are more top-down as they can change focus toward task-relevant information. As will be elaborated later, attention can improve both masked and unmasked tasks but its effect may become stronger in the latter case because the prime is distinguishable. Thus attention can be focused toward a relevant stimulus that carries information about the task.

Bottom-up processing and attention

Strong stimuli are processed straightforwardly and quickly, with minimal or no attention (e.g., Underwood, Templeman, Lamming, & Foulsham, 2007). In Li's (2000) model of bottom-up processing, the primary visual cortex can process the saliencies of visual stimuli among distractors. His finding is based on the perception of very simple objects (e.g. / and |) without colour, motion, and stereo, only based on fast and feed-forward processing of simple objects. Other findings show fast performances in object recognition. Tanaka and Curan (2001), using neuroscientific methods, investigated the categorization of well- and less-known objects in expert dog recognition. The experts recognized dogs in about 164 ms. Similar results have been found in face recognition (Bentin, Allison, Puce, Perez, & McCarthy, 1996) and in the performance of bird and car experts (Gauthier, Skudlarski, Gore, & Anderson, 2000). Fabre-Thorpe, Delorme, Marlot, and Thorpe (2001) showed that extensive training over a three week period did not increase this speed. Subjects in their experiment recognized a briefly flashed natural scene in 150 ms. The task was to decide as quickly as possible whether the scene contained an animal or not. These researchers interpreted the findings as support for feed-forward bottom-up processing.

However, bottom-up processes are not enough for complete recognition of objects all the time. Simons, Franconeri, and Reimer (2000) showed that sometimes distinctive and even salient objects do not capture attention. This phenomenon is known as attentional blindness in which subjects fail to notice salient objects. In an experiment on inattentional blindness (Most, Simons, Scholl, Jimenez, Clifford, & Chabris, 2001), it was shown that similarities and differences between an unexpected object and an attended object are related to the amount of allocated attention. In this experiment about 30% of subjects failed to notice a bright red cross moving across the display containing attended black and white items, even though it had unique features and was shown for 5 seconds. These findings show that intentional blindness in a dynamic event depends on similarity of the unexpected object to others in the display and the observers attentional set (Most et al., 2001).

As introduced before, there are several types of attention, but it is hard to completely separate their functions. Posner and his colleagues (for a review see Posner & Rothbart, 2007) have studied several anatomical networks that are activated during attention. They propose that three processes or networks are involved in attention: executive attention, alerting, and orienting. They have developed a test for attention, similar to Eriksen's Flanker test (e.g., Eriksen & Eriksen, 1974), called Attentional Network Test (ANT). It is very simple, with separate versions for adults, children, and monkeys. These flanker tasks measure congruent and incongruent stimuli (i.e., the target and the flanker), similar to the Stroop task and the priming paradigm. Posner and colleagues argue that the executive attention network mediates between stimulus and response conflict, and that alerting and orienting networks are involved in sensitivity to, and selection of, incoming information, respectively. As discussed before, attention modulates the representation strength and is considered in the model in this chapter.

Top-down attention and conflict-monitoring

The recruiting of control and top-down attention is not on the basis of all or none, so usually we do not know, in advance, which task requires control. It seems that often the demand on control is the result of primary engagement in the task (c.f., Kahneman, 1973). In this regard, it has been shown that participants have more difficulties at the beginning of the task in each block of the Stroop task (e.g. Henik, Bibi, Yanai, & Tzelgov, 1997). This phenomenon has been shown in other switching tasks and is known as switching cost, considered as a source of the cognitive demand (e.g. Rogers & Monsell, 1995). As a consequence of the interaction between incongruent processes or stimuli, a conflict occurs that can demand more control.

Studies on cognitive control attributed the main source of recruiting control to the conflict. The role of conflict in control has long been shown in information theory (Berlyne, 1957), later, in production system models (e.g. Norman & Shallice, 1986; Laired, Newell & Rosenbelum, 1987), and recently, in connectionist models (e.g., Mozer & Sitton, 1998; Botvinik, Nystrom, Fissell, Carter, & Cohen, 2001). In the Soar model, impasses occur in the case of conflict between incompatible productions (e.g. Newell, 1990). Recent connectionist models (e.g. Botvinik et al, 2001) have simulated the conflict based on changes in the Hopfield energy function (Hopfield, 1982), previously pointed out by other researchers (e.g., Mangan, 1993; see also commentaries on this target article in the same issue of *Consciousness and Cognition).*

Eriksen and Schultz (1979) used a modified flankers task (Eriksen & Eriksen, 1974) where, in addition to compatible and incompatible flankers, a distractor was included that was different from, but congruent with, the target. Similar to the previously mentioned notion of second order congruency (see Chapter 1), the results of their study showed slower RTs for these congruent trials than the regular congruent ones, showing an incongruency within congruency effect. This finding indicates a semantic effect that is different from response incongruency. Activation of the ACC has been thought to be related to response conflict (Botvinick, Braver, Barch, Carter, & Cohen, 1999) but recent studies show that pre-response cognitive processes are also involved in conflict monitoring (Weissman, Giesbrecht, Song, Mangun, & Woldorff, 2003; Kunde, 2003; Notebaert, Gervers, Verbruggen, & Liefooghe, 2006; Seiss and Praamstra, 2004; Praamstra & Seiss, 2005). Similarly, van Veen and Carter (2005) have shown that "semantic conflict" activates an area in Brodmann Area 9 (BA 9) more posterior and higher than the ACC area, frequently shown to be activated by "response conflict" tasks. This and other studies (e.g., Taylor, Kornblum, Minoshima, Oliver, & Koeppe, 1994) support the idea of a source of conflict that is relevant to pre-response conflict, i.e., stimuli, task, or semantic representation. As will be shown in the modelling method, conflict, especially at the pre-response level, seems to play the main role in priming direction in the current model.

It is well-known that any knowledge of the target facilitates its processing (Treisman, 1991; Wolfe, 1994). In AB (i.e., attentional blink) tasks, cuing the target facilitates the processing of the target (Nieuwenstein, Chun, van der Lubbe, & Hooge, 2005) and also the distractor (Meeter & Theeuwes, 2006). Attention can modulate processes that do not reach subjective reporting, both in blindsight patients (Kentridge, Heywood, & Weiskrantz, 1999) and normals (Schleghecken & Eimer, 2000; Summer, Tsai, Yu, & Nachev, 2006). The modulatory role of attention (Schleghecken & Eimer, 2000; Summer et al., 2006) supports its specific role in modulating "perceptual strength" not simply as a linear, additive factor. Sumner et al. employed Eimer and colleagues' paradigm and found that while prime duration and brightness can change the direction of priming, cuing the prime increases the size of both NCE and PCE, not changing one pattern to another.

The effect of attention on masked stimuli has been shown in other studies. For example, Kiefer and Brendel (2006) found that masked priming is amplified when attention is directed to the stimuli stream in the time window of masked prime presentation, even in the absence of any prime reportability. ERPs were recorded while participants were performing a primed lexical decision task. They demonstrated that masked automatic processes are susceptible to attentional modulation, as indexed by an increase in ERP component N4, as a function of this semantic effect.

Attentional modulation

Attention can increase neural firings and hence it enhances perceptual and decisional cognitive processes. Although the precise neural process of all types of attention is still under investigation, it seems that attention multiplicatively improves sensitivity of visual, spatial, and motor cognition (e.g., Desimone, & Duncan, 1995; O'Connor, Fukui, Pinsk, & Kastner, 2002; Bestmann, Oliviero, Voss, Dechent, Lopez-Dolado, Driver, & Baudewig, 2006; Bestmann, Ruff, Blakemore, Driver, & Thilo, 2007; Kim, Grabowecky, Paller, Muthu, & Suzuki, 2007).

A well-known effect of attention is thought to depend on modulatory neurochemical substances, the functions of which may provide a main biological basis for attention in the brain. As noted previously about attention, Posner and Rothbart, (2007) in their review paper, proposed neuroanatomical and neurochemical components of three attentional networks: executive, alerting, and orienting networks, supposedly mediated by neuromodulators dopamine (DA), Norepinephrine (NE), and Acetylcholine (ACh), respectively. Their proposed anatomical candidates for these networks are: ACC, ventro-lateral Pre-Frontal Cortex (vl-PFC), and basal ganglia for executive; the brain nucleus Locus Coeruleus (LC) in the dorsal pones of brainstem, right PFC, and parietal cortex for alert; and finally, superior parietal, temporal parietal junction, frontal eye fields and superior colliculus for orient attention. Among these types of attention, arousal or alertness plays an important role, by enhancing attention's underlying neural activities (see below). As mentioned by Posner and Rothbart (2007), alertness has been studied experimentally by changing the warning signal before the target, and the neuromodulatory neurotransmitter NE mediates this effect of warning signals on alertness (Marroccoo & Davidson, 1998).

As reviewed by Aston-Jones and Cohen (2005), the LC–NE system plays an important role in attentional control and goal-driven behaviours, although the precise LC mechanism is still not well-known. LC is a major source of NE, and is known to be involved in arousal, affective, and conscious states such as sleep-wake cycles (for a review see Aston-Jones & Cohen, 2005, for other work on attention system, see Corbetta & Shulman, 2002). Recent neurophysiological and modelling studies have shown the relationship between attentional bottleneck and refractory effect (as in attentional blink, see Chapter 1 and next chapter) and the refractory period of LC activities because of NE-related self-inhibitory mechanism (Aghajanian & Cedarbaum, 1977; Aston-Jones, Rajkowski, Kubiak & Alexinsky, 1994; Usher, Servan-Schreiber, Rajkowski, & Aston-Jones, 1999; Gilzenrat, Holmes, Rajkowski, Aston-Jones, & Cohen, 2002; Nieuwenhuis, Gilzenrat, et al., 2005).

Previous computational models have shown that LC-dependent neural dynamics can simulate target detection and simple decisions in monkeys and humans (Gilzenrat et al., 2002; Usher et al., 1999; Usher & Davelaar, 2002; Nieuwenhuis, Gilzenrat, et al., 2005). A detailed computational model of the LC suggests that the attentional refractory period depends on the strength and duration of the inputs coming to the LC (Brown, Moehlis, Holmes, Clayton, Rajkowski, & Aston Jones, 2004). As mentioned by Nieuwenhuis, Gilzenrat, et al. (2005), studies on masking have shown that masked stimuli are punctuate, hence having a short life. This activation pattern causes a burst phasic neuronal response (Keyress & Perret, 2002). Brown et al.'s model shows that punctuate stimuli (therefore masked prime in the current study) produce a strong refractory period; therefore, masked inputs generally produce a strong refractory period comparable to unmasked inputs. LC modulates many targets in cortical areas. As shown below, its modulatory effect has been implemented by a non-linear (i.e., sigmoid) function that becomes steepened (Servan-Shreiber, Printz, & Cohen, 1990).

It has been shown that irrelevant stimuli (i.e., distractors) activate less or no phasic activation in LC attentional responses (Clayton et al., 2004). Clayton et al. found that when the distractor was a flanker, monkeys could not discriminate between the relevant and irrelevant stimuli after months of training, a task that can be acquired by human participants in seconds, especially with brief instructions. LC has two firing modes, phasic and tonic (Aston-Jones et al., 1994; Aston-Jones & Cohen, 2005). On one hand, in the phasic mode, LC has a lower baseline activity but it has a strong phasic response to task-relevant stimuli. On the other hand, in the tonic mode, LC baseline activity is higher but it has a small burst response to stimuli. The NE released from LC is inhibitory within LC itself but can potentiate many cortical brain areas. Indeed it is also driven mainly by direct projections from ACC and OFC (Aston-Jones & Cohen, 2005). Activation of the ACC has been related to the response conflict (Botvinick et al., 1999) but recent studies (as had been noted by Botvinick et al., 2001, and discussed above) show that pre-response cognitive processes are also involved in this conflict monitoring system (Weissman et al., 2003; Kunde, 2003; Notebaert et al., 2006; Seiss & Praamstra, 2004; Praamstra & Seiss, 2005).

Another nucleus that has a role in directing attention is sub-thalamic nucleus in the basal ganglia (e.g., Lo & Wang, 2006). There may be other brain areas with similar functions but the LC is taken as an example to simulate these kinds of attentional processes, that even may act through recurrent interactions between areas (e.g., Dehaene, Sergent, & Changeux, 2003). Therefore, I simply assume that LC modes are driven by a (conflict) monitoring process. Several studies on monkeys have shown the phasic activation of LC for the correct recognition of target stimuli and no or small activations for the non-target or distractors (e.g., Aston-Jones et al., 1994; Rajkowski, Majczynski, Clayton, Aston-Jones, 2004; Clayton et al., 2004; for a review see Aston-Jones & Cohen, 2005). As mentioned before, the NE released by the LC in the brainstem has long been known for its roles in arousal (e.g., Foote, Aston-Jones, & Bloom, 1983) and in regulating higher order cognition (Aston-Jones et al., 1994; Usher et al., 1999). Its increased activities enhance decision-making cognition; involved in more exploitatory or reward processing; its increased baseline activities increase responses to distractors involved in more exploratory or reward-seeking behaviours (Servan-Schreiber et al., 1990; Usher et al., 1999; for a review, see Aston-Jones & Cohen, 2005). As mentioned above, it seems that LC is influenced not only by external inputs but also by cortical areas especially the ACC through direct projections to LC (see, Aston-Jones & Cohen, 2005). Due to the involvement of DA in goal-driven behaviours (for a review see O'Reilly, 2006), I assume that it mediates these projections to LC.

Description of the model

Based on these assumptions and previous models, this model aims to simulate the behavioural data in the current experiments and previous relevant studies to illustrate the underlying mechanism in masked and unmasked priming. The model is inspired by recent progress in biologically plausible connectionist modelling. The processing elements in the current connectionist model are a few neurons with self-excitation, lateral inhibition, and accumulative activation that have a strong computational power in simulating most of the basic cognitive processes (e.g., Usher & McClelland, 2001; Gilzenrat et al., 2002). It has been demonstrated that these types of reduced models can resemble the neural computation of a large group of neurons (e.g., Wong & Wang, 2006).

The model is a multi-layer dynamic neural model that consists of a feed-forward component for perceptuo-motor processing from the Input Layer (IL) to an intermediate layer, called Representation Layer (RL), and from there to the Motor Layer (ML). The ML simulates the representation of motor response, not final manual movement.

I assume that the type (lines, numerals, and symbols) and distance (close and far) factors are related to the strength of representation, and can be simulated by connection weights. The strength of representation is implemented simply by changing the weights between IL and RL while the weights between RL and ML remain fixed. Decreasing the weights is intended to make the representations weaker or less direct (i.e., harder) and increasing the weights is intended to make the representations stronger or more direct (i.e., easier).

Another assumption is that the cognitive processing, including the response, is modulated by attention. Three attentional resources are included in the model, similar to the three networks proposed by Posner and colleagues (e.g., Posner & Rothbart, 2007), as mentioned above: alert attention, orient attention, and executive attention. For the sake of simplicity, here in the model (see Figure 4.6) it is assumed that: the Alert Attention (henceforth, AA) layer has equal modulatory effects (e.g., neuromodulatory NE) on all processes including stimulus representation and response (and joint activations of prime and target used in conflict monitoring, see below). Orient Attention (henceforth, OA) directly affects stimulus representation (e.g., by neuromodulatory ACh); and executive attention is only modelled through its effects on AA (presumably mediated via neuromodulatory DA signals that affect the cortical direct projections to LC) using a

Cognitive Layer (henceforth, CL) for conflict monitoring (or "object updating"). The CL and ML are affected by both prime and target. The ML is not shown in Figure 4.6 for the sake of simplicity, but its architecture is identical to CL except it sends no outputs to other layers.

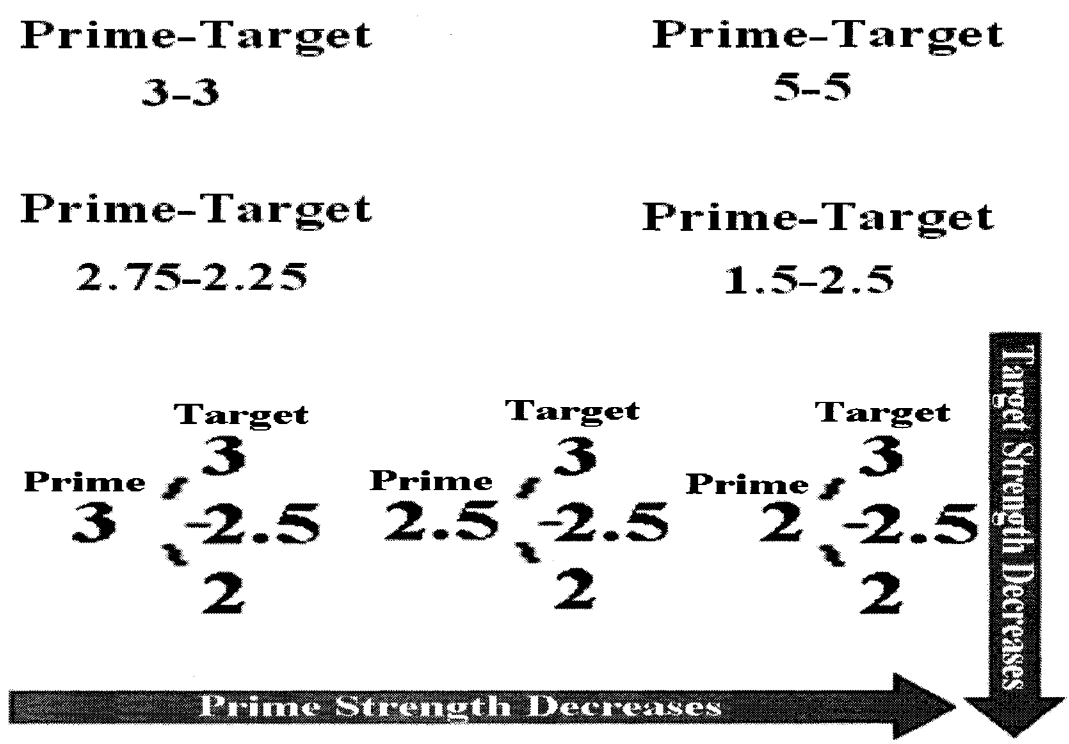


Figure 4.4. Top: Prime and target strength in Simulation 1. Middle left: Prime and target strength in Simulation 2. Middle right: Prime and target strength in simulation 10a (simulating primes with low brightness). Bottom: Prime and target strength with three levels of strength, used in Simulation 3 and all other simulations.

As pointed out previously, in the "object updating" hypothesis of the masked priming (Lleras & Enns, 2004), replacing an object that is currently represented actively by a newer object plays an important role. Therefore "object updating" and conflict monitoring appear to be related concepts. However, conflict monitoring places more emphasis on the relation between stimuli, i.e., being congruent or incongruent. It is also worth noting that "object updating" focuses on the mask-prime relationship, but in the current model it is mainly assumed to represent the prime-target relationship, which is also affected by the mask. The prime and target are represented by having two opponent units each, to implement "dialectic" or opposite "natural pairing" (Verleger et al., forthcoming paper cited in Jaśkowski & Ślósarek, 2006).

The OA component is employed for simulating experiments where attention is driven by cues (e.g., spatial, semantic, and contextual). For the sake of simplicity, OA is simulated as an extra input unit, implemented like other input units but with a modulatory (not direct excitatory or inhibitory) effect (it may also be simulated by holding in a working memory layer). As will be described later, the OA and AA are implemented by a reduced dynamic model of spiking neurons. OA only modulates RL while AA modulates RL, CL, and ML but is triggered by RL and is affected by CL. OA was employed in two simulations on cued attention but AA was employed in all simulations.

In sum, when the prime is presented and *calls* for attentional resources in AA, if the target comes early enough (i.e., when prime activation is still high as in stimuli with strong representations) they can share the resource that has limited capacity. In this case a PCE occurs. Otherwise, the second phase called by the target faces the refractory period of the AA. The prime activates AA, but, consequently, leads to a stronger attentional refractory period in AA for a target that comes late (either because it is presented late or has low strength). This effect causes an NCE because in the incongruent trials the refractory period is decreased by conflict (through CL). Activating OA by cuing (as employed in some simulations) can also compensate for the refractory period of AA, but it decreases NCE because it affects the target in both congruent and incongruent trials. The cue also activates AA before the prime, therefore causing a refractory period if it comes long before the prime, hence, weakens the prime representation. The whole process is supposed to change the priming direction and is affected by many factors (for more details see the simulations and Appendix D, Part 1).

Stimuli			Target			
	Type		Numeral		Symbol	
		Distance	Far	Close	Far	Close
Prime	Numeral	Far	3-3	3-2.5	3-2.5	3-2
		Close	2.5-3	2.5-2.5	2.5-2.5	2.5-2
	Symbol	Far	2.5-3	2.5-2.5	2.5-2.5	2.5-2
		Close	2-3	2-2.5	2-2.5	2-2

Figure 4.5. Encoding the representation strength using connection weights, used in Simulation 3. For example, Far Number=weight 3, Far Symbol=weight 2.5, Close Number=weight 2.5, and Close Symbol=weight 2.

The weights between IL and RL layers for both prime and target are assigned according to Figure 4.4 (see also Figure 4.5, and Table 4.1). To get the modelling results with minimum variability in the parameters, the RL to CL and RL to ML weights are fixed in all simulations. For most simulations, three levels of connection strength are used for prime and target: high (3), medium (2.5), and low (2), as shown in Figure 4.5. Other weights used in the simulations are 1.5, 2.25, 2.75, and 5 (see Figure 4.4). These weights are arbitrary and, depending on other parameters in the model, could be different. They could be set using learning algorithms (see Appendix F, Part 2) but they are set manually as the learning process is not considered here. This parameter is fixed at those levels in most simulations to focus on the main effects, although a more precise weight adjustment can provide a better result.

Each condition in a simulation consists of 20,000 trials (200 independent blocks of 100 trials each, with congruent and incongruent trials counterbalanced randomly within each block). Each trial takes 1100 cycles. Each block starts with 500 cycles without changes in IL to let the units in other layers reach a steady state of activation. Similarly the Inter-Trial Interval (ITI) for each trial is 500 cycles, which let the activation of units return to baseline after the responses. The prime is presented by clamping one of the two units in the IL to 1, intended as smaller or larger than *five,* or left or right in the case of lines or arrows. The mask units in IL are set to 1 at the time of mask presentation and otherwise are set to 0. Therefore, the recognition of the stimuli is implemented with a localized representation (see Appendix F, Parts 3-4, for some examples of distributed representation), only encoded as a binary code (i.e., the left unit is turned on when the stimulus is less than five in the case of numerals and symbols, or points left in the case of arrows, or longer part of the line appears at the left in the case of line; otherwise the right unit is turned on). Accordingly, as will be described below, in the congruent condition, the two corresponding units (e.g., the left unit of the prime and target in IL) is set to 1 or

0 at the presentation time in each trial, while in the incongruent condition one of the two relevant units of the prime or target is set to 1 and the other to 0 (or to real normalized values, e.g., .9 and .1, in some simulations for specific reasons such as stimulus degradation or mask density).

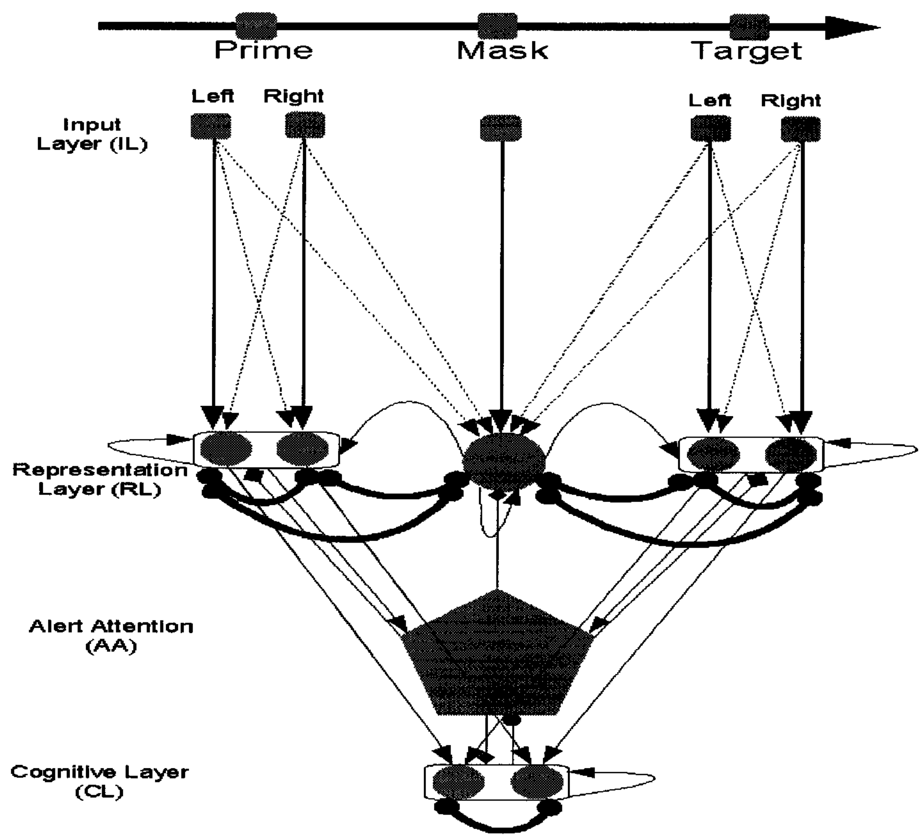


Figure 4.6. Architecture of the model showing hypothetical networks and connections with relevant neuromodulators/neurotransmitters. *Unit types:* ■ IL ● RL, CL, and ML (not shown here) ⬟ AA. *Attention types:* -♦ Alert (NE) Orient (ACh) (not shown here) -● Executive (DA). *Activation types:* ∩ Self-excitation and recurrent excitation (receptors and slow channels *N*-methyl-D-aspartate, NMDA) ●-● Lateral inhibition (γ-aminobutyric acid, GABA) -▶ Feed-forward activation (α-amino-3-hydroxy-5-methyl-4-isoxazolepropionic acid, AMPA).

The units in each layer make connection, via excitatory weights, to their corresponding units in other layers. The activations of these units are calculated by a sigmoid (logistic) function of the incoming information (and a small amount of random noise). This function creates non-linearity (and bounds activations to prevent negative values, if any, that happen computationally but not biologically, c.f., Cohen & Huston, 1994). The RL sends excitatory activities to ML and CL continuously but activates AA only if a unit of the prime or target reaches a designated threshold, .62. Similarly when one of the two units in the ML reaches the same threshold it triggers a manual response (i.e., initiating a hand movement). When AA is activated and its activation reaches a threshold, it starts modulating information processing in RL, CL, and ML by making the activation function of their units steeper (Servan-Shreiber et al., 1990; see below).

Modelling details

As shown in Figure 4.6, the IL represents the prime, the mask, and the target, mapped to RL, i.e., through excitatory connections. The OA unit, employed in two simulations, like AA, will modulate the units in RL, if the trial contains a cue relevant to the prime or target. When the cue is presented it activates AA and OA. Similar to previous connectionist models (e.g., Cohen, Dunbar, & McClelland, 1990; Cohen & Huston, 1994; Nieuwenhuis, Gilzenrat, et al., 2005; Sohrabi, 2005; Sohrabi, West, & Brook, 2006), for the sake of simplicity, prime and target, as well as an identical mask for each (shown as a single unit in Figure 4.6 for the sake of simplicity) and cue, if any, were implemented in two separate paths. All units in RL have a self-excitation connection, intended as mutual excitation among a group of neurons. Connections between mutual units (for prime and target) from IL to RL have small cross-talks (see Table 4.1), indicating feature overlaps/similarities among stimuli. The units also have lateral inhibition with neighboring units within the same layer (see below).

The mask is activated after the prime and before the target for a specific time. It has lateral inhibition with prime and target units that causes interruption of the prime, as it comes after it and before the target. The lateral inhibition has been proposed as a good way to simulate masking (Wiesstein, 1968; Rolls & Tovee, 1994). In addition to lateral inhibition, the model simulates the similarity of the mask to the prime and target through a recurrent excitation from mask to the prime and target. It plays a role by this recurrent excitation and can affect ML and AA (and CL), indirectly, through its effect on prime and target. The prime and target units, but not the mask, have feed-forward projections into the ML, CL, and AA layers. Therefore, the mask acquires meaning through its relationship with the prime and target. Because it comes right after the prime, it can activate the prime if they are similar. So, it acts partially like the prime and increases the attentional responses to it, making it to stay longer. As mentioned in Chapter 1, according to Lleras and Enns (2004), distinct physical events of prime and mask can be interpreted as an evolving instantiation of a single object. On the other hand, if its similarity with prime and target decreases, its inhibitory effect dominates and interrupts the prime, causing it to decay faster.

All units receive additive Gaussian noise (zero mean and variance σ), intended as general, irrelevant incoming activities. The activations in the model are represented using units with real valued activity levels. The units excite and inhibit each other through weighted connections. Information propagates through the network when the IL is clamped with input patterns, leading to a final response. As will be described below, the states of units in RL, ML, and CL are adopted in a method similar to a noisy, leaky, integrator algorithm or Leaky Competing Accumulator (LCA) model (Usher & McClelland, 2001, see also Usher et al., 1999; Brown & Holmes, 2001; Usher & Davelaar, 2002; Gilzenrat et al., 2002). These types of models are noisy versions of previous connectionist models (Anderson, Silverstein, Ritz, & Jones, 1977; McClelland, 1979; McClelland & Rumelhart, 1981).

In a typical masked trial or epoch, one of the prime units in the IL is turned on and the network is left active for 43 cycles, then the mask units in IL are turned on for 71 cycles, followed by turning on the target input in IL for 200 cycles (similar to a trial in Experiments 1-4, except no forward mask is presented). The prime and target units in the IL are used to represent the stimuli features (direction or magnitude). However, as mentioned before, the recognition of the stimuli is not implemented in detail, but only is encoded as a binary code. For example, 1 is used for the left unit in the case of arrows, if it points left, or in the case of line, if the longer part of the line is at the left side, or finally in the case of numerical stimuli, if the stimulus is less than *five*, and 0 is used for the opposite unit. In the congruent condition, the RL units of the prime and target at the same side (left or right randomly) are turned on or off in each trial at the time of stimulus presentation. In contrast, in the incongruent condition the two units at the opposite sides are turned on and the other two are left off, with random selection of the two possible cases.

The RL is governed by a modified version of LCA model (Usher & McClelland, 2001; see also Usher et al., 1999, Usher & Davelaar, 2002; Gilzenrat et al., 2002), which is calculated with discrete integrational time steps using the dynamic equation:

$$X(t+1) = \lambda_x X(t) + (W^0 - \lambda_x)\, f\, [\alpha(W_{X_iX_i} X_i(t)) + W_{X_iI_i} I_i(t) - \beta(W_{X_iX_j} X_j(t)) - \theta_{X_i} + \xi_{X_i}] \quad (1)$$

Likewise, ML and CL are modelled in a similar way with their inputs coming from RL:

$$Y(t+1) = \lambda_y Y(t) + (W^0 - \lambda_y)\, f\, [\alpha(W_{Y_iY_i} Y_i(t)) + W_{Y_iX_i} X_i(t)) - \beta(W_{Y_iY_j} Y_j(t)) - \theta_{Y_i} + \xi_{Y_i}] \quad (2)$$

In equations (1) and (2), X and Y denote the activity of units through time t, W is the weight of the connections between units, I is the input, and the subscripts i and j are indexes of the units. Here W^0 is the synaptic projection related to the leaky integrative process (fixed to 1, as in Usher & Davelaar, 2002) and the other three weight parameters in the brackets correspond to recurrent self-excitation, feed-forward excitation, and lateral inhibition, respectively. However, for the sake of simplicity in equation 1 the recurrent excitation from mask to the prime and target, $W_{X_iX_j} X_j(t)$, and the cross-talk in prime and target to reciprocal units and mask, $W_{X_iI_j} I_j(t)$, are not present. The term θ is the bias, the term ξ is noise, the terms α and β represent the excitatory and inhibitory coefficients, and f is a sigmoid function (see equation 3 and Figure 4.7). The term λ represents neural decay (Amit & Tsodyks, 1991) which is related to the discrete integrational time steps in the underlying equation, characterizing neuronal gating with a fast rise followed by a slow decay (Wang, 1999).

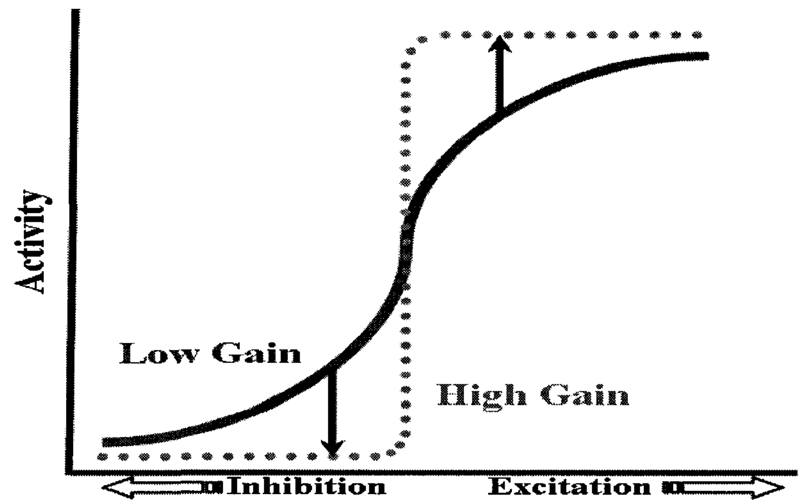


Figure 4.7. Effect of gain modulation on nonlinear activation function (adapted from Servan-Shreiber et al., 1990, see also Aston-Jones & Cohen, 2005).

The AA modulates other layers by changing their activation from sigmoid toward binary responses (Servan-Shreiber et al., 1990; Cohen et al., 1990; Cohen & Huston, 1994; Usher et al., 1999; Gilzenrat et al., 2002; Usher & Davelaar, 2002; Nieuwenhuis, Gilzenrat, et al., 2005; McClure, Gilzenrat, & Cohen, 2005). The activation function, *f,* transfers the net input, X, of a unit, and modulatory gain, *g,* to its activity state, implementing the firing rate of a neuron (or the mean firing rate of a group of neurons):

$$f(X)=1/(1+exp\ (-Xg)) \qquad (3)$$

A conflict-monitoring measurement was employed to take the activations of the units in the CL layer to adjust AA phasic and tonic response mode. The CL itself may be equivalent to a "convergence zone" (Damasio, 1990; see also Appendix F, Part 8) that combines different information (here from the prime and target). It may partially involve the temporal lobe, but the conflict is supposed to mainly be involved in ACC and PFC (e.g., Botvinick et al., 1999; Dehaene, Artiges, et al., 2003). The activation of the CL units was used to measure Hopfield energy function (Hopfield, 1982) between units, as used by Botvinick et al. (2001). As they mentioned, one way to measure conflict is to calculate it as the co-activation of incompatible representations. So, conflict can be defined as the concurrent activation of the competing units, as the joint effect of both prime and target in CL.

As described by Botvinick et al. (2001), Berlyne (1957) has provided three methods for measuring conflict: (a) it should increase with the absolute activation of competing activations; (b) it should increase with the number of competing activations; and (c) it should be maximal by equal activations. He has proposed a measure based on the information-theoretic model of entropy (i.e., multiplying entropy by the average activation in competing activations). Botvinick et al. propose that this approach has a technical disadvantage because it requires activation levels to be translated into probability values. Alternatively, it is possible to employ Hopfield energy function which has also been employed previously by Botvinick et al. (2001). In Hopfield recurrent neural network, units can be represented as 1 and 0, or 1 and -1 while they are connected by -1 (as lateral inhibition). When the two units are inactive, or only one of the units becomes active, energy does not increase, indicating no conflict. On the other hand, if both units are active, energy increases. Hopfield energy can be calculated as

$$E = -.5\ X^t W X$$

$$= -.5\ [X_1\ X_2] \begin{bmatrix} 0 & -1 \\ -1 & 0 \end{bmatrix} \begin{bmatrix} X_1 \\ X_2 \end{bmatrix},$$

that even can be made simpler, to show that it is the product of the values (or absolute values, if negative values are involved) of the two units (not employed in the model),

$$= -.5\ (-2\ X_1\ X_2)$$

$$= X_1\ X_2 \tag{4}$$

where E denotes energy, X denotes the activity of a unit, W is the weight of the connection between units, and the subscripts $_1$ and $_2$ are indexes of the two units. The energy can also be normalized (equation 5, not employed in the model) for the trial while the activations change by learning (McClure et al., 2005):

$$E = \frac{X_1 . X_2}{|X_1|\,|X_2|} \tag{5}$$

As noted above, CL combines prime and target activations and measures conflict between the units. When one CL unit is active and the other is inactive conflict is low. However, when both units are active concurrently, the level of conflict (product of their activations) is high. According to Botvinick et al., importantly the level of conflict in the model is not a parameter to be set by the experimenter; rather conflict is an inherent property of the model that depends on the relative activation levels of the units. As can be understood from the last part of the formula (equation 4), the energy (E) and the Berlyne's (1957) method for measuring conflict provide the same result. Here, instead of directly and dynamically measuring activations in the CL units for measuring conflict, those activations are converted to 1 if they are equal to or greater than .5, and to 0 otherwise (i.e., using a threshold function). Also, E>.5 is considered as conflict, otherwise as no conflict. The CL is similar to the ML but has faster integration and decay and lower noise (see Table 4.1 for the parameters used in the model). While the ML produces the output response and sends no input to other layers, the CL role is to affect AA layer by changing its response mode.

The AA and OA have a similar dynamic behaviour. The AA modulates all other layers but has limited activation because of its refractory period. The OA only modulates RL and is employed in a few simulations to show the role of cuing. While AA is supposed to be a model of LC, which involves inhibitory NE, OA is assumed to be a model of cortical areas and its function is supposedly mediated by phasic modulatory ACh. Therefore, OA is exactly like AA but it is faster (because of no NE-related self-inhibition). The AA has a phasic and a tonic mode controlled by the conflict in CL (assumed to be mediated by DA). The RL represents prime, mask, and target. When the activation of a prime or target unit in RL reaches the designated threshold, the AA is activated with a phasic or tonic mode, depending on the absence or presence of conflict, respectively.

Here the AA is modelled using a reduced or abstracted version of LC neurons in a Willson-Cowan type of system (e.g., Wilson & Cowan, 1972) adopted recently (Usher & Davelaar, 2002, see also Gilzenrat et al., 2002 for a similar model; for detailed implementation see Usher et al., 1999 and also Brown et al., 2004).

$$X(t + 1) = \lambda_x X(t)$$

$$+ (W^0 - \lambda_x)\, f\, [c\, (a_x X(t) - bY(t) + I_x(t) - \theta_x)],$$

$$Y(t+1) = \lambda_y Y(t)$$

$$+ (W^0 - \lambda_y)\, f\, [c\, (a_y X(t) - \theta_y)],$$

$$G(t+1) = \lambda_g\, G(t)$$

$$+ (W^0 - \lambda_g)\, X(t) \qquad (6)$$

where f is again a sigmoid function (as in equation 3), X is the fast variable representing AA activity and Y is a slow auxiliary variable, together simulating excitatory/inhibitory neuron groups in the LC (Usher & Davelaar, 2002). The X and Y variables have decay parameters λ_x and λ_y, excitatory/inhibitory coefficients, a_x and a_y, as well as thresholds θ_x and θ_y, respectively. The G variable is the output of the AA, which is based on X. The g (used in equation 3) is computed from G: g = G * K. The AA modulates other layers when g crosses a threshold, 1. Its activity modes can be phasic or tonic depending on the conflict state, *low* or *high*, respectively. In all conditions the CL can change the AA modes according to the conflict between prime and target (i.e., using within-trial conflict). The phasic and tonic modes of AA responses are implemented using high or low c value (*3* or *1*), respectively (see equation 6). The c value is 3 at the beginning of each trial (for the prime) but if the conflict state changes, the c is set to 1 (for the target). However, to simulate the between-trial or contextual conflict (only at the beginning of an unmasked trial), the changes in AA modes are simulated by setting c to a value between 1.5 and 3 (i.e., 1.5, 1.7, 2, and 3), manually. OA is like AA but it is simply modeled by setting its $G(t+1)$ to $X(t)$. The AA phasic response can be activated by getting input from the RL (when a unit reaches a designated threshold, .62). AA can also be activated by the cue, as employed in one simulation.

Simulations

The number of computer simulation cycles from the target onset until one of the ML units reached a designated threshold was considered as RT. I report these cycles as RT (ms). In addition to this, in most simulations an arbitrary constant is added to make the results similar to human data as much as possible. The constant can be assumed as early stimulus processing (about 200 ms, e.g., Dehaene, 1996; Schwarz & Heinze, 1998) and manual response (about 150 ms, e.g., Libet et al., 1983), as well as the differences in processing time between different types of stimuli (e.g., numerals, symbols, and arrows).

Table 4.1. *Parameters in the model, fixed for all simulations, unless otherwise mentioned.*

WX_iI_i (IL to RL) [P & T] & WY_iX_i (RL to ML) [P & T]	1.5-5 & 1.5
WX_iI_i (IL to RL) [M] & WY_iX_i (RL to CL) [P & T]	1.5 & 1
WX_iX_i (RL) [P & T], WX_iX_i (RL) [M], WY_iY_i (CL), & WY_iY_i (ML)	1.5, 1.25, 1, & .9
WX_iX_j (RL) & WY_iY_j (ML & CL)	1 & 1
WX_iX_j (RL) [M to P & T] & WX_iI_j (IL to RL)	.75$\pm$.1 & .33
K (AA) & K (OA)	4.52 & 5
α & β (RL, CL, & ML) [M, P, T]	1 & 1
θ_x, θ_y (AA), θ_x (RL), θ_y (CL), & θ_y (ML)	1.25, 1.5, .5, .85, & 2
b,c, a_x & a_y (AA)	4, 1-3, 2, & 3
λ_x, λ_g, & λ_y (AA)	.92, .98, & .996
λ (CL), λ (ML), & λ (RL)	.75, .925, & .95
σ (CL), σ (RL) [P & T], σ (ML), & σ (RL) [M]	.025, .2, .25, & 1.25

IL=Input Layer; RL=Representation Layer; CL= Cognitive Layer; ML=Motor Layer; AA=Alert Attention; OA=Orient Attention; P=Prime; T=Target; M=Mask.

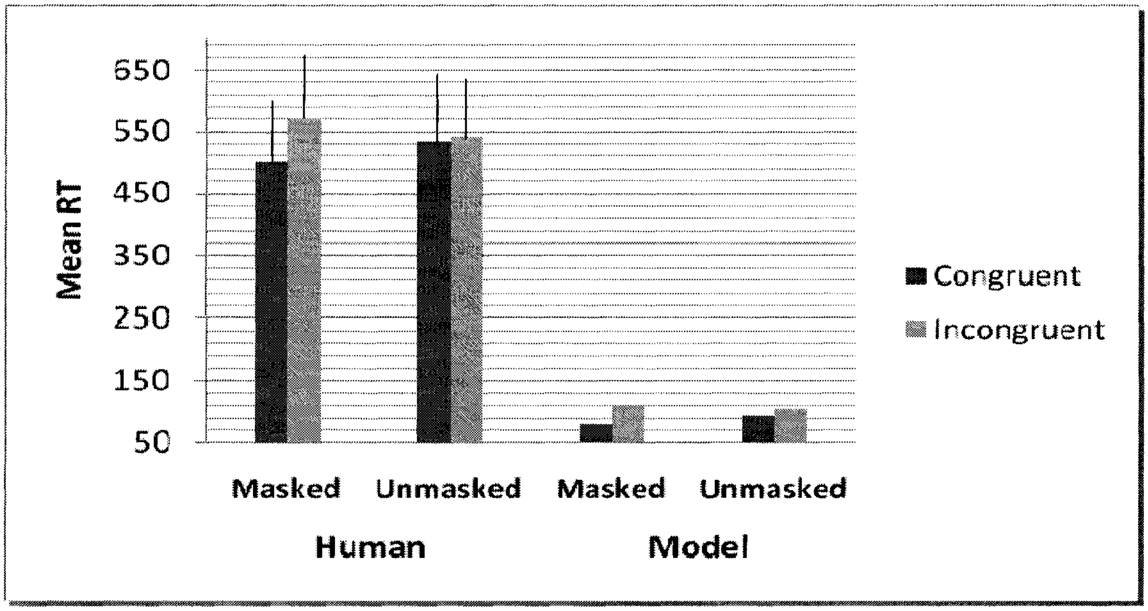
In all simulations, the RTs were averaged across 20,000 epochs (10,000 for congruent and 10,000 for incongruent trials, randomly counterbalanced) for each condition. The model showed different types of errors including wrong responses (late errors), premature incorrect responses called early errors, premature correct responses called pre-hits (reaching the threshold before the target presentation), and missed trials (failing to cross the threshold by the trial deadline). However, to get reliable results with a relatively small number of epochs in each simulation and to focus on the main idea (i.e., RT priming effects that is most consistent in different studies), the model was set up to not produce these types of error responses frequently, usually about 1% (see the section on errors and the discussion). For all simulations, parameters in Table 1 were used, and were fixed in all simulations unless otherwise mentioned.

Simulation of the main results in the current experiments

Simulation 1: Simulation of human data in Experiment 1

This simulation was designed to simulate data from Experiment 1. It focused on the interaction between masking and congruency. Although illusory line length is different from real line length, here both were treated as the same, because of similar behavioural results. The masking and congruency interaction in Experiment 1 was a PCE for masked condition and a small non-significant PCE for unmasked condition. Because there is no mask in the unmasked condition to interrupt the prime, I assume that the prime draws less attention because of the contextual information from the prime visibility (i.e., the prime is ignored). This was simulated by changing the mode of AA response to the prime in the unmasked condition. With high phasic AA attention, in the unmasked condition the prime's activation becomes very high (and can cause many pre-hit and early wrong responses in the model). But, as mentioned before, there is computational and electrophysiological explanations why masked stimuli can cause more phasic attention compared to unmasked (except if the prime is relevant, see the next and the last simulations). Moreover, error RTs in the unmasked conditions in Experiment 1 (and Experiment 2) were slower than in the masked condition (Appendix C). The slower error RTs in the unmasked could be caused by less phasic attention to the prime, simulated by making changes in the mode of the AA response to the prime manually. The decrease in the AA response decreases the match of the representation strength and, hence, decreases the priming effect.

The changes in the AA mode might happen in a more dynamic way and be based on learning and contextual information (see for example, McClure et al., 2005). However, in the model, to simulate the unmasked condition, the AA mode for the prime was manually put in a less phasic response mode ($c=1.7$, instead of $c=3$ as in the masked condition) at the beginning of the trial and no masks were presented (after the prime, c was set according to within-trial conflict, as in all other simulations). The OA attention may also play a role in making the difference between masked and unmasked condition, but only the AA was employed, because both have similar functions. The weights (connections from IL to RL) for prime and target were set to 3 and the prime-target SOA was 114 ms (i.e., mask-target SOA 71), as in Experiment 1. The result of the simulation is depicted in Figure 4.8a that shows a PCE in the masked condition and no priming in the unmasked condition, similar to human data in Experiment 1. However, a better fit was found (see Figure 4.8b) by increasing the prime and target strength from 3 to 5, (and changing the *c* from 1.7 to 1.5), knowing that the representation of perceptual stimuli is stronger than that of symbolic stimuli (see next simulations).



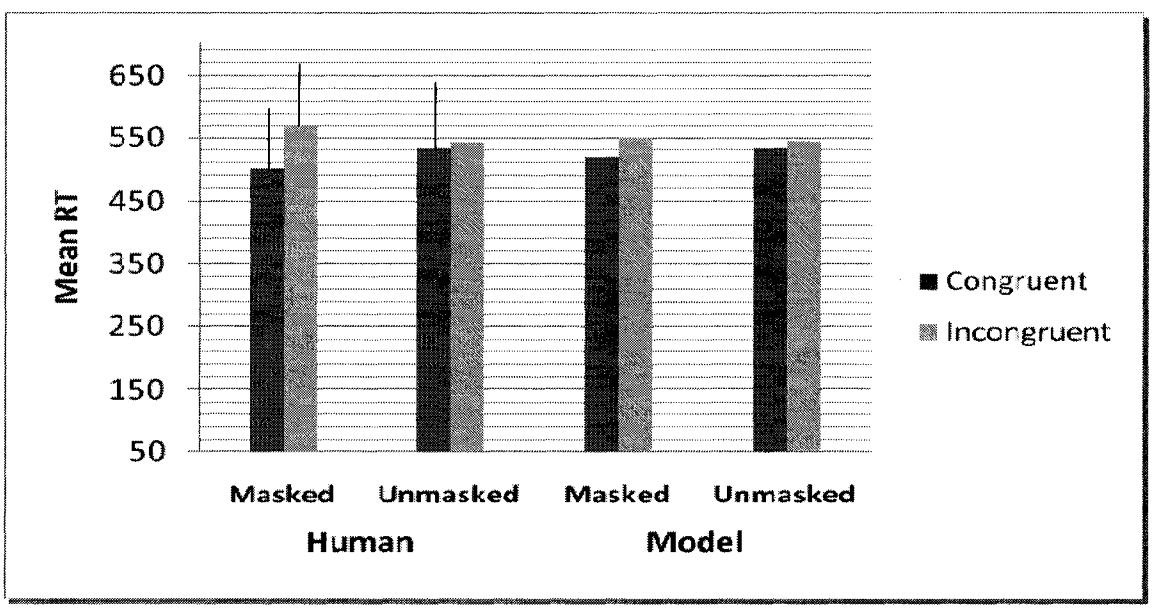


Figure 4.8a. Top: Simulation result of the masked and unmasked conditions in Experiment 1. Bottom: The same result by adding 440 cycles to the simulation data.

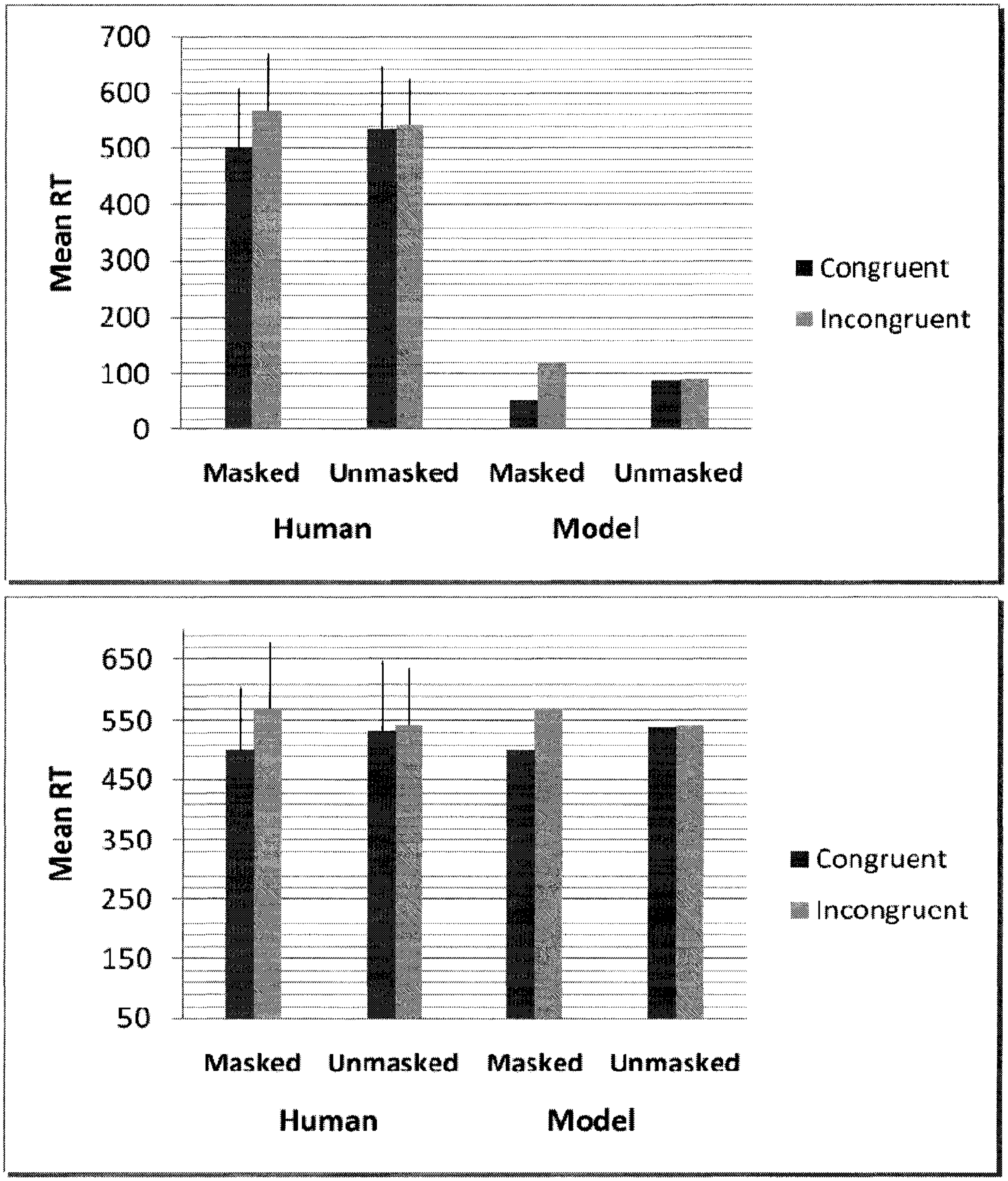
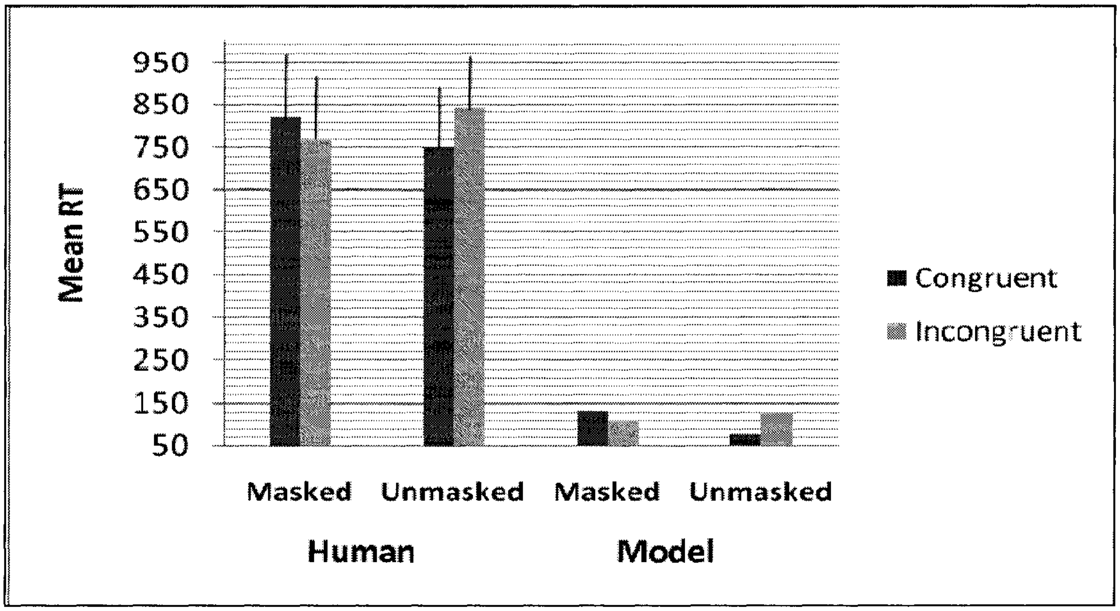


Figure 4.8b. Top: Simulation result of the masked and unmasked conditions in Experiment 1. Bottom: The same result by adding 450 cycles to the simulation data.

Simulation 2: Simulation of human data in Experiment 2

In Experiment 2, the masked Number-Symbol condition (i.e., when numerals primed symbols), an NCE was found while in the unmasked Number-Symbol (i.e., when numerals primed symbols) a PCE was found (though it was not significant). As will be shown in the next simulation, numerals and symbols are represented by a fixed weight (connections from IL to RL) of 2.5 and 2, respectively. To represent the numerical distance, a value of .5 was added to the weights for numbers far from *five*. However, in the current simulation the weights for prime and target were set to 2.75 and 2.25, respectively. These weights were chosen to represent numeral prime (strength 2.75) and symbol target (strength 2.25), excluding numerical distance. The prime-target SOA was 114 ms (i.e., mask-target SOA 71), as in Experiment 2. Moreover, the AA response mode was changed for both masked and unmasked conditions. Remember that the masked and unmasked conditions were mixed together in Experiment 2. Presumably participants had less phasic attentional response to the prime in the masked and unmasked conditions, compared to Experiment 1 where masked trials were not mixed with unmasked trials. This might have been caused mainly by the prime visibility in the unmasked trials. To simulate this result by the model, the AA mode for the prime was put in a medium phasic response mode for both masked and unmasked conditions. The phasic mode was set to medium ($c=2$, compared to $c=1.7$ and $c=1.5$ in the unmasked condition of the previous simulation) because the prime in Experiment 2 was not completely irrelevant and could help to predict the target type at least in the unmasked condition (see Chapter 3). As shown in Figure 4.9, the simulation result was an NCE in the masked and a PCE in the unmasked conditions, similar to human data in Experiment 2, when numerals primed symbols. Similar to the result of Experiment 2, with short interval between prime and target, a PCE in unmasked condition has been also found in previous studies (e.g., Dehaene, Artiges, et al., 2003; Jaśkowski, 2007).



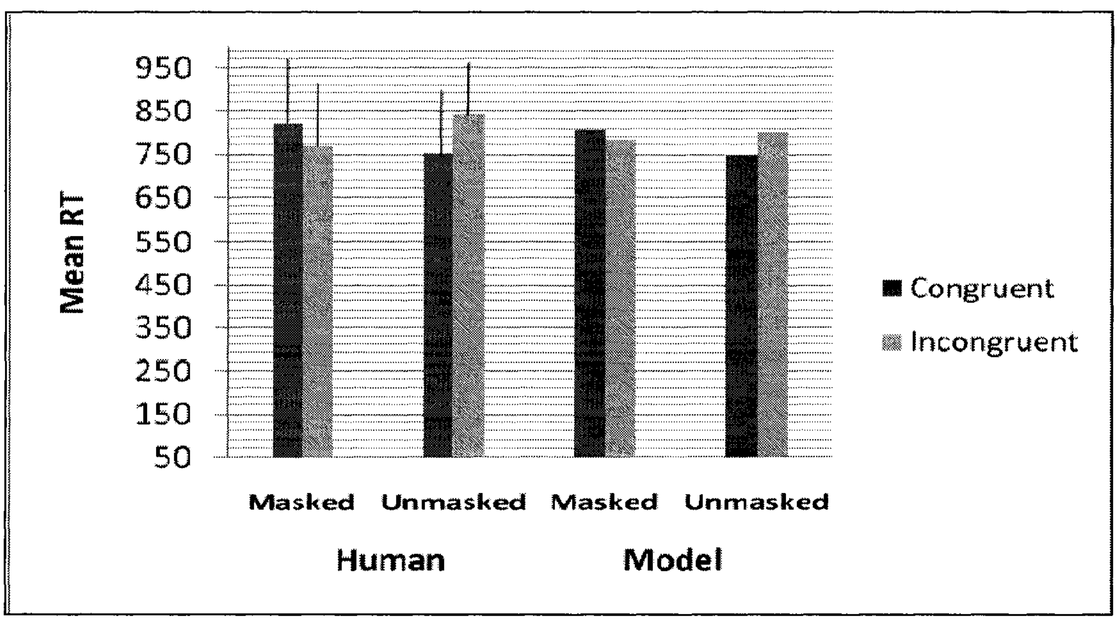


Figure 4.9. Top: Simulation result of the masked and unmasked conditions in Experiment 2. Bottom: The same result by adding 675 cycles to the simulation data.

Simulation 3a: Simulation of human data in Experiment 3

This simulation was designed to simulate data from Experiment 3 to show the general idea of the representation strength of prime and target in terms of IL-RL weights. The main result of this simulation is shown in Figure 4.10 (RTs for all weight combinations). Figure 4.11 shows the same result using RT differences (Incongruent - Congruent). As the weights of prime and target decreased, the priming pattern changed from positive to negative. A stronger weight caused a PCE and a weaker weight caused an NCE. However, this relationship was not linear, as making the weight too weak did not cause larger NCE (see below).

In general, the PCE and NCE patterns correlated with the experimental data in Experiment 3. Remember that symbol and close distance were considered as having low strength and numeral and far distance were considered as having high strength. When the prime and target weights were strong, a PCE was found, but when the prime and target weights were weak, an NCE was found. Another point is that the NCE was not increased linearly by increase in weights, especially the prime weights. Instead, when the weights decreased to 2, the minimum here, the NCE no longer increased but actually decreased. This result is similar to the behavioural data especially in Experiment 2, when symbols primed numerals, because symbols caused a small non-significant NCE. This result was found by simply representing the close distance and symbol type in the same way by weak weights, and by adding a small, equal weight (.5) for each of them, for far distance and numeral type.

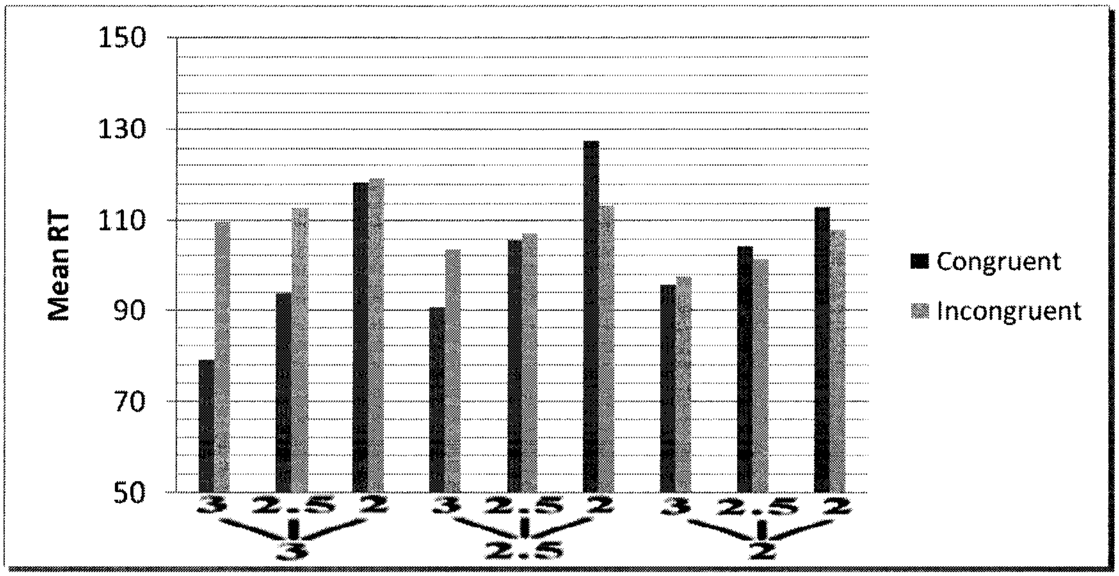


Figure 4.10. Simulation 3: Modelling results for all prime-target weight combinations.

Stimuli		Target			
	Type	1		2	
	Magnitude	1	2	1	2
Prime 1	1	✓✓ 30.38	✓ 18.7	✓ 18.7	✓ [illegible]
	2	✓ 12.82	✓ 1.39	✓ 1.39	✓✓ -13.98
Prime 2	1	✓ 12.82	✓ 1.39	? 1.39	? -13.98
	2	✓ 2.1	✓ -2.85	? -2.85	? -5.42

Figure 4.11. Relationship between the data from Simulation 3 and Experiment 3 (see Figures 4.3, and also see 4.3 for result of Experiment 2). √√= results consistent with significant human data; √= consistent but human data was not significant or the exact levels of all factors were not controlled; ?= no human data were available.

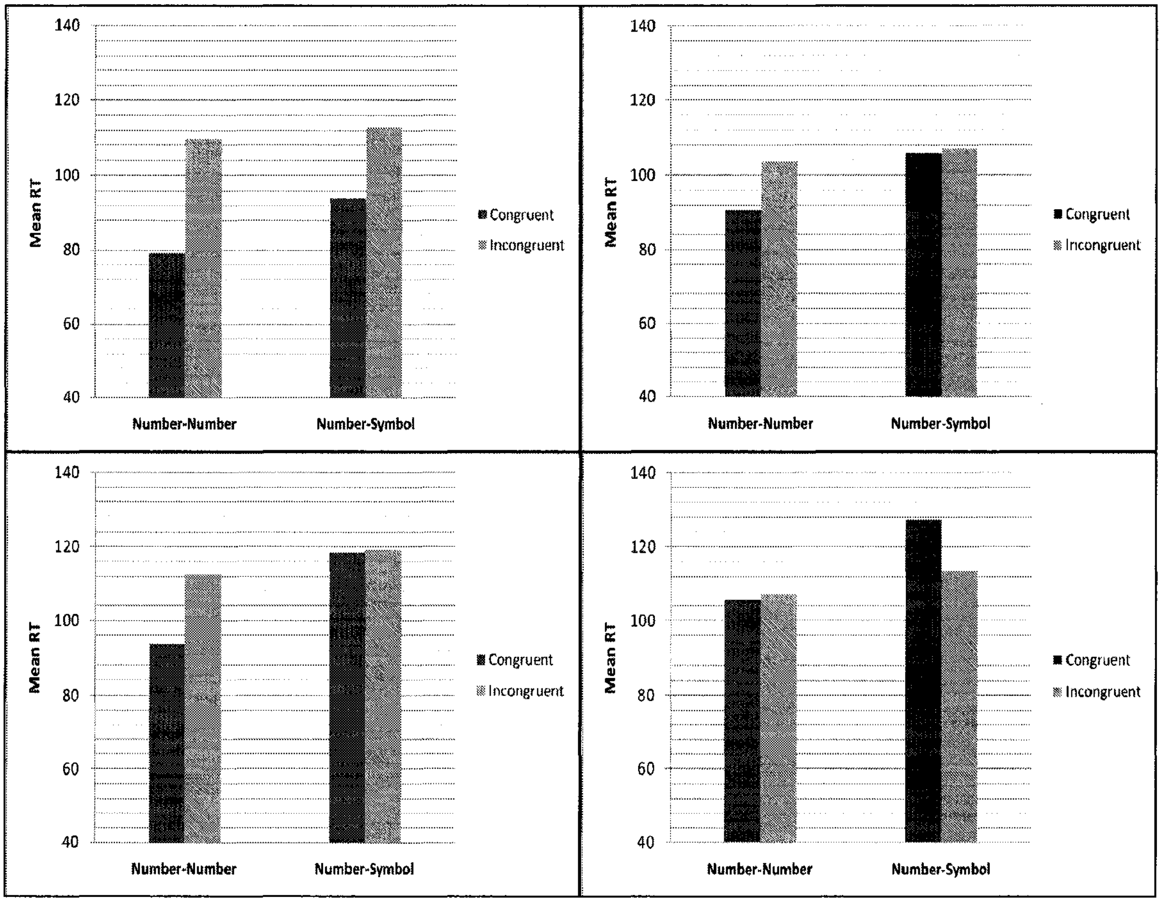
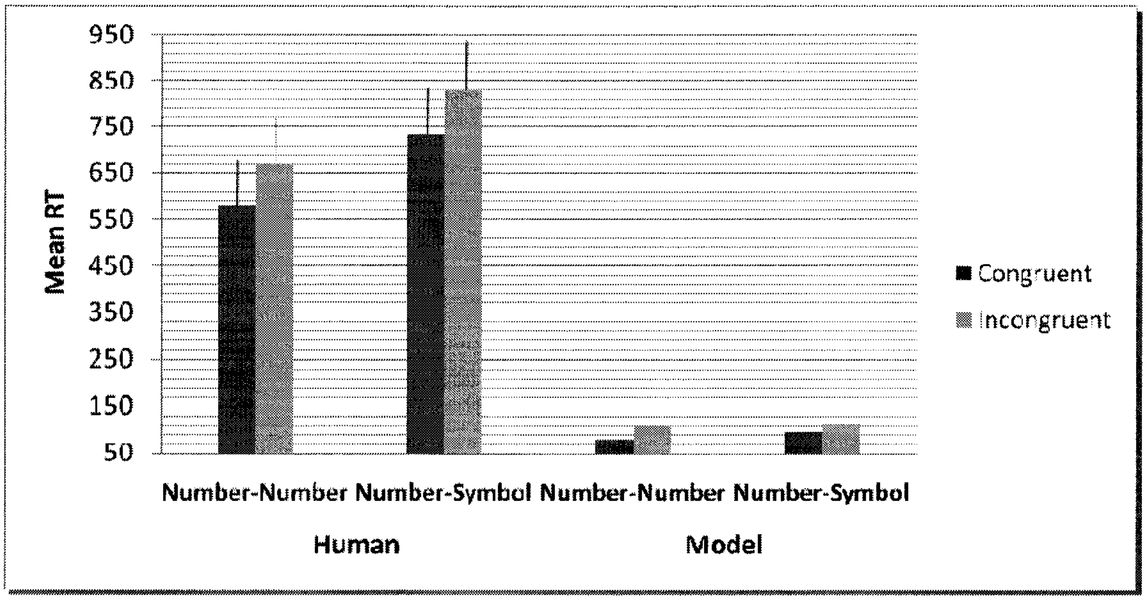


Figure 4.12. Data extracted from Figure 4.10 that simulate human data from Experiment 3 (see next figures). Top left: the result of 3-3 and 3-2.5 weights that simulate PCEs in Number–Number and Number–Symbol, respectively (at Far Prime-Far Target distance). Top right: the result of 2.5-3 and 2.5-2.5 weights that simulate a non-significant PCEs in Number–Number and Number–Symbol, respectively (both at Close Prime-Far Target distance). Bottom left: the result of 3-2.5 and 3-2 weights that simulate non-significant PCEs in Number–Number and Number–Symbol, respectively (both at Far Prime-Close Target distance). Bottom right: the result of 2.5-2.5 and 2.5-2.0 weights that simulate a non-significant PCE in Number–Number and an NCE in Number–Symbol, respectively (both at Close Prime-Close Target distance).



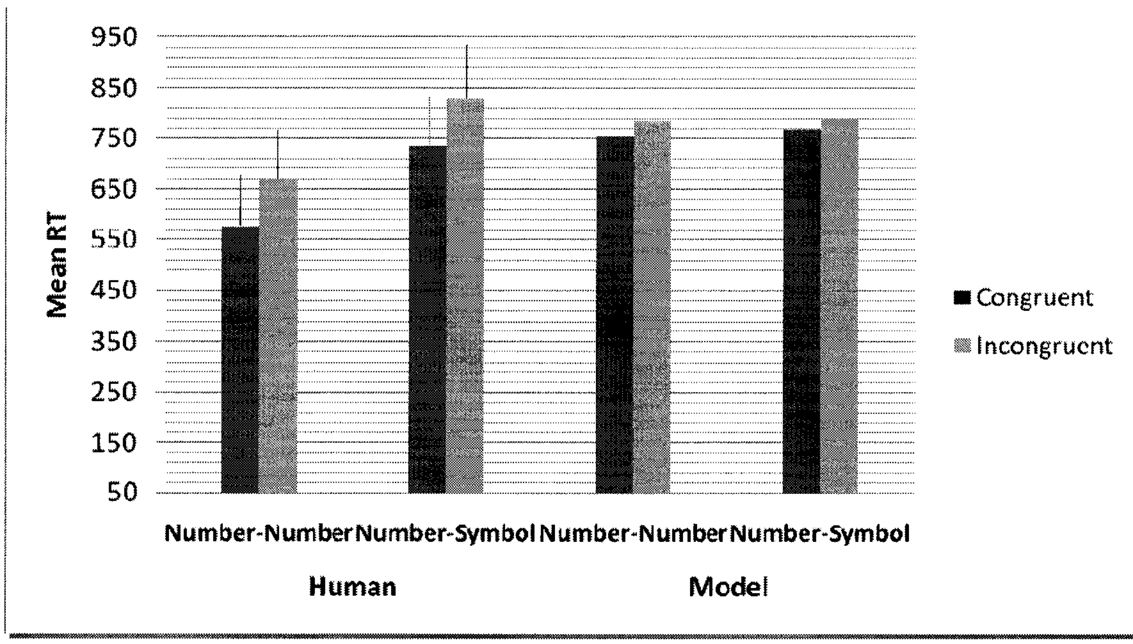
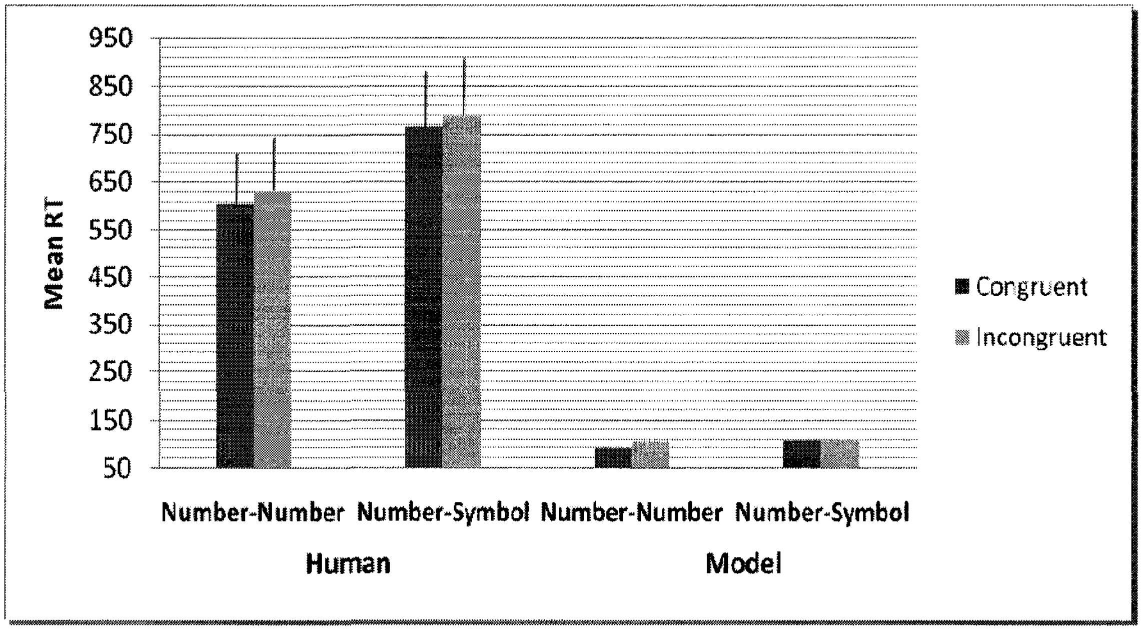


Figure 4.13. Simulation extracted from Figure 4.10 and human data from Experiment 3 for qualitative comparison. Top: the result of 3-3 and 3-2.5 weights that simulate a PCE in Number–Number (human data, t=4.555, p=.001) and a marginally significant PCE in Number–Symbol (human data, t=2.084, t=.067), respectively (at Far Prime-Far Target distance). Bottom: The same result by adding 675 cycles to the simulation data.



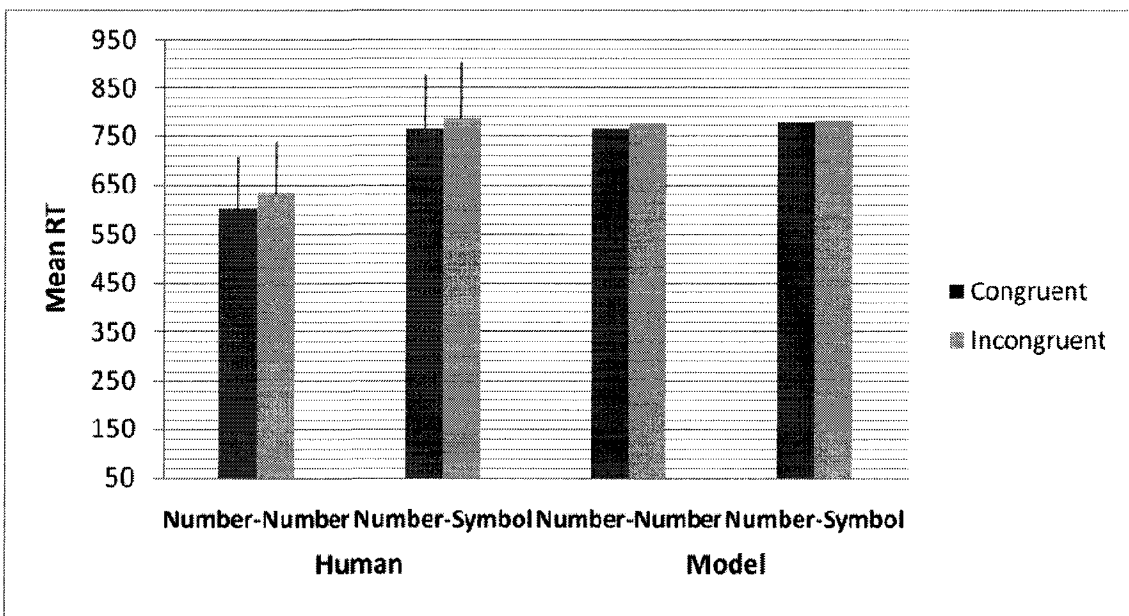
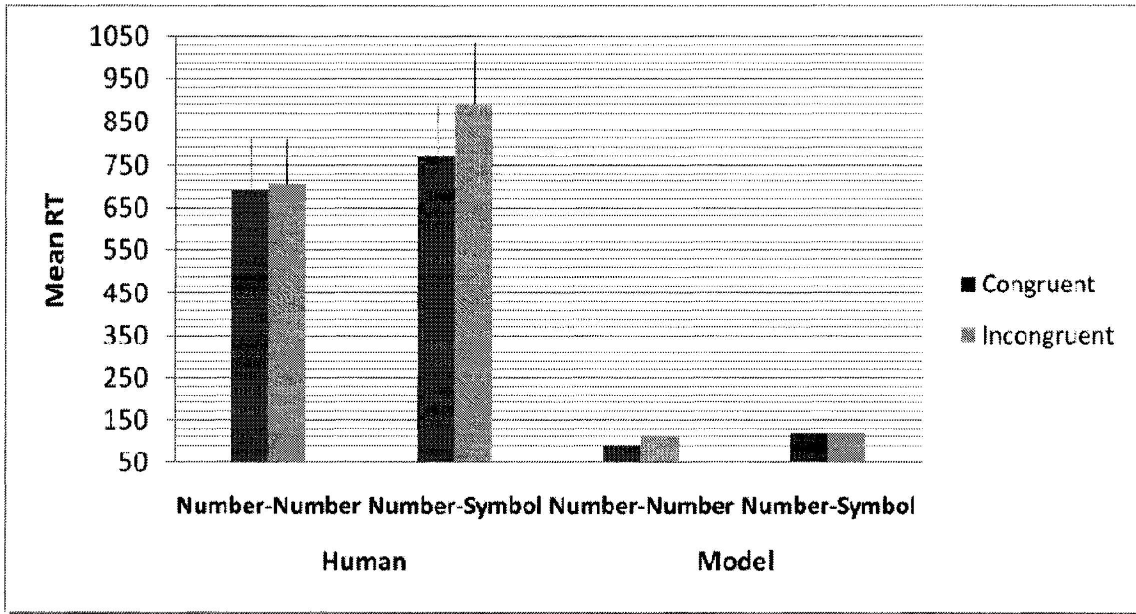


Figure 4.14. Simulation extracted from Figure 4.10 and human data from Experiment 3 for qualitative comparison. Top: the result of 2.5-3 and 2.5-2.5 weights that simulate non-significant PCEs in Number–Number (human data, t=.980, p=.352) and Number–Symbol (human data, t=.657, p=.527), respectively (both at Close Prime-Far Target distance). Bottom: The same result by adding 675 cycles to the simulation data.



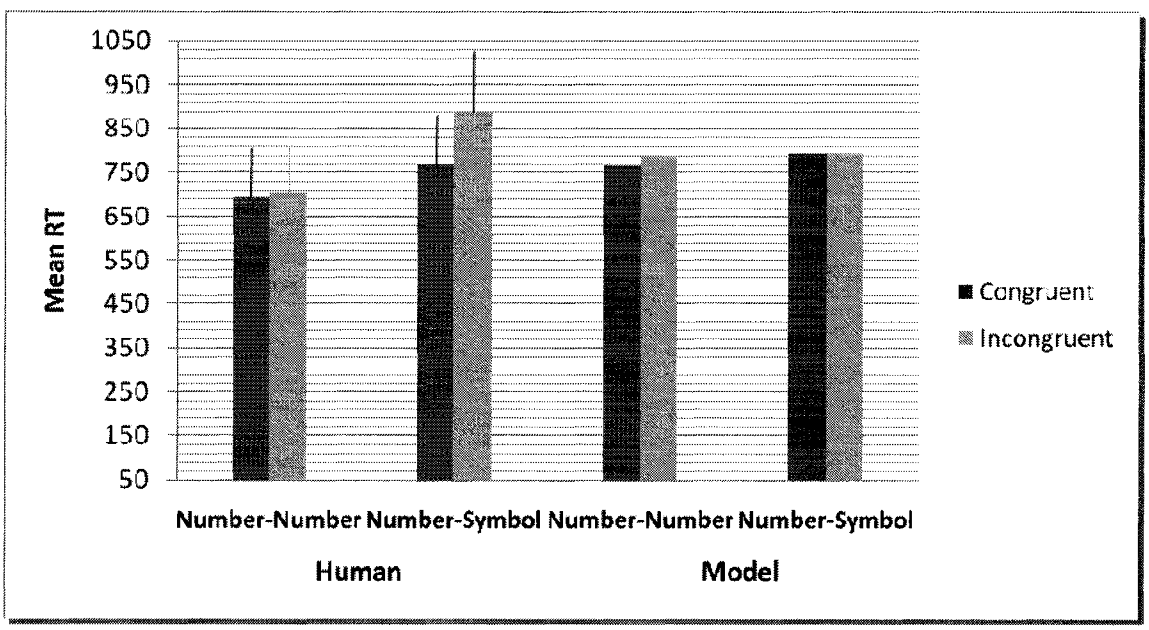
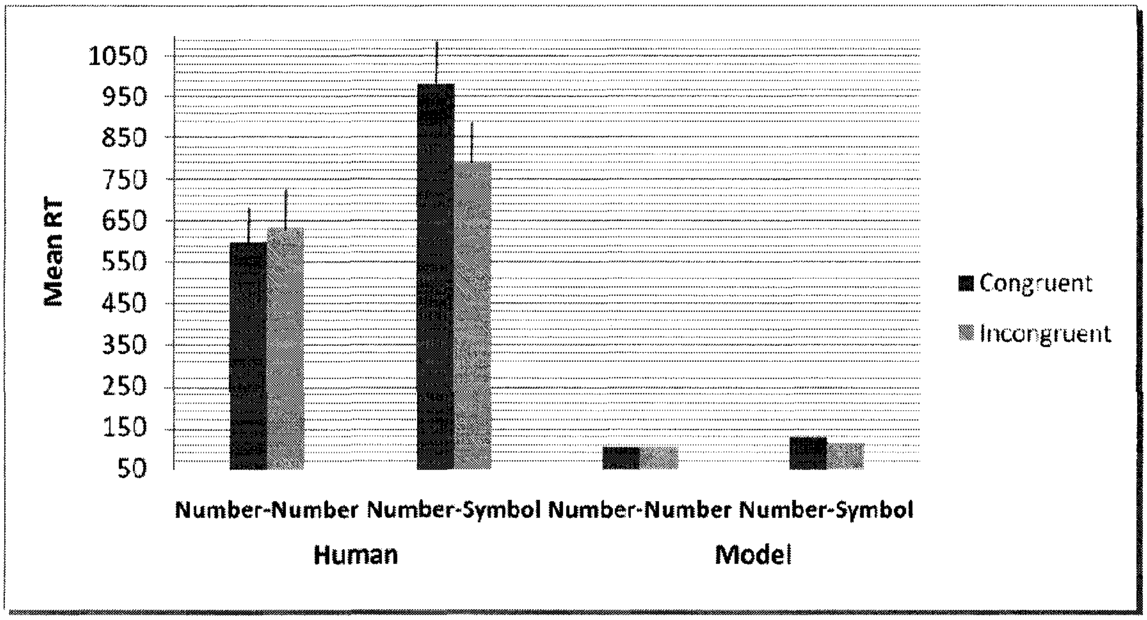


Figure 4.15. Simulation extracted from Figure 4.10 and human data from Experiment 3 for qualitative comparison. Top: the result of 3-2.5 and 3-2 weights that simulate a non-significant PCE in Number–Number (human data, t=.441, p=.67) and a marginally significant PCE in Number–Symbol (human data, t=2.039, p=.072), respectively (both at Far Prime-Close Target distance). Bottom: The same result by adding 675 cycles to the simulation data.



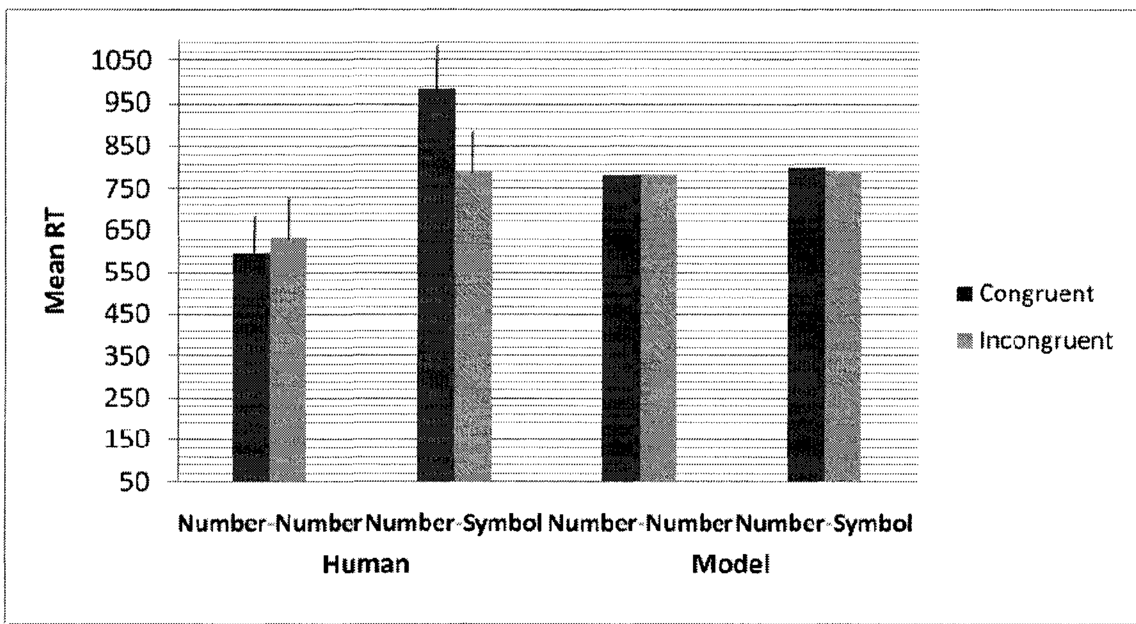
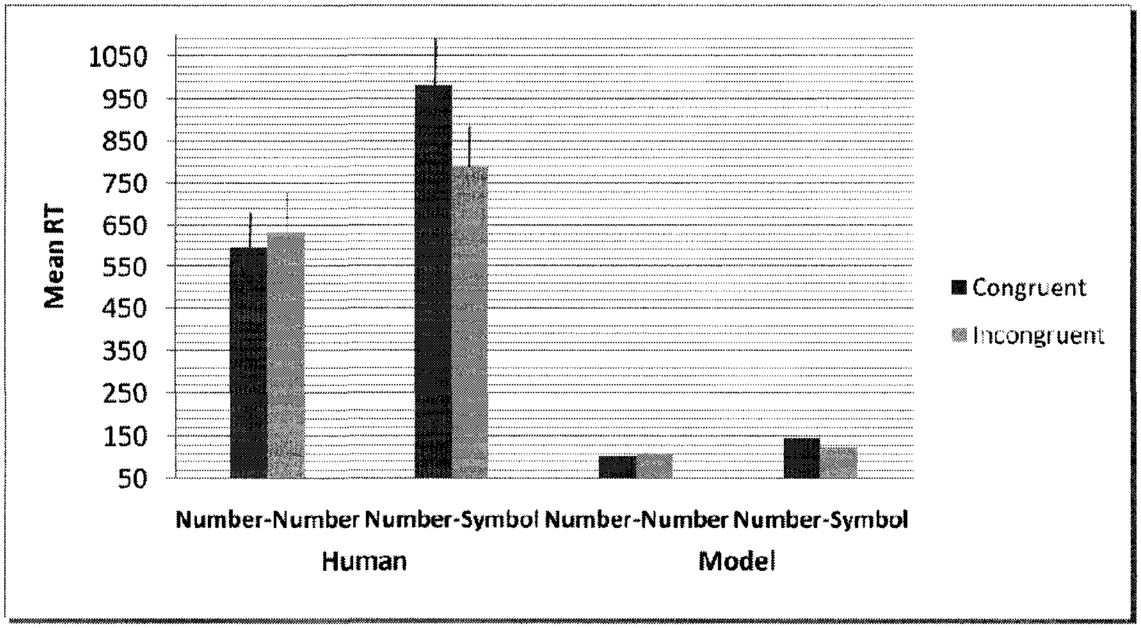


Figure 4.16. Simulation extracted from Figure 4.10 and human data from Experiment 3 for qualitative comparison. Top: the result of 2.5-2.5 and 2.5-2.0 weights that simulate a non-significant PCE in Number–Number (human data, t=1.545, p=.157) and an NCE in Number–Symbol (human data, t=3.692, p=.005), respectively (at Close Prime-Close Target distance). Bottom: The same result by adding 675 cycles to the simulation data.



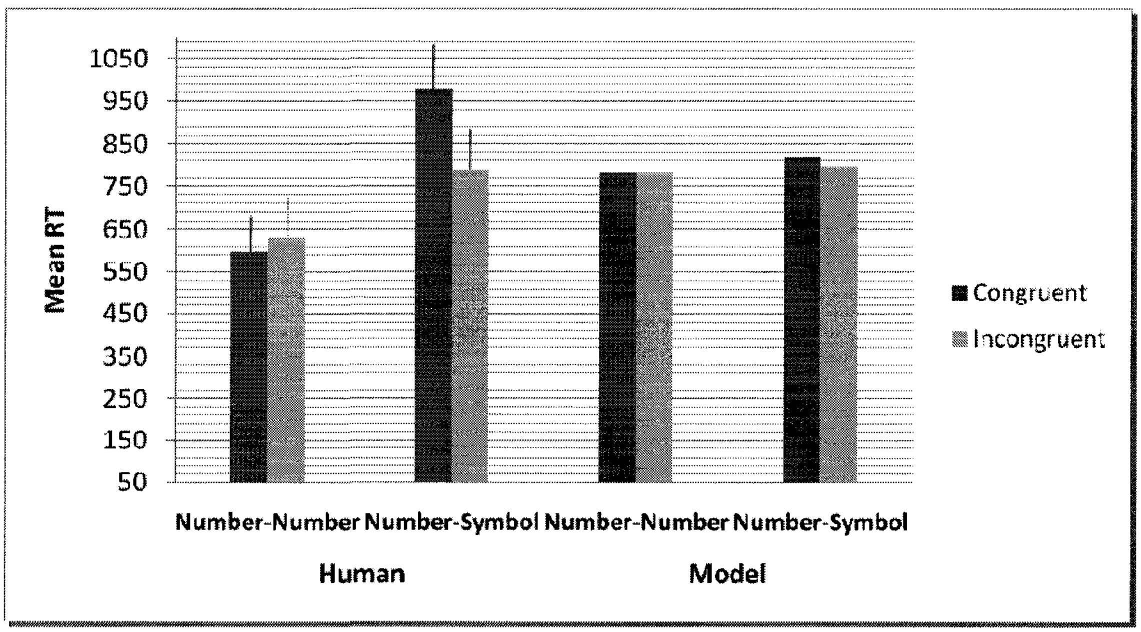
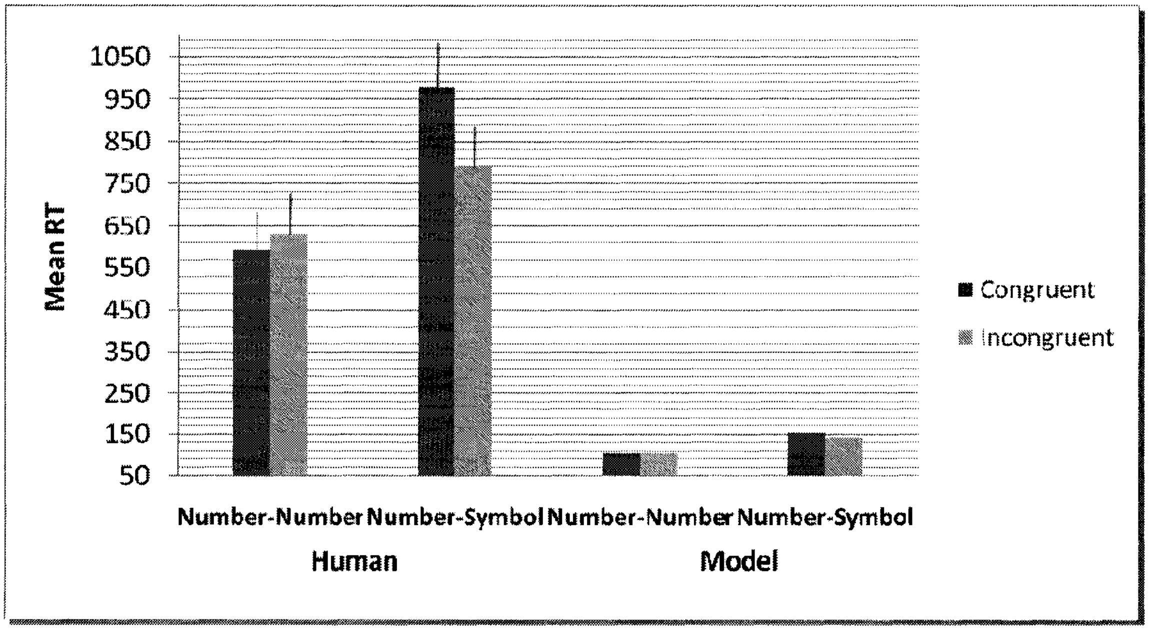


Figure 4.17a. Simulation 3b. This figure is similar to Figure 4.16, but the simulation data has been improved by using a smaller self-excitation for the symbol target (1.3 compared to 1.5 in other simulations). Top: the results of 2.5-2.5 and 2.5-2.0 weights that, similar to Figure 4.16, simulate a non-significant PCE in Number–Number (human data, t=1.545, p=.157) and an NCE in Number–Symbol (human data, t=3.692, p=.005), respectively (both at Close Prime-Close Target distance). Bottom: The same result by adding 675 cycles to the simulation data.



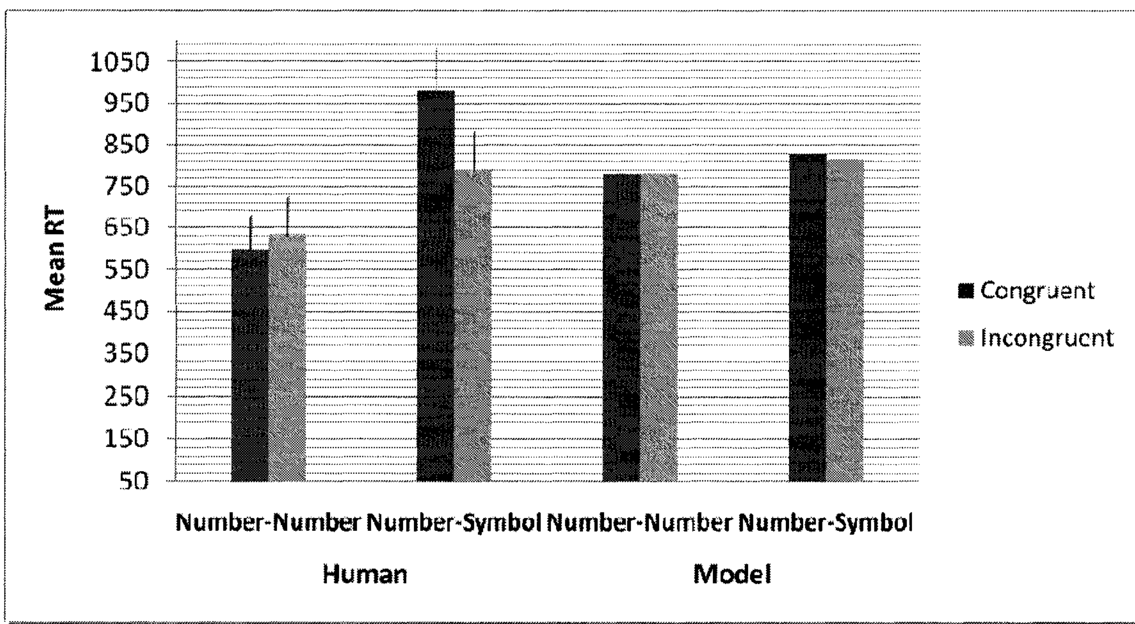


Figure 4.17b. Simulation 3b. This figure is similar to Figure 4.16, but the simulation data has been improved by using a smaller self-excitation for the symbol target (1.4 compared to 1.5 in other simulations), and a smaller weights between RL and ML (1.4 compared to 1.5 in other simulations). Top: the results of 2.5-2.5 and 2.5-2.0 weights that, similar to Figures 4.16 and 4.17a, simulate a non-significant PCE in Number–Number and an NCE in Number–Symbol, respectively (both at Close Prime-Close Target distance). Bottom: The same result by adding 675 cycles to the simulation data.

To focus on the main result, Figures 4.12-4.16 depict only the relevant conditions that are to be compared between the simulation data (extracted from Figure 4.10) and human data in Experiment 3. These figures show similarity between the main results of Experiment 3 and the corresponding simulation data. However, the result of Close Prime-Far Target and Far Prime-Close Target did not closely match the human data. But these conditions in Experiment 3 were not significant and probably have been caused by outlier RTs, as no data trimming was done (but see Appendix B, Figure 14-17).

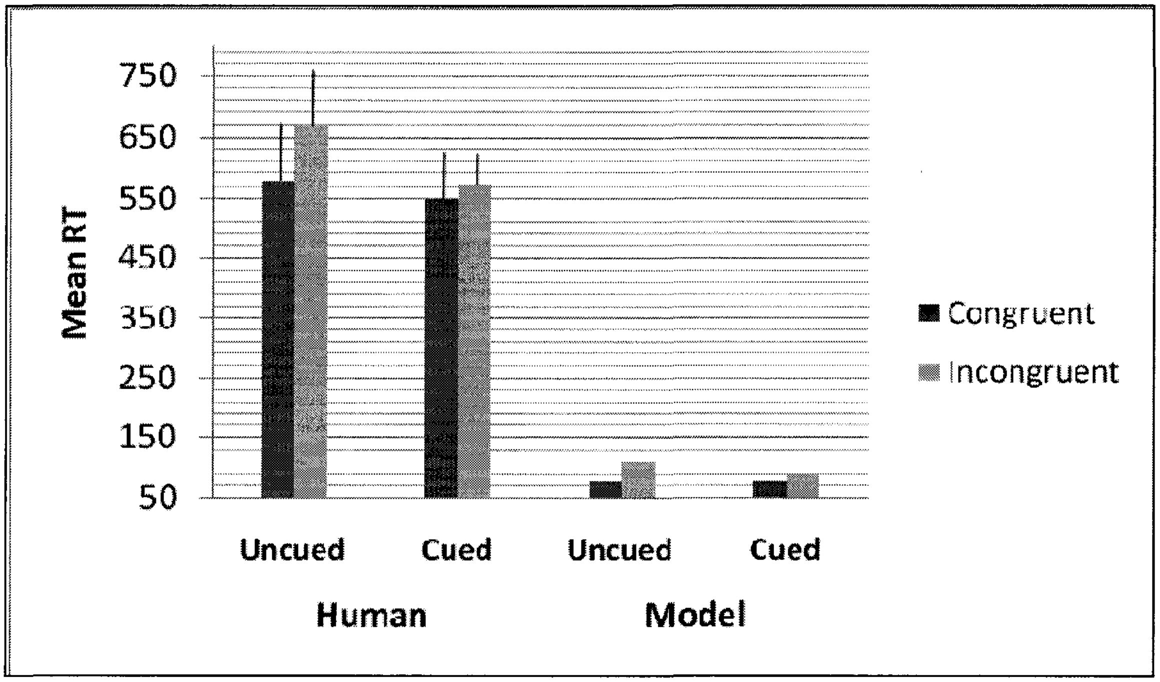
Simulation 3b: An example of improvement in the results to simulate the decrease in RT with symbol target.

The result of previous simulation was not very similar to the human data, especially when the target was symbol. A problem with the results of this simulation is that the difference between symbol target and numeral target is not as much as that in the human data. In the human data, the RTs for trials with symbol target were much slower than those with numeral target. Although this pattern was found in the simulation data, the result did not fit the human data very well. One reason for symbols to take longer is the low strength of the symbols compared to numerals. As mentioned before, the symbol target could cause very long RTs and the numeral target could cause very short RTs. A data trimming by excluding very short and very long RTs in Experiment 3, showed a better results in terms of the similarity between simulation and human data (Appendix B, Figure 14-17). Very long RTs could happen in trials that caused missing in the model (mainly with weak, i.e., symbol, target) and excluded from the simulation results. In this case, participants might respond randomly but slowly. In the model, very short RTs could also happen (mainly with strong, i.e., numeral, target) because of crossing the threshold before the target presentation. These RTs (pre-hits) were also excluded from the simulation results.

A simple way to get a better simulation result is to change parameters that decrease the processing time, for example thresholds, self excitation in RL, and the weight between RL and ML for the target. Here, I simply changed self excitation of the target from 1.5 to 1.3. The result (Figure 4.17a) showed a better fit, but still the difference is not as much as the human data. A more decrease in RT for the symbol target was found (Figure 4.17b) by using self-excitation 1.4 and RL-ML weight 1.4 (compared to 1.5 in other conditions). Perhaps some extra processes are involved in the processing of symbol target compared to numeral target. For example, symbols may be retrieved from memory longer than numerals (not included in the model).

Simulation 4. Simulation of human data in Experiment 4.

One reason for no significant NCEs in Experiment 4 could be due to the target type, especially symbols that could cause a significant NCE if it was unpredictable. The cue could cause semantic activation of the symbol, which can be explained by the NCE in 2.5-2 versus PCE in 2.5-2.5 condition in simulation 3. However, the cue also decreased the PCE as no significant PCEs were found even at Far-Far Number Number. Therefore, I assume that cue activates AA and OA. For this purpose a simulation was run using mask-target SOA 71 cycles with strength 3-3 (Far Number-Far Number) and 2.5-2 (Close Number-Close Symbol) that without cue caused a PCE and an NCE, respectively (see previous simulation). In Experiment 4, the cue was presented for 500 ms and followed by



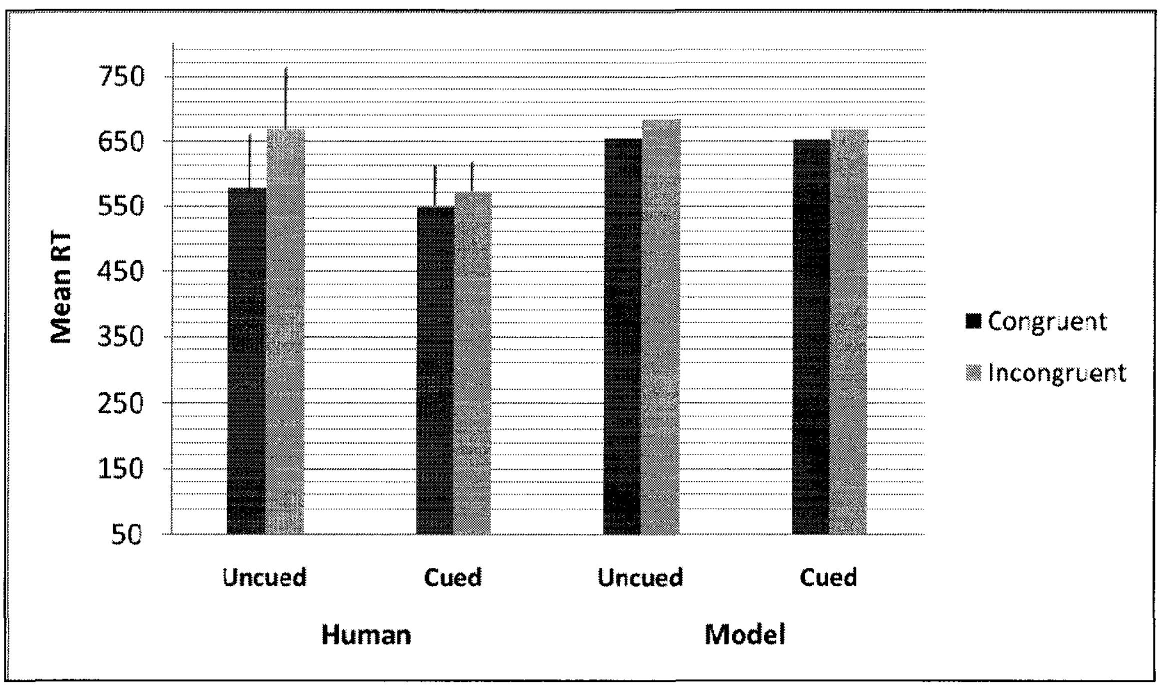
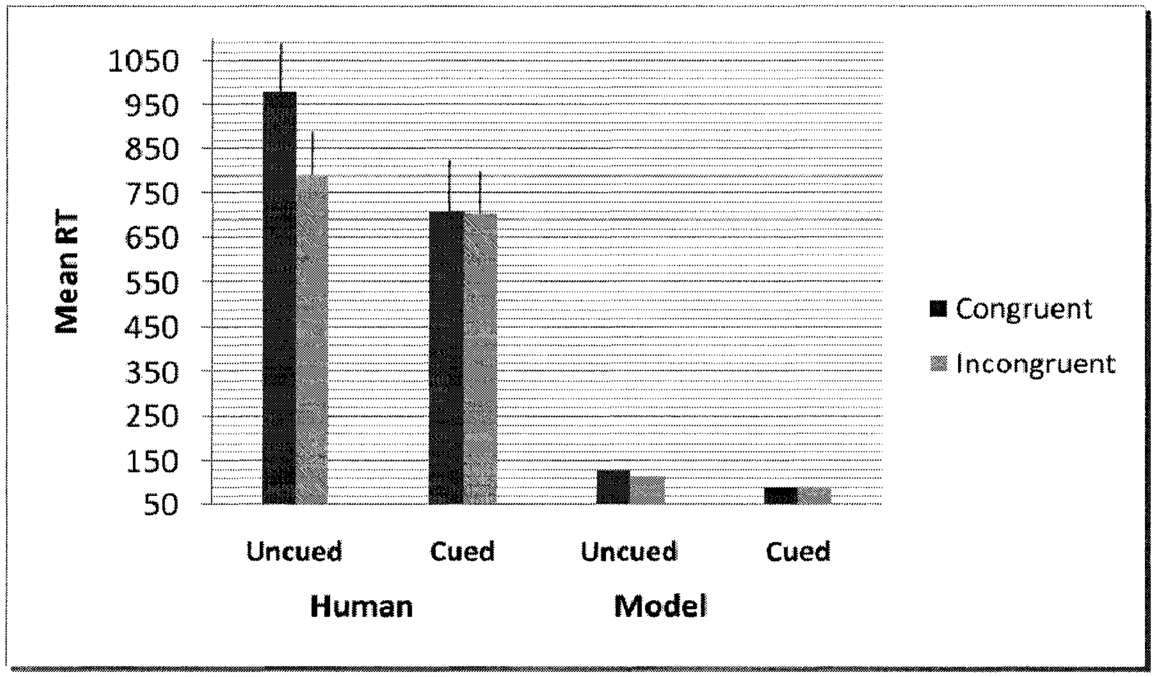


Figure 4.18. Top: Orient attention to the target in a simulation with prime and target strength 3-3 and mask-target SOA 71 (compared to no attention). Bottom: The same result by adding 575 cycles to the simulation data.



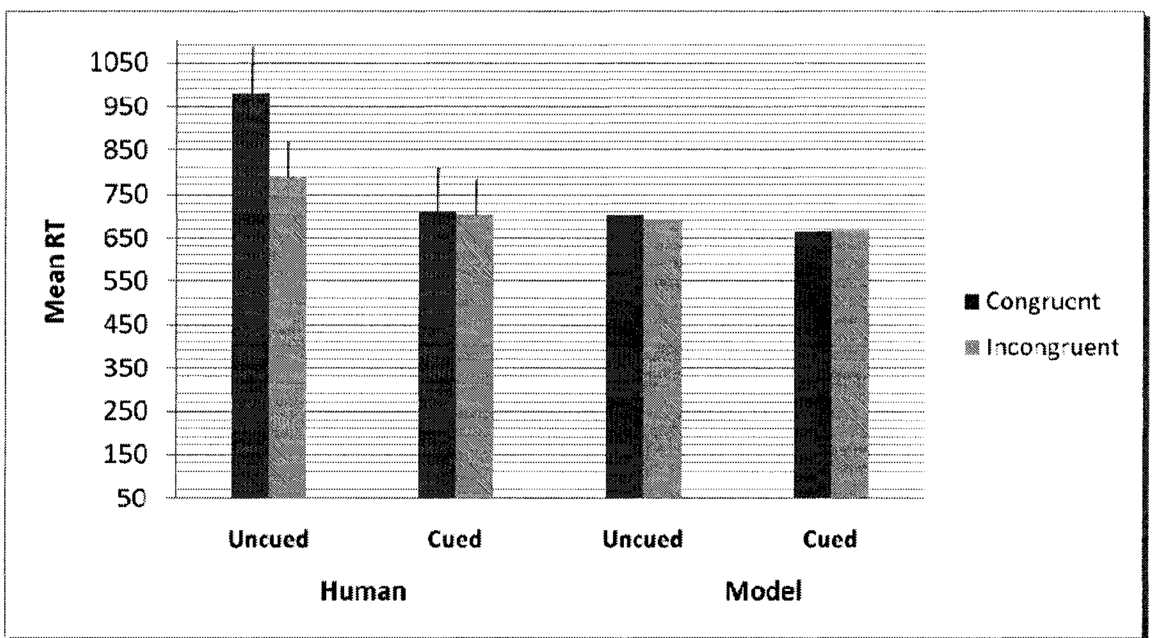


Figure 4.19. Top: Orient attention to the target in a simulation with prime and target strength 2.5-2 and mask-target SOA 71 (compared to no attention). Bottom: The same result by adding 575 cycles to the simulation data.

the forward mask after 300 ms. Here, a cue was presented for 275 cycles and was followed by the prime after 225 cycles. The cue activates the AA and causes a refractory period for the prime (similar to the refractory period that prime causes for the target). This refractory period weakens the prime. Moreover, the cue activates OA from the onset of the target for 60 cycles to modulate RL. This can strengthen the target because it compensates for the refractory period of AA for the target (see Simulation 10a for the effect of orient attention on the prime). As shown in Figures 4.18 and 4.19, the PCE and NCE (found in Experiment 3) were disappeared by the cue, similar to human data in Experiment 4. The simulation did not show decrease in RTs in the cued compared to uncued as much as the human data. This decrease might have been an effect of learning (not included in the simulation), as Experiment 4 was run after Experiment 3.

Simulations of the data from previous studies

Simulation 5a: Different mask-target SOAs with short mask duration

To simulate the general idea in Eimer et al.'s paradigm, i.e., a PCE and an NCE with short and long mask-target SOAs, respectively (e.g., Schleghecken & Eimer, 2002; Eimer & Schleghecken, 2003; Jaśkowski & Ślósarek, 2006) with no changes in the parameters except the mask-target SOA, I used the model in previous simulations with medium prime and target strength (2.5-2.5). Seven intervals of the mask-target SOA (from 71 to 251, with 30 cycles interval) were used to show their effects on priming pattern. Here the mask was presented for 71 cycles, but a longer mask duration has a similar effect (see Simulation 5b as well as all other following simulations).

Based on Eimer and colleagues' results, and other similar experiments, it is more likely to find NCE at longer SOAs. As shown in Figure 4.20, at the first SOA the priming pattern had a small PCE (stronger PCE can be found with shorter SOAs, see next simulation), and at longer SOAs it showed NCE, then NCE and RT slowly decreased and finally it became slightly positive again (see other simulations and the discussion for more details). Note the decrease in RT through time in Figure 4.20 which is similar to previous behavioural data (e.g., Schleghecken & Eimer, 2002; Eimer & Schleghecken, 2003; Jaśkowski & Ślósarek, 2006), and the U-shaped curve of the RT difference (Figure 4.21), both of which are mainly because of recovery from the attentional refractory per-

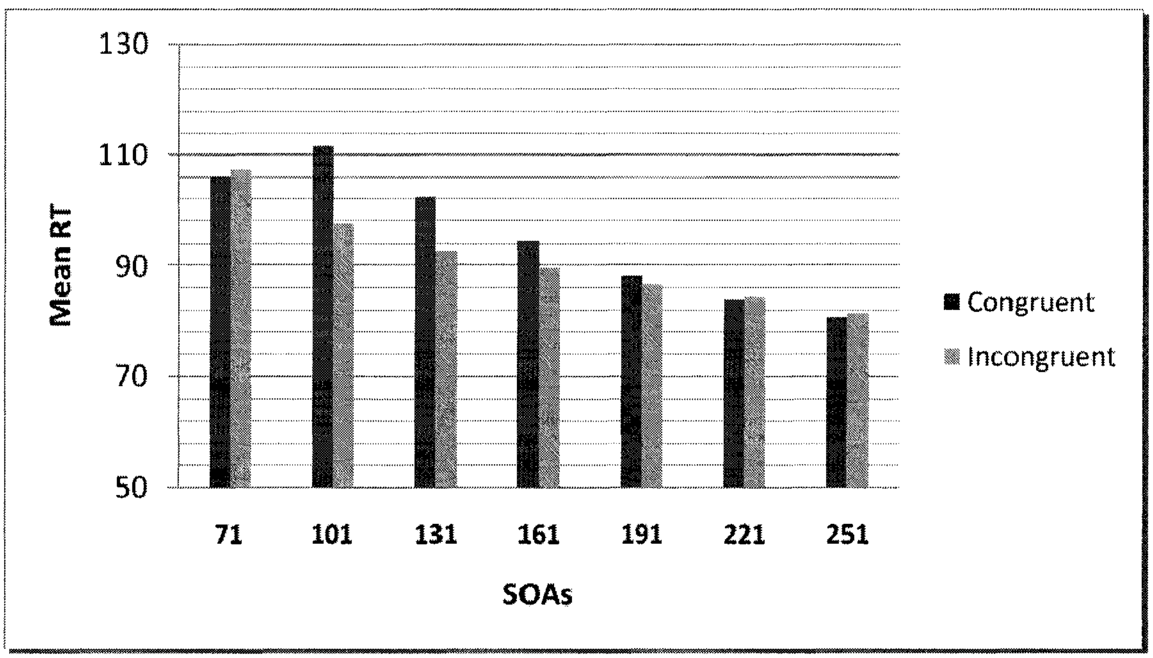


Figure 4.20. Modelling result at seven levels of mask-target SOA, starting from 71 (for another starting point and longer mask duration, see Figure 4.24). Each SOA follows 30 cycles after the previous one, with mask duration of 71 cycles. This interval is less than the actual SOA in ms but a better real time fit could be found by a better parameterization.

iod (see Appendix D, Figure 3). Figure 4.21 is also similar to the result of AB paradigm mentioned in Chapter 1 (e.g., Enns & Di Lollo, 2000), showing a similar attentional basis for AB (e.g., Nieuwenhuis, Gilzenrat, et al., 2005) and priming in the current study.

Error patterns in the model (Simulation 5a as a case)

Due to the high interaction between noise and behaviour in these types of models (e.g., Brunel & Hansel, 2006), I used a relatively small noise level in the simulations to focus on RT, which is the main finding in priming, especially NCE. The Model can show error patterns (incorrect responses, premature correct and incorrect responses, and misses) as discussed before (see also the discussion). With the current noise level, the model showed incorrect responses mainly for incongruent trials. Because of the competition, when a unit (e.g., left) wins, the other unit is suppressed. This process prevents the random activation of the opposite unit in the congruent trials. But in the incongruent trials, the activation of the prime can cause a response early after the target onset or even before, leading to an error called early errors. An early activation of the prime in the congruent trials sometimes cause a correct response before the target presentation, here called a pre-hit. Another pattern related to errors is a missing trial. After the target presentation, if a unit activation fails to cross the threshold by the end of trial deadline, it is recorded as a miss. Probably human participants randomly pick one of the two alternatives in these situations (Ratcliff, 2006). Although picking an alternative seems to depend on the level of activation in the two motor units, I assume that 50% of missing trials turn into errors eventually. This has been shown to account better for error patterns in LCA models (Ratcliff, 2006).

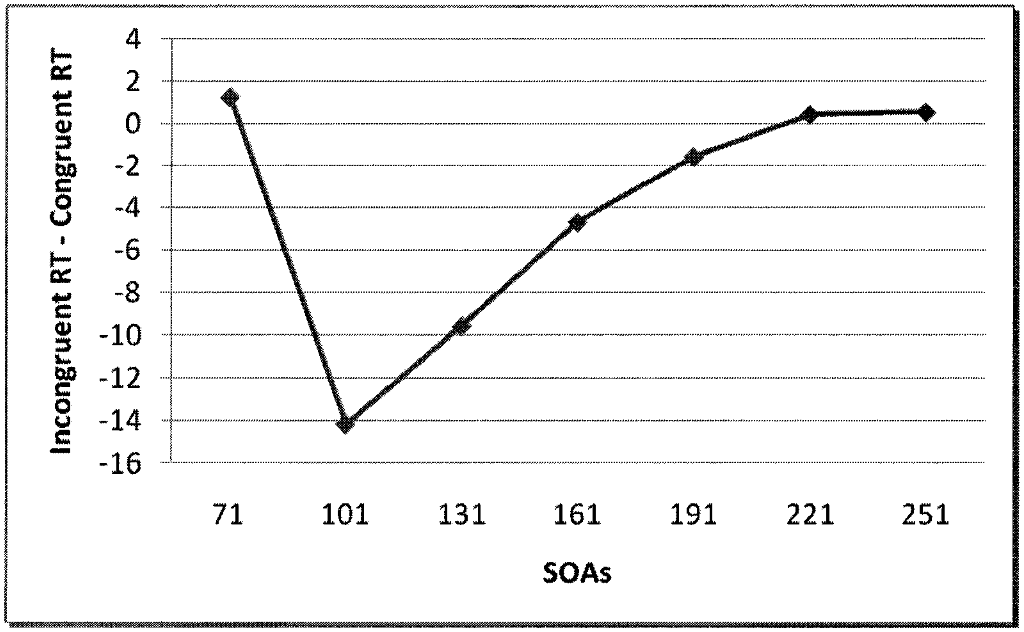


Figure 4.21. The congruency difference (Incongruent - Congruent) in the seven SOAs similar to lags in AB paradigm, showing a similar attentional basis for priming and AB.

In the model it is clear that errors caused by missed responses (mainly in the congruent trials) would have longer RT compared to early errors mentioned earlier, caused by early activation of response by the prime in the incongruent trials. The reaction times of incorrect trials, namely error RTs, are usually thrown away from the analysis by the experimenter. Inspired from the model, I reconsidered the error RTs in the experiments (Appendix C). It turned out that error RTs in the incongruent trials were shorter than in the congruent trials (except Experiment 1 because of small numbers of errors), especially in the masked trials and in trials with high strength primes (e.g., numerals far from *five*). This means that in these cases, errors in the incongruent trials are

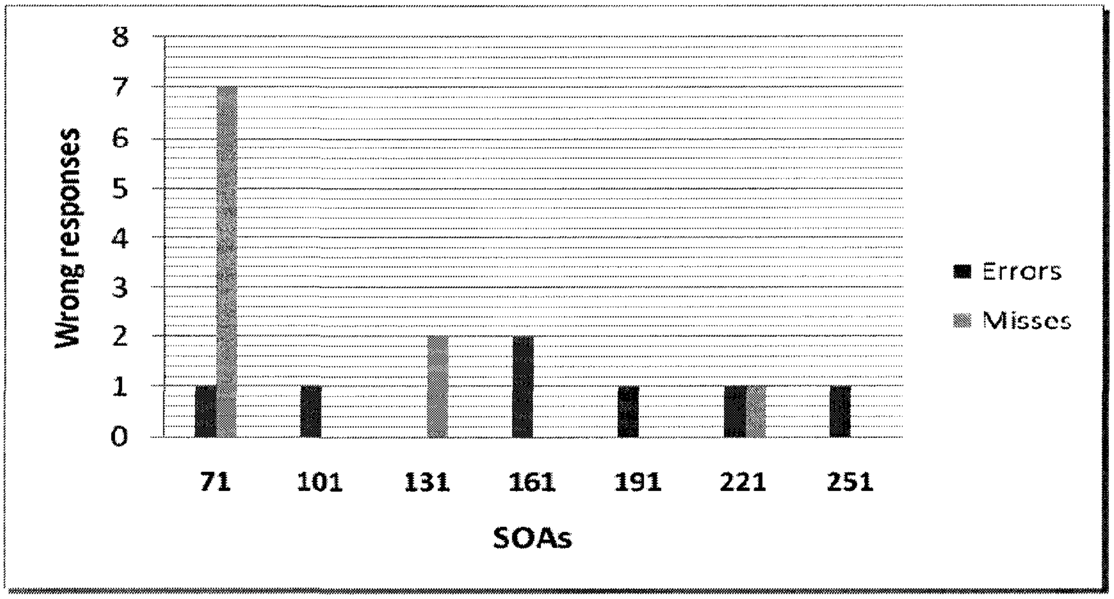


Figure 4.22. Different types of errors in the incongruent epochs.

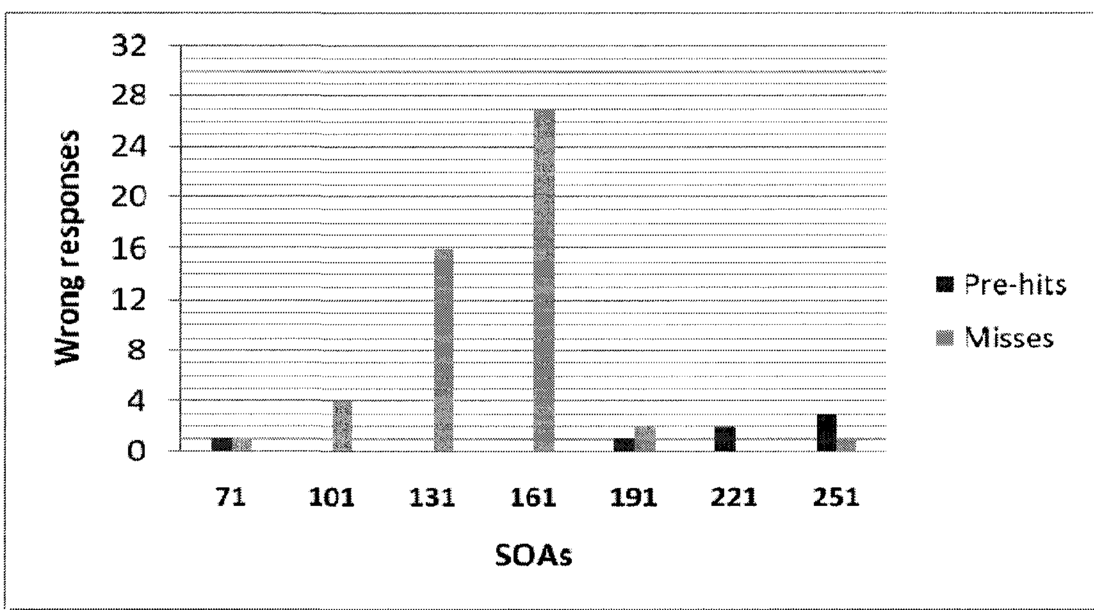


Figure 4.23. Different types of errors in the congruent epochs.

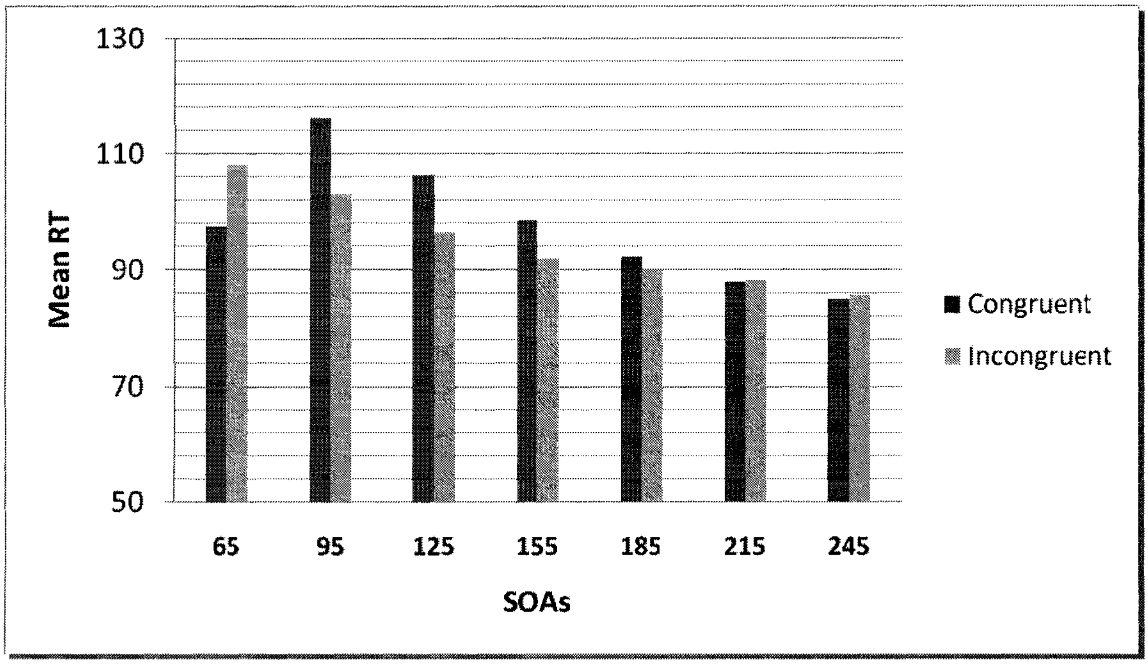
caused mainly by early activation of response by the prime, and errors in the congruent trials are mainly caused by missing.

I assume a similar error RT pattern for Eimer et al.'s paradigm, though I could not find any report on this in their studies. These types of incorrect responses are shown for simulation 5a, as an example (Figures 4.22 and 4.23), though the strong mask and low noise for the prime and target prevented more errors from happening.

Simulation 5b: Different mask-target SOAs with long mask duration

This simulation was exactly like Simulation 5a, but the duration of the mask was 100 cycles and the first mask-target SOA was 65 cycles, to simulate human data that have used longer masks (e.g., Schleghecken & Eimer, 2000; Eimer & Schleghecken, 2003; Jaśkowski & Ślósarek, 2006). The result of this simulation is shown in Figure 4.24. This result is similar to Simulation 5a but at the first SOA of mask-target SOA, the PCE is larger because the mask-target SOA was 10 cycles shorter than the first SOA in that simulation. To compare the results with human data, RTs are depicted at different SOAs in Figures 4.25 and 4.26a, b. Figures 4.26a and 4.26b show the same simulation data for human data using shape and arrow stimuli respectively. Here the strength was 2.5-2.5 but a better result for arrow can be found using strength 3-3 (see Simulation 9).

The change from PCE to NCE and the drop in RTs by increasing SOA can be related to the LRP patterns in masked priming (e.g., Eimer & Schleghecken, 1998). The LRP for the congruent trials goes to the opposite direction prior to the target-related motor activity and their final minimum is larger (and occurs later) than that of incongruent trials (see Appendix D, Figure 2).



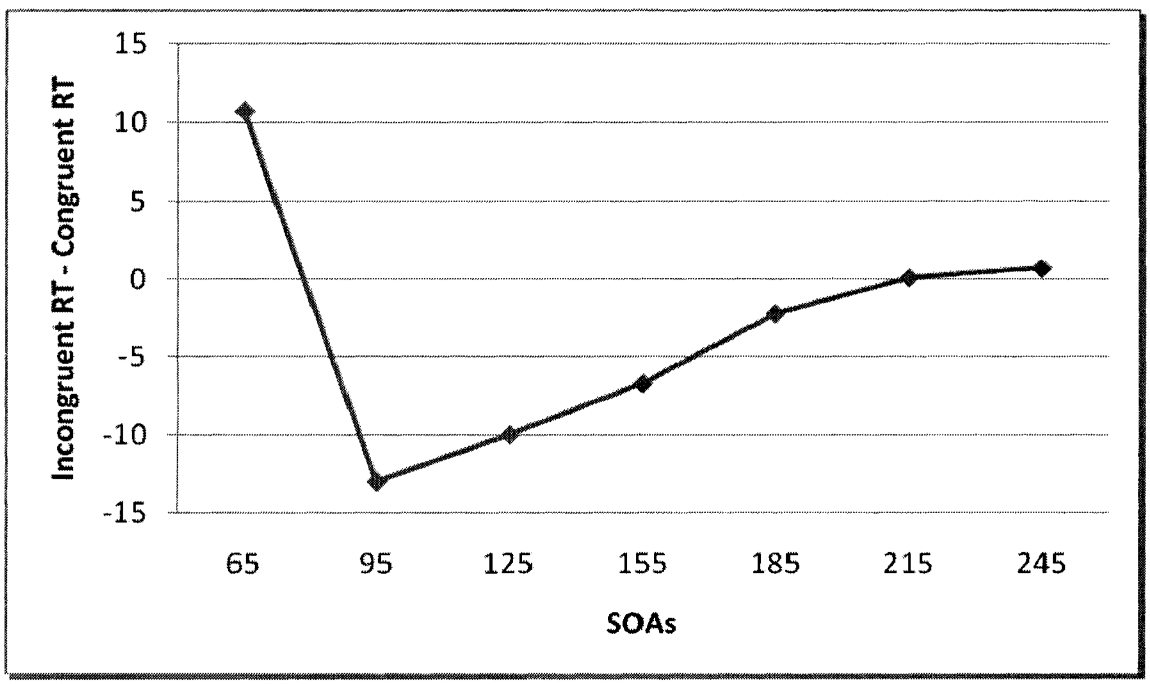


Figure 4.24. Top: Modelling result at seven mask-target SOAs. Each SOA followed 30 cycles after the previous one (the duration of the mask was 100 cycles and the first SOA was 65). Bottom: The same result in terms of Incongruent – Congruent (cycle).

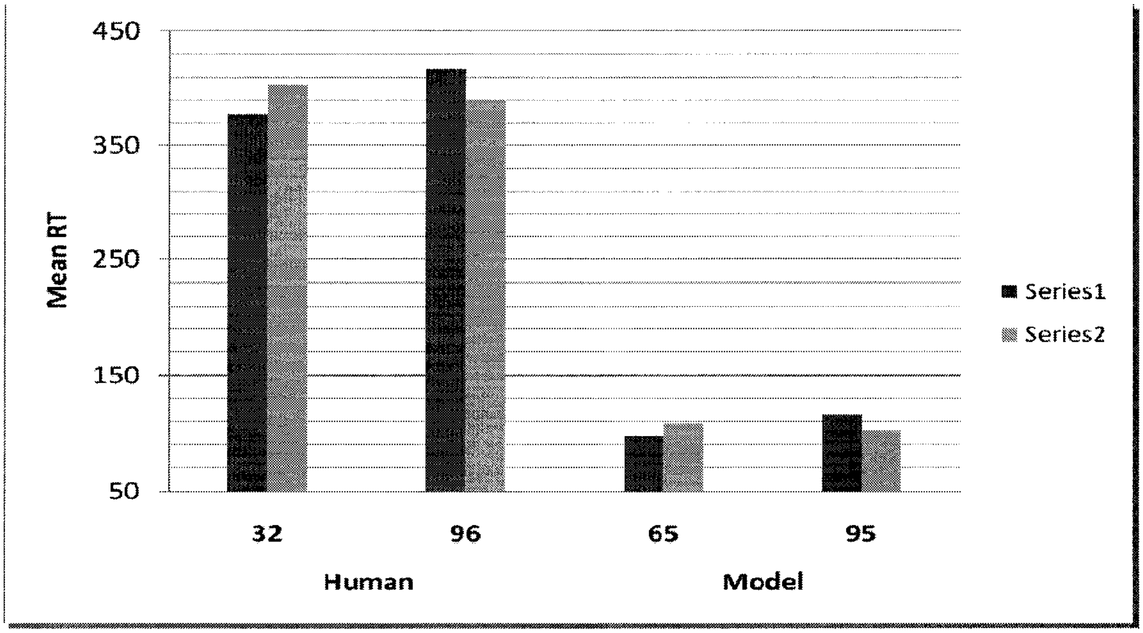


Figure 4.25. Simulation data at SOAs 65 and 95, to compare with human data at 32 and 96 SOAs (Schleghecken & Eimer, 2000).

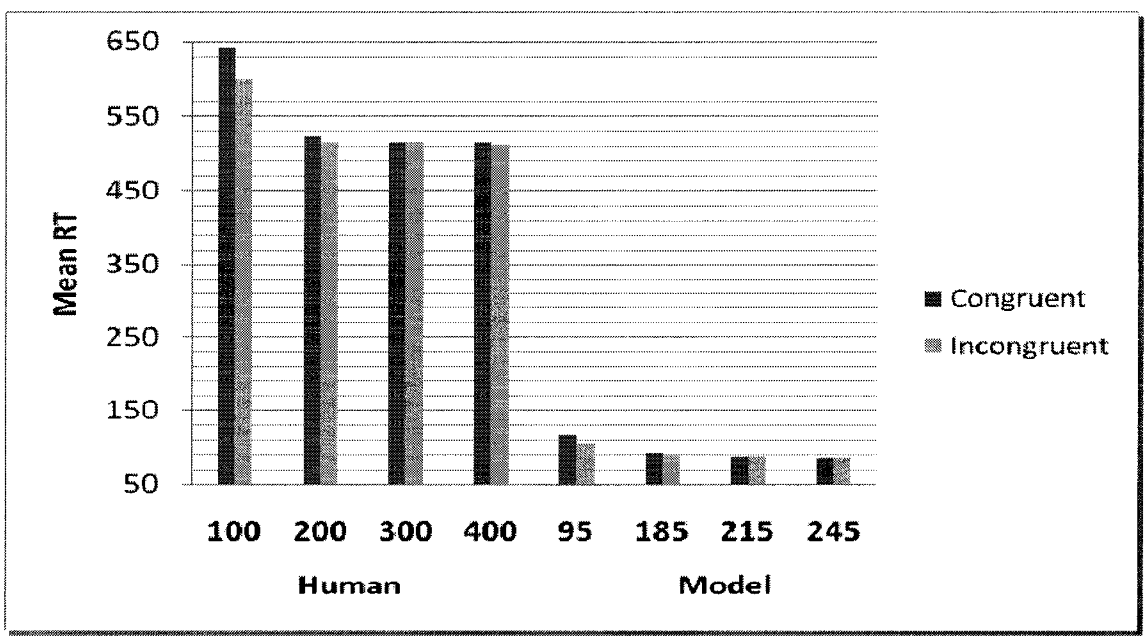


Figure 4.26a. Simulation data at SOAs 95, 185, 215, & 245, to compare with human data at SOAs 100, 200, 300, & 400, shape stimuli (Jaśkowski & Ślósarek, 2006, Exp. 2).

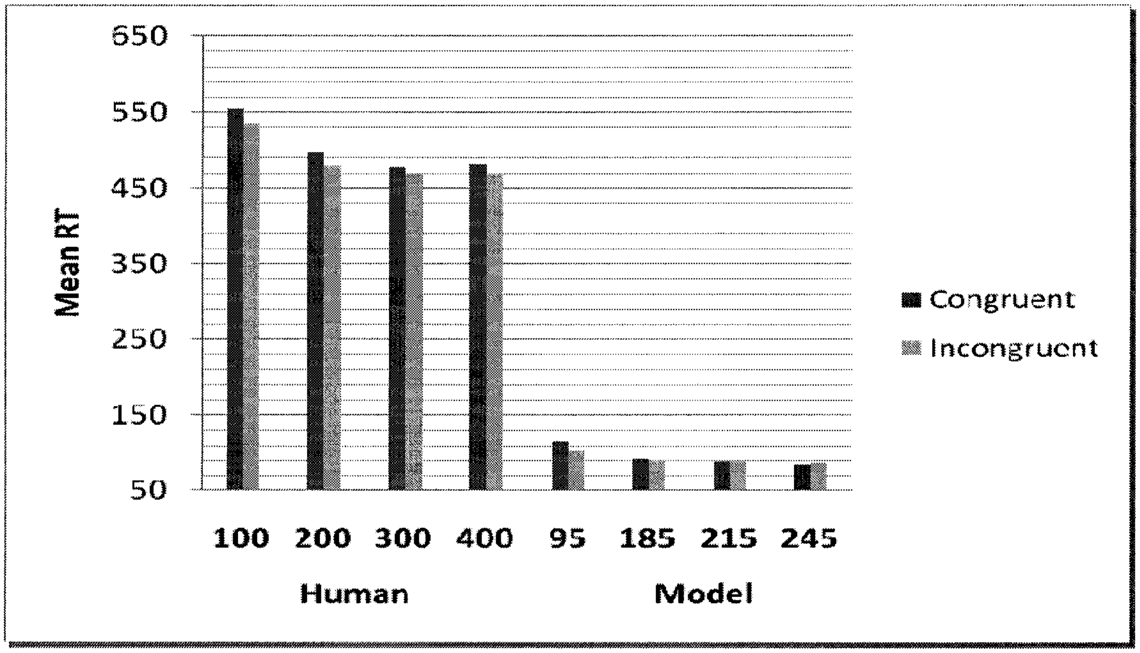


Figure 4.26b. Simulation data at SOAs 95, 185, 215, & 245, to compare with human data at SOAs 100, 200, 300, & 400, arrow stimuli (Jaśkowski & Ślósarek, 2006, Exp. 1).

Simulation 6: Stimulus degradation

As mentioned in Chapter 1, Schleghecken and Eimer (2002, Exp. 4) found that degradation of stimuli, by adding small random dots to all stimuli, turns NCE into PCE. Here, the degradation of stimuli was simulated by using lower input activation in IL compared to the usual 1 and 0 and increasing the noise of the prime and target in RL. Two levels of degradation were created by using .85 (opposite unit .15) and .75 (opposite unit .25), while 1 (opposite unit 0) was considered as encoding an intact stimulus. The noise of the prime and target units in RL was increased from .2 to .3. The IL-RL strength for the prime and target were 2.5 and the mask-target SOA was 125. The model successfully simulated the human data as shown in Figure 4.27a. With degradation, the NCE turned into PCE and RTs were increased with more degradation.

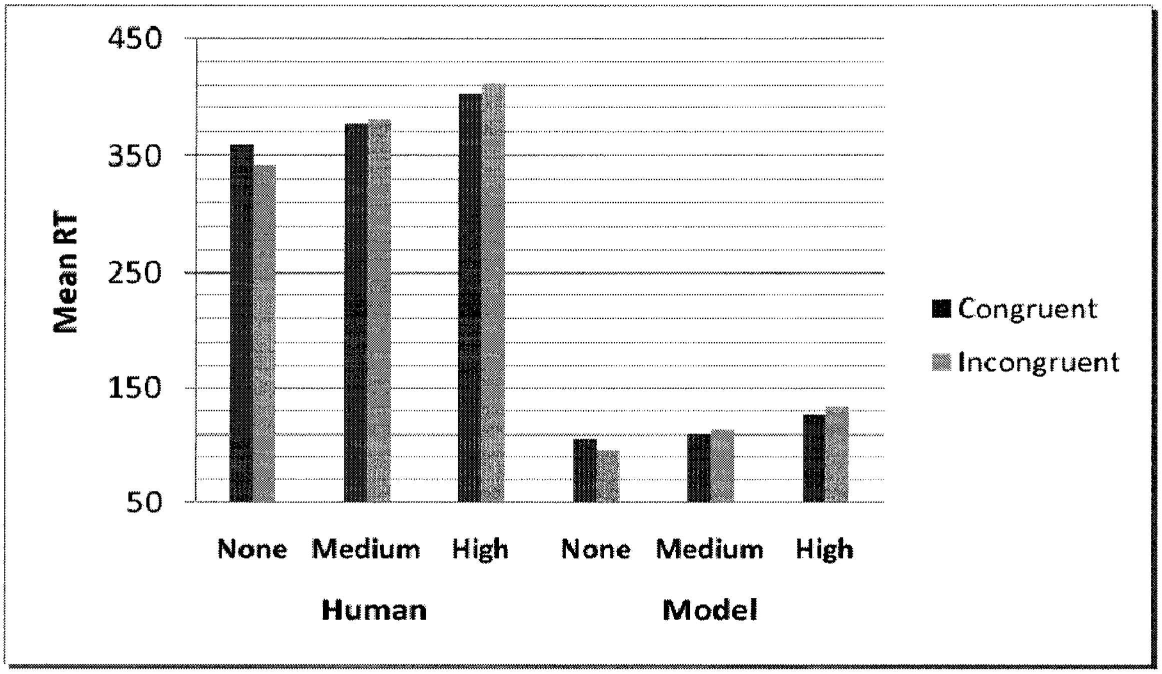


Figure 4.27a. Degradation with three levels of prime and target activation in IL: 1 (no degradation), .85 (medium degradation), .75 (high degradation), and an increase in noise. With degraded unit activations NCE turned into PCE and RTs increased, as in Schleghecken & Eimer (2002, Exp. 4).

In another experiment, Schleghecken and Eimer (2002, Exp. 3) added random dots to all stimuli, but the dots did not cover the target (presented above or below the target, randomly). They found that in this case, while degradation changed the NCE into PCE, similar to the other experiment, it did not increase the RTs. For simulating this experiment, a simulation was run identical to the previous one but only the prime was degraded. The result was similar to the human data. As shown in Figure 4.27b, the NCE turned into PCE, but the RTs did not increase. This shows that if the target is not degraded the RTs do not increase, because the target is stronger and is processed faster.

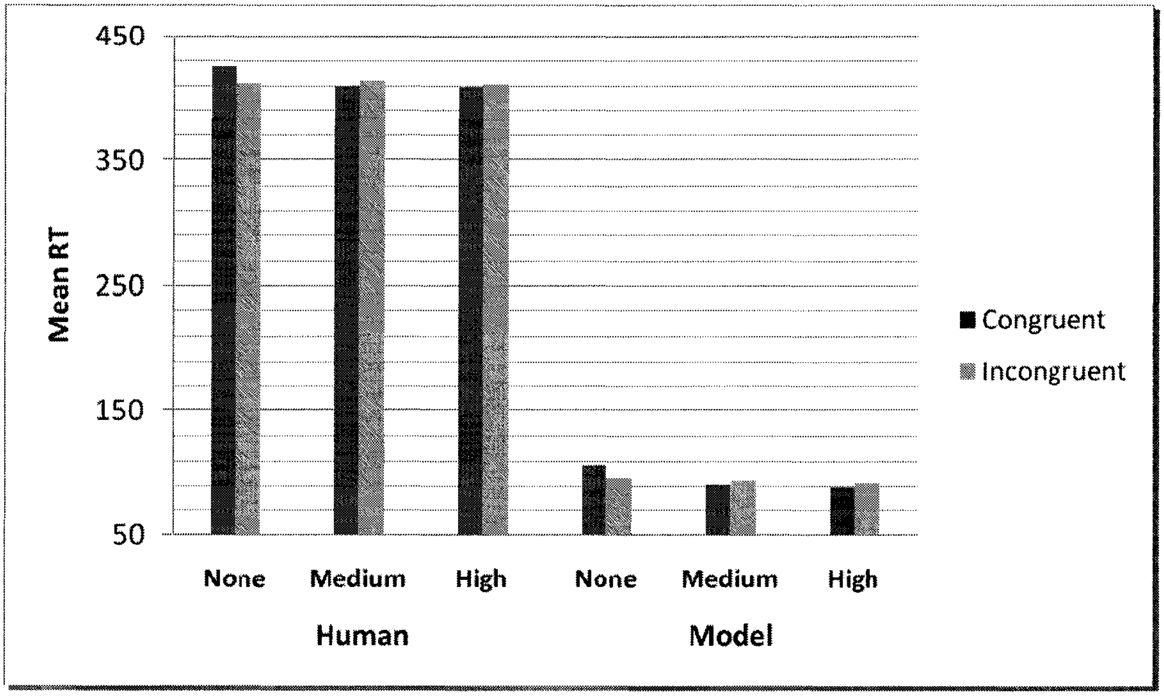


Figure 4.27b. Degradation with three levels of prime activation in IL: 1 (no degradation), .85 (medium degradation), and .75 (high degradation), as well as an increase in noise. Degrading only the prime units, turned NCE into PCE but did not increase the RTs, as in Schleghecken & Eimer (2002, Exp. 3).

Simulation 7a: Mask density

It has been shown that mask needs to be dense enough at a specific rate to cause NCE and that decreasing the density changes NCE to PCE (e.g., Eimer & Schleghecken, 2002), though beyond that it has no major effects (c.f., Lleras & Enns, 2006). In this simulation, mask density was simulated by changing the inputs of the mask units in IL to .55 (medium density) and .45 (low density), instead of 1 (very high density, used in simulations of usual masked conditions), all with strength 2.5-2.5 at mask-target SOA 125. As shown in Figure 4.28, similar to human data (e.g., Eimer & Schleghecken, 2002, Exp. 1) decreasing the mask density from 1 to .55 decreased NCE and then to .45 and 0 turned NCE to PCE. The effect of unmasking (i.e., 0 mask density) was shown before (see also Simulation 11), which even with low phasic attention (Simulation 2) showed a large PCE.

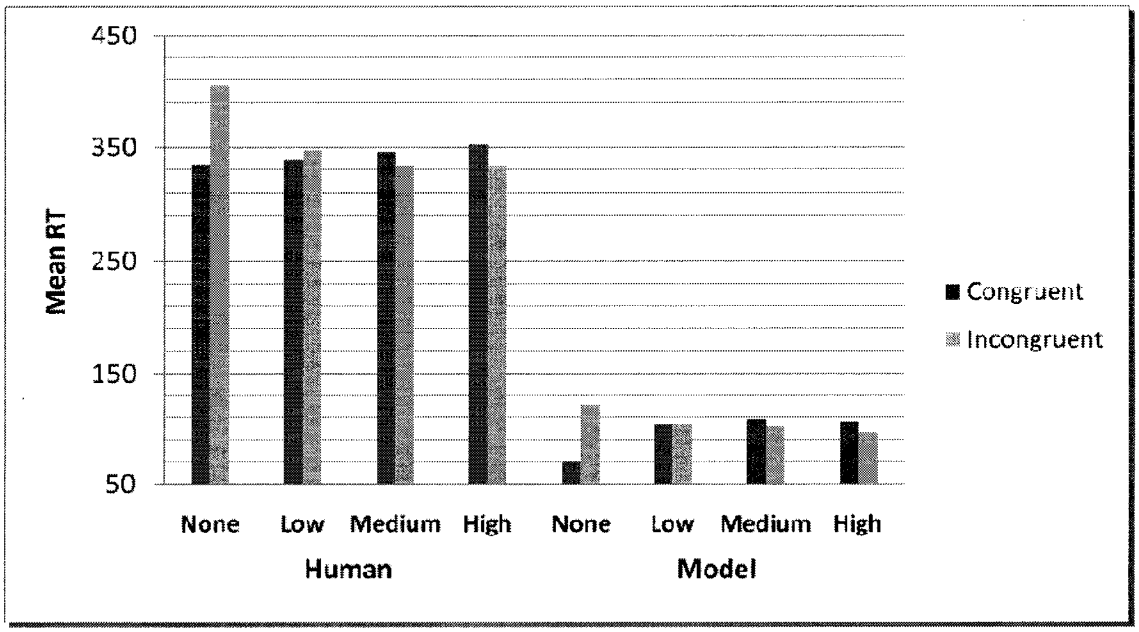


Figure 4.28. Four levels of mask density: 1 (no mask), 2 (low), 3 (medium), and 4 (high), simulated by mask unit's activations 0, .45, .55, and 1 compared to masks with ≥ 15, 10, 5, and 0 random lines in human data, respectively (Eimer & Schleghecken, 2002, Exp. 1).

Simulation 7b: Mask relation (similarity or feature overlaps)

As discussed in Chapter 1, the mask not only is not neutral but also has an important role in priming effects, especially NCE. A small or no NCE has been found if mask is not relevant (or is not similar) to the prime or target and conversely an increase in NCE has been found by using a mask relevant (similar) to the prime or target (Lleras & Enns, 2005; see also Lleras & Enns, 2006; Bennett, Lleras, Orient, & Enns, 2007). I assume that this is especially caused by overlaps of the semantic and physical features of the mask and other stimuli (especially the prime) causing stronger representation and/or larger attentional modulation. In the model, the similarity of the mask to the prime and target were simulated by recurrent excitation from the mask to the prime and the target. This parameter was .75 (intended as medium) for all simulations but here two other levels were also employed to show the role of mask similarity or relation: .65 for irrelevant or less similar mask and .85 for more relevant or more similar mask. The IL-RL strength for the prime and target were 2.5 and the mask-target SOA was 125.

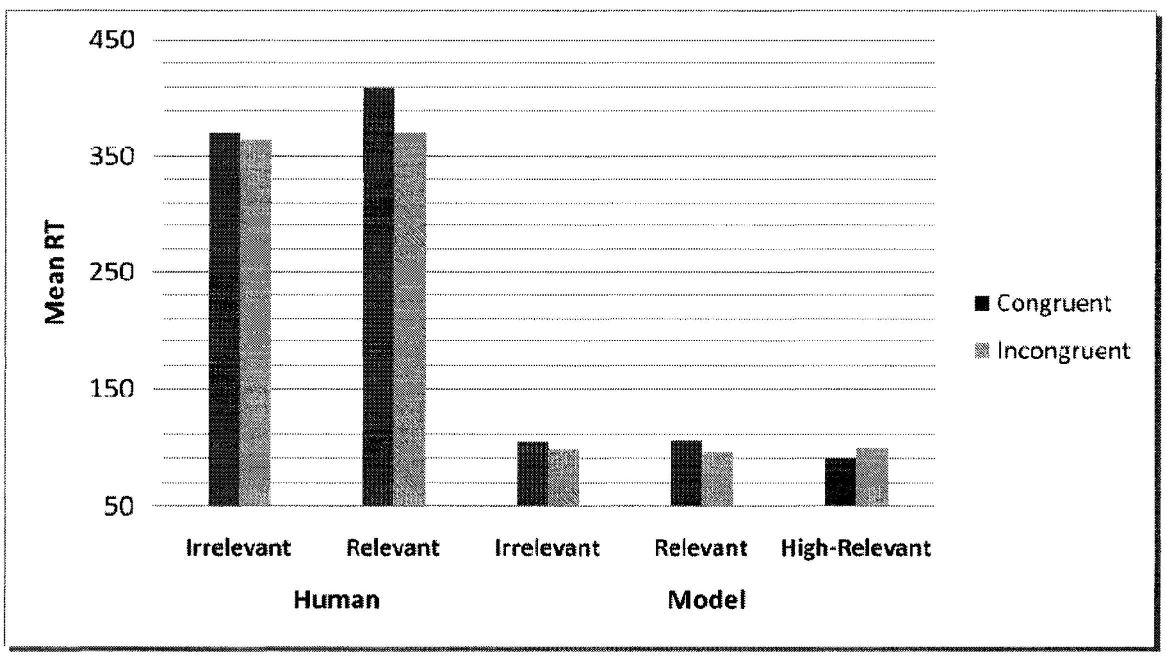


Figure 4.29. Mask relation simulated with three levels of excitation: .65 (irrelevant), .75 (relevant), and .85 (high relevant) compared to irrelevant and relevant masks in human data (Lleras and Enns, 2005). No human data for high relevant mask.

As can be seen in Figure 4.29, while medium mask similarity caused NCE in this condition, less similar mask caused less NCE and more similar mask caused PCE and slightly decreased RTs, as expected. While decreasing mask similarity makes NCE smaller, its increase causes larger NCE to some degree then turns it to PCE. However, this pattern would be different for other conditions, for example at different SOAs. Other processes may also be involved, such as an effect on CL and ML, not included in the current model.

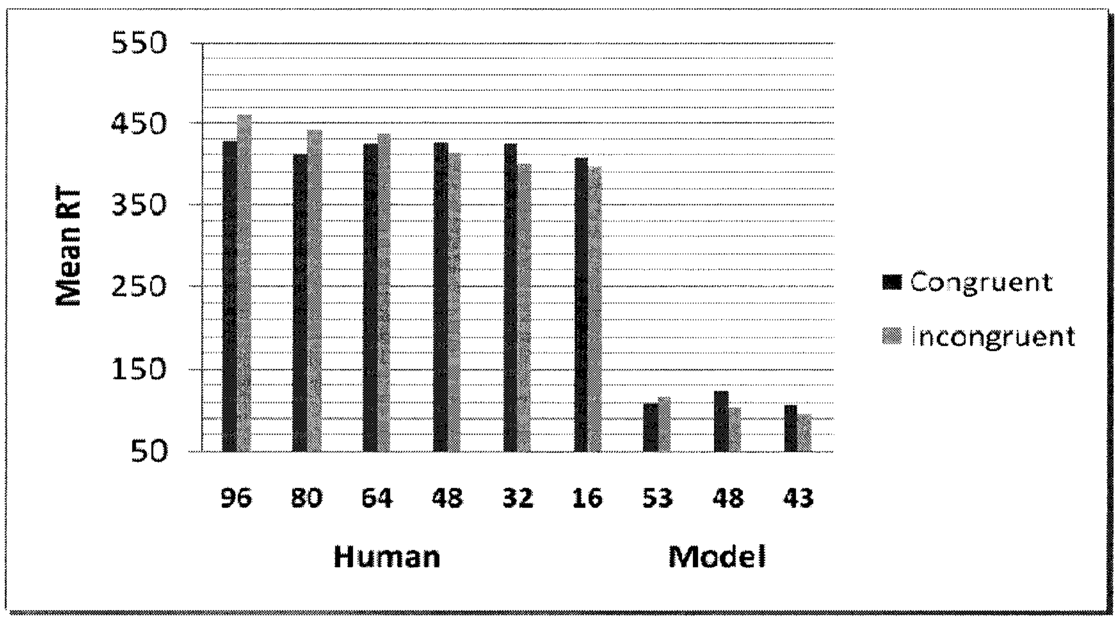


Figure 4.30. Simulation results for three levels of prime duration: 53 ms (long), 48 ms (medium), and 43 ms (short), to compare with 96, 80, 64, 48, 32, 16 ms in human data (Eimer & Schleghecken, 2002).

Simulation 8: Prime duration

Prime duration has an obvious role in priming, stimuli with longer duration have stronger representation and also activate more attentional responses. It has been shown that increasing the prime duration increases NCE to some extents and changes it to PCE after a specific rate, controlling other factors (Eimer & Schleghecken, 2002). The current simulation shows the priming effects for three prime durations: 43, 48, and 53. The IL-RL strength for the prime and target were 2.5 and the mask-target SOA was 125.

As shown in Figure 4.30, increasing the prime duration caused larger NCE, but further increase turned it into PCE, like other factors in the match of representation strength framework. Interestingly, increasing the prime duration does not decrease RTs and even has an opposite effect, something that has also been found in human data (e.g., Eimer & Schleghecken, 2002, Exp. 2). Decreasing the duration decreases NCE and eventually can make the priming effect disappear. NCE with shorter duration can only be found with stimuli that have strong representations, as the NCE has been found mainly with arrows.

Simulation 9: Interaction between prime and target strength and SOA

This simulation shows the interaction between mask-target SOA and the prime and target weights (strength), as the two main factors in changing priming direction. Among different combinations of the prime and target strengths, four were chosen, 2.5-2.5, 2.5-3, 3-2.5, and 3-3, and their NCE sizes were assessed at two mask-target SOAs; 105 and 125. The results are shown in Figure 4.31 and 4.32. At SOA 105, the largest NCEs are found in trials with medium or strong prime strength but only with medium target strength. At a slightly longer SOA (125), the trials with strong prime, medium target still have highest NCE but now the trials with strong prime and strong target have higher NCE than those with medium prime, medium target strength. A decrease in NCE with stimuli with weaker representation (non-arrow shapes mapped to left and right direction)

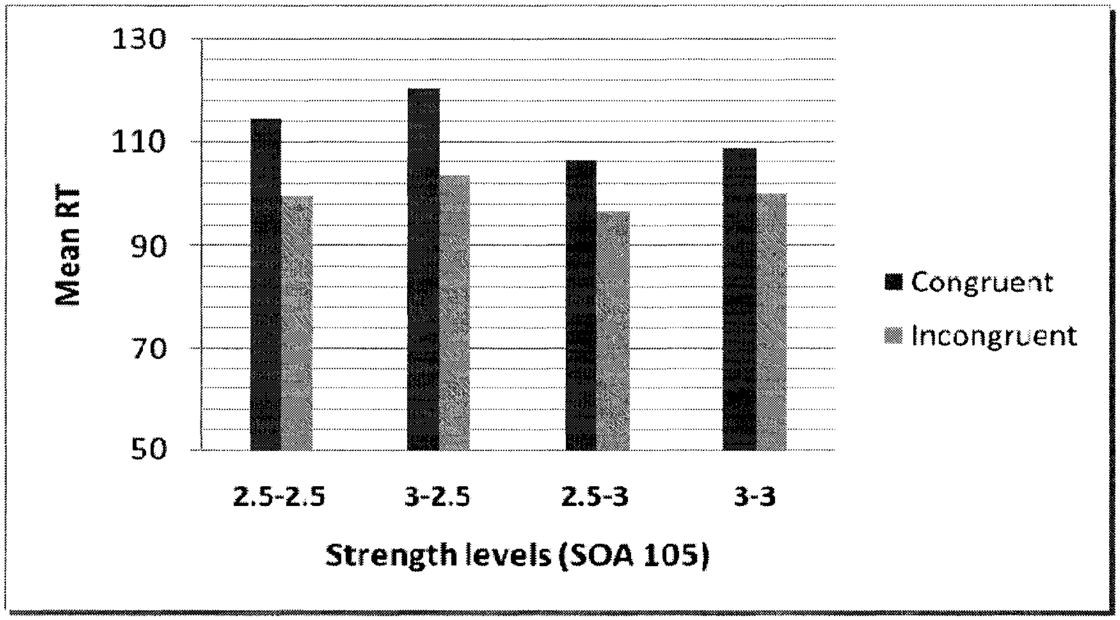


Figure 4.31. Interaction between SOA and prime and target strength at mask-target SOA 105.

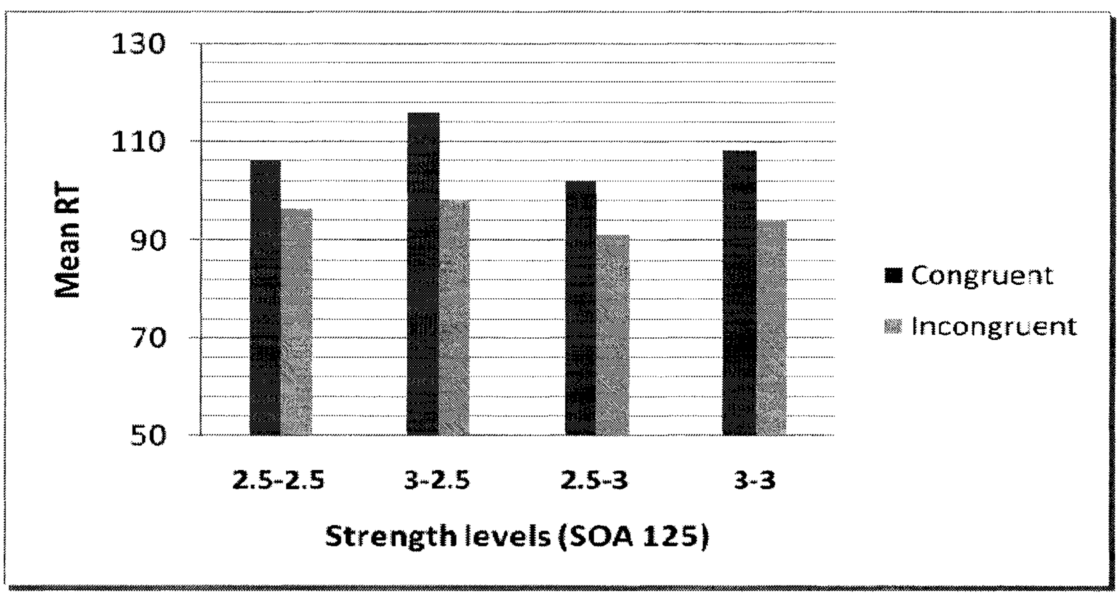


Figure 4.32. Interaction between SOA and prime and target strength at mask-target SOA 125.

compared to those with stronger representation (arrows) has been reported without explanation (Jaśkowski & Ślósarek, 2006). Here, the model shows this pattern because strong stimuli cause more attentional refraction (although other processes may be involved too).

Simulation 10a: Prime duration and brightness and the effect of attention

It has been shown that spatial attention can change priming effects (Schleghecken & Eimer, 2000; Summer et al., 2006). Sumner et al. employed Eimer and colleagues' paradigm and found that while changes in prime duration and brightness ("perceptual strength") can change the direction of priming, cuing the prime increases the size of both

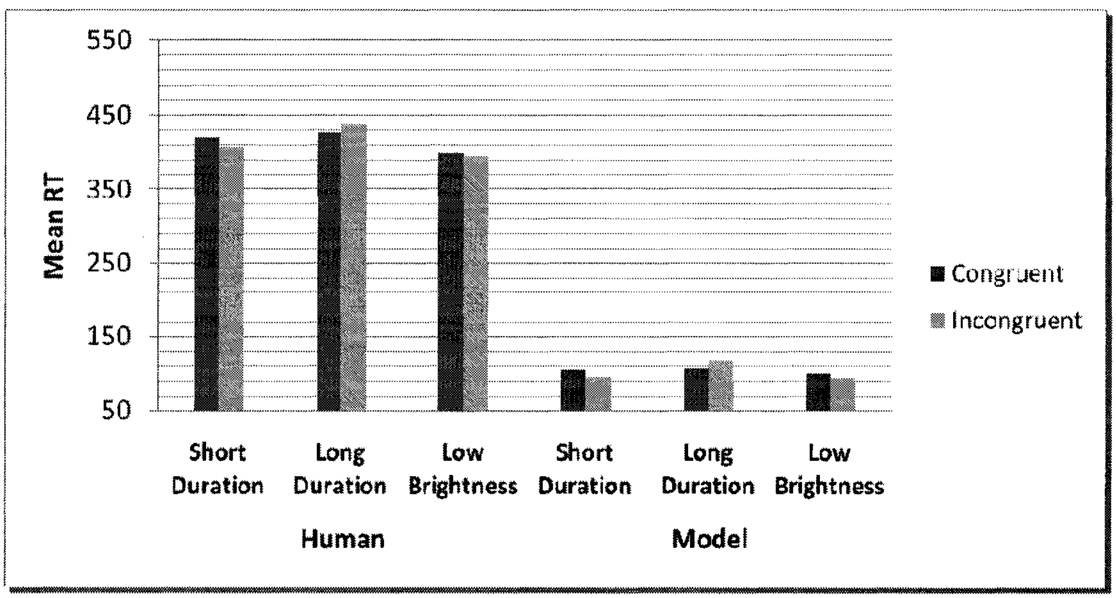


Figure 4.33. No spatial attention condition: The three conditions of no OA attention include two prime durations, short and long (43 and 53 with medium brightness, implicitly by having medium prime weights 2.5) and one brightness level (low, i.e., prime weight 1.5 with long duration prime) all with target weight 2.5 and SOA 125.

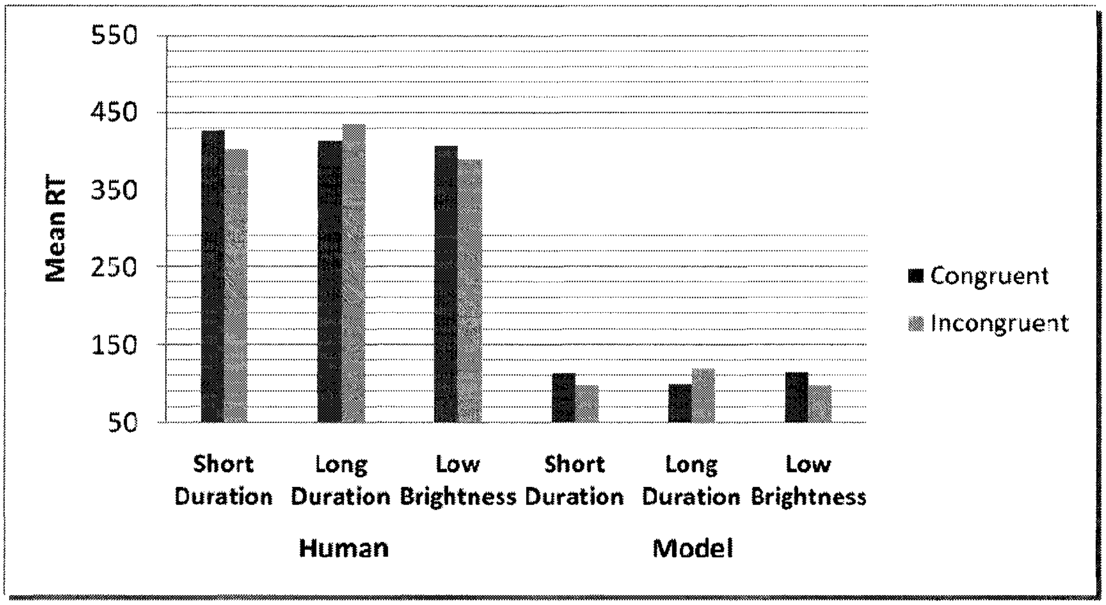


Figure 4.34. Spatial attention modulatory effect on priming: The three conditions include two prime durations, short and long (43 and 53 with medium brightness, implicitly by having medium prime weights 2.5) and one brightness level (low, i.e., prime weigh 1.5 with long duration prime) all with target weight 2.5 and SOA 125.

priming effects (PCE and NCE), not simply changing one pattern to the other. Similar to the effect of target cuing, as in Simulation 4, here attention to the prime (OA attention) was simulated by activating OA for 20 cycles but from the onset of the prime. However, here the activation of AA by the cue was not simulated, as the interval between cue and the prime in the experiment (Sumner, 2006) was too short (50 ms), causing no refractory period (but see simulation 4). To simulate the interaction between orient attention and prime duration, two prime durations were used, 43 and 53 cycles. To simulate the interaction between orient attention and prime brightness two weight levels of prime representation (like other simulations, between IL and RL layers) were used: 2.5 and 1.5 both with a target weight of 2.5 (at mask-target SOA 125). The simulation results of prime duration and brightness for no-cue (Figure 4.33) and cue (Figure 4.34) (see also Figure 4.35) showed a modulatory effect of orient attention on priming effect similar to human data (Sumner, 2006).

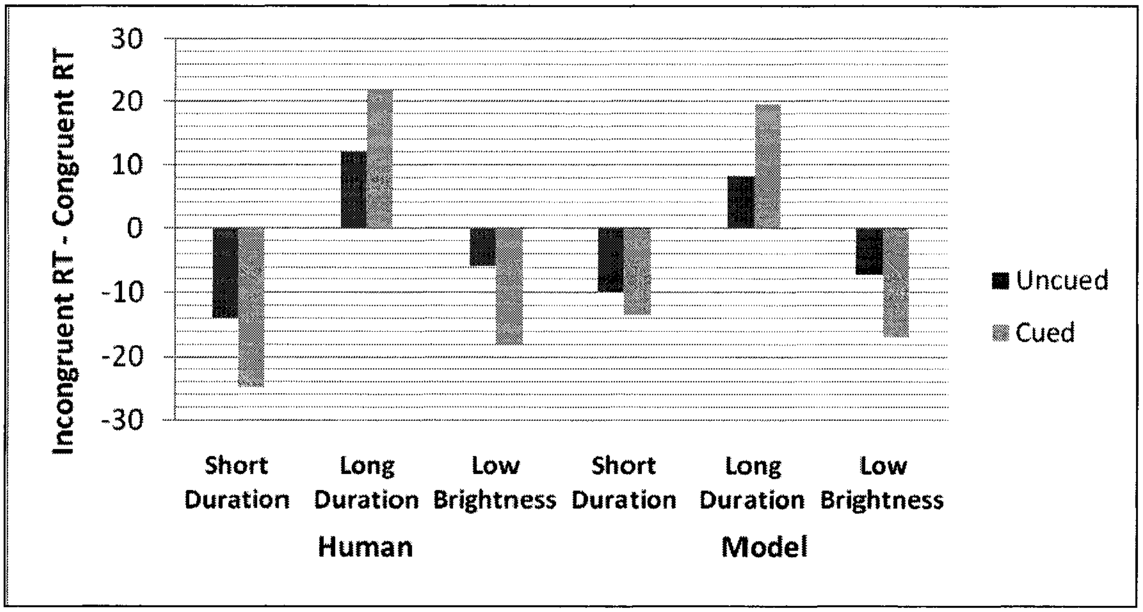


Figure 4.35. RT difference (Incongruent - Congruent) in the spatial attention modulatory effect on priming (see Figure 4.33) compared to no effect (see Figure 4.34).

Simulation 10b. The effect of orient attention on the target at mask-target SOA 105 ms

To show the cuing effect on the target (with a longer SOA compared to simulation 4), the current simulation was run. Here the mask-target SOA was 105 and the strength was 3-3. The result is shown in Figure 4.36. The OA attention to the target (20 cycles form the onset of the target) decreased the NCE and RTs (especially in the incongruent condition). This result seems to be related to the effect of cuing on second target (T2) report in attentional blink. It has been shown that cuing the target can reduce the attentional blink (Nieuwenstein et al., 2005). It seems that attention evoked by the cue makes T2 strong enough to skip the attentional blink, as it decreased the NCE by increasing the strength of the target in this priming paradigm.

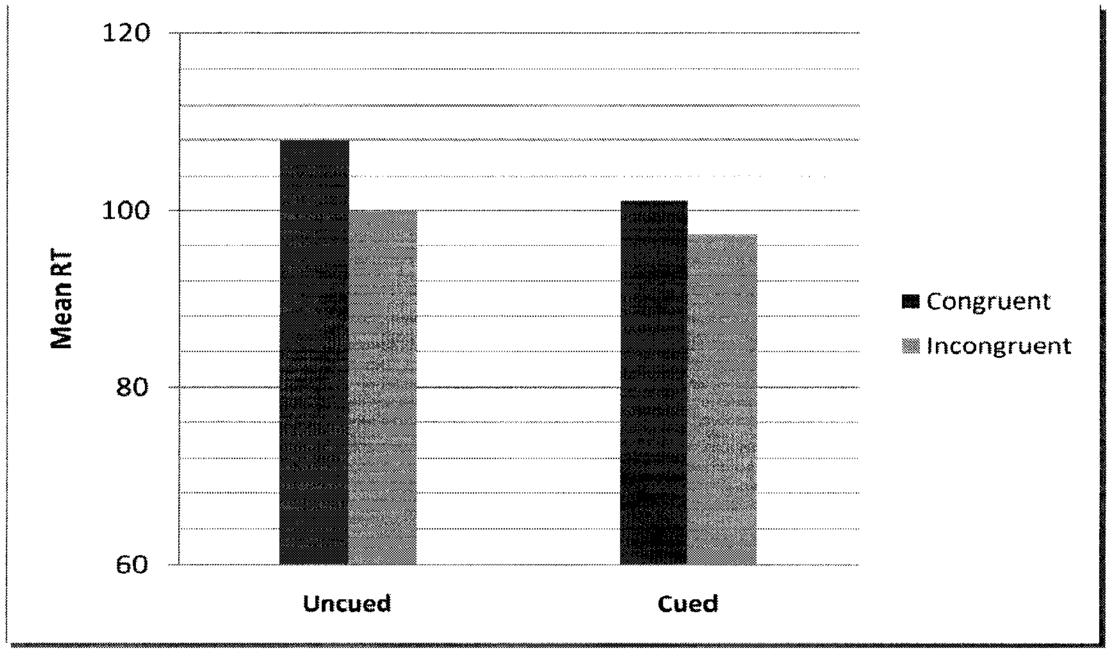


Figure 4.36. Orient attention to the target. The prime and target strength was 3-3 and the mask-target SOA was 105 (compared to no attention).

Simulation 11: Unmasked priming with relevant prime

As mentioned in Chapter 1, a relevant unmasked prime causes larger PCE and NCE at short and long prime-target SOA, respectively. A few studies have previously shown an NCE in the unmasked condition. Here it is assumed that this effect was found in those studies because they used a medium (Koechlin et al., 1999) and long (Jaśkowski, 2007) prime-target SOA, and especially the tasks required action on (which requires attention too), or attention to, the prime, respectively. In the former, especially because of controlling physical repetition priming (and an action on the prime was required as on the target), and in the second, especially because of prime relevance (participants were told that prime highly predicts the target), the NCE was large. It could be caused by the strong refractory period created by attention to the unmasked prime. To simulate this phenomenon, in this simulation the prime was unmasked and AA mode for the prime was put in the high phasic mode (*c=3*), as with simulations of masked conditions.

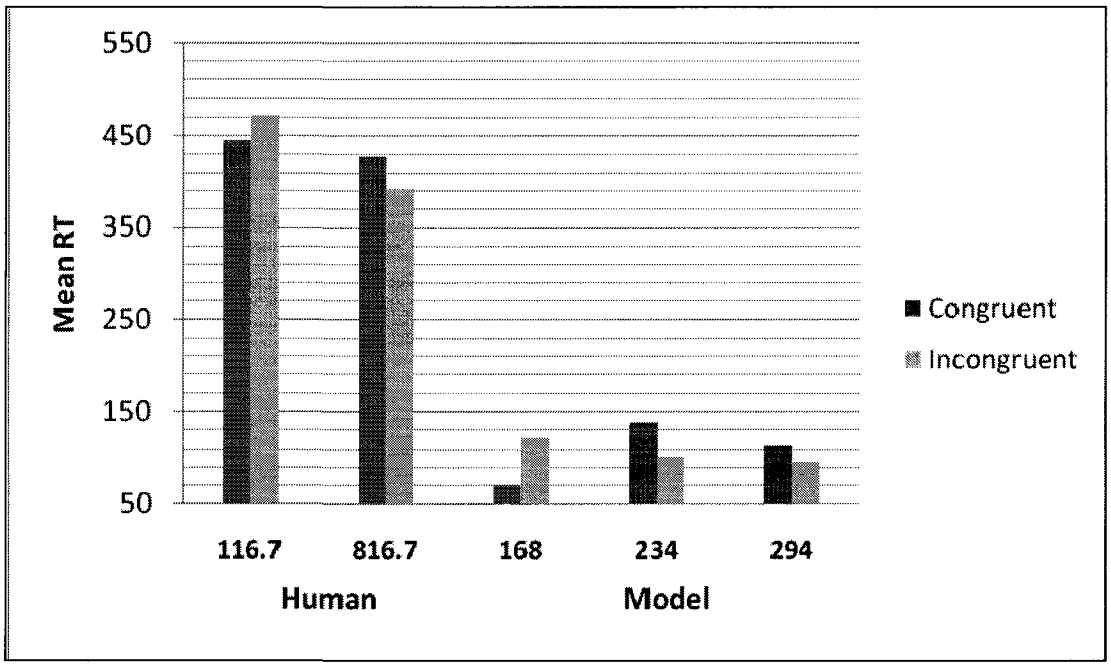


Figure 4.37. Unmasked but relevant prime at 168, 234, and 294 prime-target SOAs, indicated by 1, 2, and 3, respectively, compared to 116.7 and 816.7 SOAs in Jaśkowski (2007), indicated by 1 and 2, respectively.

To create the short and long prime-target SOA conditions, a relatively short SOA (168) and two relatively long SOAs (234 and 294) were used with prime and target strength 2.5. As shown in Figure 4.37, a strong PCE was found at prime-target SOA 168 and a strong NCE was found at SOA 234 and 294. At prime-target SOA 234 (i.e., mask-target SOA 191 in masked condition), only a small or no NCE was found for the masked condition with the same parameters (see Simulation 5a, b). In the unmasked condition, in the current simulation, NCE remains high with a further increase in SOA but it decreases slowly. The results in Figure 4.37 show a change from PCE to NCE and a drop in RTs, similar to the human data. However, the SOA in the long condition in Jaśkowski (2007) is much longer than the long conditions in the current simulation, due to a limited time course in the model, as the parameters were set for a short trial.

Discussion

Consistent with the human data in the experiments, the model showed both PCE and NCE by manipulating specific factors. The main factor, the strength of stimulus representation, was implemented simply by changing the weights between input and representation units (i.e., IL to RL), while the weights between representation and response units remained fixed (i.e., RL to ML). When the prime and target were easy, they could be processed mainly with the initial attentional response. When they were harder (as with lower prime and target strength in Simulation 3) or when a delay was introduced between them (as with longer mask-target SOA in Simulation 5a), the second phase of attention (for the target) was not strong enough to activate the target quickly. This happened because attention showed a phasic response with a refractory period. The conflict was measured based on the incongruency in the stimuli relationship. It decreased the effect of this refractory period by putting the second phase of attention (to the target) in a less phasic but a longer duration mode, enhancing the processing of the incongruent trials where conflict occurred (but not the case in the congruent trials). When both prime and target were hard (i.e., by having low strength weights) the priming pattern was inverted (NCE). In other cases when prime or target or both were easy (having higher strength weights), the priming was PCE.

Moreover, the NCE from Eimer and colleagues' paradigm was simulated by increasing mask-target SOA, with no other changes in the model. A PCE and an NCE were found with short and long mask-target SOA, respectively. The model also showed the effects of other factors on priming directions such as prime duration, cue attention, stimulus degradation, brightness, mask density, and similarity of the mask to the prime and target, all proposed to involve the match of representation strength as the main construct. For example, a prime or target with longer duration, less degradation, higher brightness has a strong representation that causes a large PCE if the target comes early and a large NCE if it comes late.

The difference between masked and unmasked was simulated by assuming that an irrelevant prime causes less phasic activation in alert attention to the prime, similar to the effect of conflict on the target. In the unmasked condition, when the prime was relevant, it caused phasic activation similar to a masked prime. Because there was no interruption by the mask, in the relevant unmasked prime condition, a PCE was found for short prime-target SOA. In this case, the PCE was large, consistent with the unmasked condition in Experiment 2 and, especially, Jaśkowski (2007). With an irrelevant unmasked prime, the PCE disappeared, consistent with the unmasked condition in Experiment 1. At longer prime-target SOA, the relevant unmasked prime caused an NCE even larger than an equivalent masked condition, consistent with Jaśkowski (2007).

Interestingly, the conflict period caused by an unmasked incongruent prime (in all unmasked conditions) was longer than that of masked incongruent prime (see Appendix D).

Researchers have pointed out the differences between masked and unmasked conditions and some of them have taken these differences as evidence of a fundamental difference between the so called unconscious and conscious states (e.g., Klapp & Hinkley, 2002; Eimer & Schleghecken, 2002, Breitmeyer et al., 2005; but see Verleger et al., 2004; Lleras & Enns, 2004, 2006). For example, as described in Chapter 1, Breitmeyer et al. attributed the difference in priming caused by prime duration to its visibility not duration *per se*, while the model showed that the duration (and unmasking) causes big changes in the priming direction. Lleras and Enns (2006) showed that changes in the priming effect have no straight relations to the visibility of the prime. Therefore, previous studies have not shown reliable differences between reportable and unreportable primes.

The model also showed that decreasing the activation of input units (e.g., from binary, 1 and 0, to real normalized numbers, .9 and .1, or less, for simulating stimulus degradation) turns NCE into PCE. This supports the idea that the NCE is not caused merely by a decrease in the incoming perceptual information but by a decrease in the representation strength, i.e., connection weight, especially in intermediate layers (that are neither input nor motor). The involvement of an attentional bottleneck in the decisional rather than perceptional processes has been proposed previously (Sigman & Dehaene, 2005).

The role of attention was simulated using modulatory effects, not simply additive, consistent with experimental studies (e.g., Schleghecken & Eimer, 2000; Summer et al., 2006). As described earlier, the attentional modulation, to some extent, increases the size of large activations and decreases the size of small activations (i.e., rich gets richer and poor gets poorer). The interaction between attention and conflict was assumed to be part of executive attentional control, though executive functions are broader than the way I treated here. The simple way I chose to implement conflict was not meant to represent all the processes in executive functions. However, its two-state nature, while simple, is relevant to the binary or rule-based processes of executive functions, especially in PFC (e.g., O'Reilly, 2006).

The biological plausibility of the model was previously noted by some neuroscientific evidence from previous studies. Moreover, the neural dynamic in the model is similar to ERP data in Eimer and colleagues' paradigm (for a review see, Eimer & Schleghecken, 2003), with an earlier neural activation dominance in the congruent condition and a later dominance of the incongruent condition in motor responses (reflected as NCE, see also Appendix D, especially Figure 2). Furthermore, the role of conflict has been supported by the previous studies (e.g., Carter, 1998, Botvinick et al., 2001; Dehaene, Artiges, et al., 2003; van Veen & Carter, 2005). The changes in priming effects have been shown in diseases such as Parkinson's (Seiss & Praamstra, 2004, 2006; Praamstra & Seiss, 2005) and schizophrenia (Dehaene, Artiges, et al., 2003).

Compared to the previous models of priming (e.g., Bowman et al., 2006), the current model, in addition to being more biologically compelling, shows many dynamic effects in RT and error patterns that have not been shown previously (such as the changes in RT and the size of priming effects through time). While in the current model the NCE disappeared and became a very small PCE at very long SOAs, Bowman et al.'s model showed a huge PCE at very long SOAs inconsistent with human data (e.g., Jaśkowski & Ślósarek, 2006). The NCE was simulated without a specific motor self-inhibition, unlike Bowman et al.'s model (for another model based on motor inhibition, using conflict monitoring, see Sohrabi et al., 2006; and also Appendix F, Part 7).

In Bowman et al. (2006), mask only plays a role through negative cross-talks (i.e., reciprocal feed-forward inhibitions) between input units (mask, prime, and target). However, a good mechanism for masking is lateral inhibition (Rolls & Tovee, 1994), used in the current model. Their model uses lateral inhibition between units in the response layer, but not in the perceptual layer. In addition to lateral inhibition, the current model simulated the relation of the mask to the prime and target through recurrent excitation from mask to the prime and target. This can be imagined as the featural and semantic relationships between these stimuli. The mask gets meaning through its relation to the prime and target. If it is similar to those stimuli, it can activate the prime because it comes right after it. So, the mask acts partially like the prime and increases the attentional responses to the prime, making it stay longer. On the other hand, if its similarity with prime and target decreases, its inhibitory effect dominates and interrupts the prime, causing it to decay faster.

Bowman et al.'s (2006) model included a mechanism called opponent processing or OFF node. The OFF node accumulates activations coming from response units, then it inhibits back the response units. The mask causes this inhibition to be reversed, by removal (or interrupting) of sensory evidence for the corresponding response and initiating its suppression. As they put it, this motor self-inhibitory mechanism is "arising from a low-level emergency break mechanism … because removal of sensory evidence for a particular response causes the (already) build-up OFF node activation to be released" because of no more bottom-up excitation. If there is no mask, the stronger activation in response units compensates inhibition coming from the OFF node.

While Bowman et al. (2006) showed an effect of strength in their model, their approach differs from the one here. First, they only dealt with prime strength. Second, by strength they meant the amount of sensory information. Their only evidence is the degradation experiment (Shleghecken & Eimer, 2002), so they treated high degradation as low strength. Third, in fact from their paper it is not clear how they have implemented the strength. In the current model, degradation was simulated by less incoming information (and higher noise) and the strength was implemented by connection weights between input and representation layers for both prime and target. The strength and other activations such as attentional activities and self-excitation all affected the overall unit activations, considered as the match of representation strength, as they increased the activation of one alternative against competing ones.

Bowman et al.'s (2006) model also shows no error responses. The current model showed early error RTs (i.e., errors with short RTs) mainly in the incongruent condition and missing trials mainly in the congruent condition, matching the error RT patterns in the behavioural results (Appendix C). In the behavioural data, the lower number of errors (and slower error RTs), found in the unmasked more than masked condition, could be the result of a less phasic attentional response to the prime. However, the process involved in this case should be rather dependent on between-trial or contextual learning, not implemented precisely in the model for the sake of simplicity. This may be relevant or equivalent to dynamic or strategic changes in the response threshold here for the prime (see Ratcliff, 2006).

While the current model showed some responses that are considered as errors, more studies are needed to find a better error measurement. As mentioned earlier, in the case of missed responses, human participants probably randomly pick one of the two alternatives in the case of missed responses by the deadline. The error trials in the current experiments had slower RTs for the congruent compared to the incongruent trials (except Experiment 1, where only a few errors occurred). This is consistent with the model, in that it showed more missed responses in the congruent compared to the incongruent trials, especially when the effect was an NCE, and conversely, more early errors in the incongruent compared to the congruent trials, especially when the effect was a PCE. The missed trials were caused by inability to reach the response threshold by the response deadline. This happened mainly in the congruent trials because the refractory period was decreased by the conflict in the incongruent trials. I simply assumed that 50% of missing trials (and presumably pre-hits) turn into errors eventually. This has been shown to be a good measurement for error patterns in LCA models (Ratcliff, 2006).

Fast error RTs were caused by early wrong responses to the incongruent primes, because congruent primes led to correct responses (pre-hit), not errors. Correspondingly, Ratcliff and Smith (2004) have shown that fast error RTs occur when a fast response is required and, in contrast, slower RTs occur when accuracy is emphasized. The classic model of two-choice decisions in psychology assumes that a decision is made between two alternatives when the accumulated evidence in favour of one of the two alternatives crosses a threshold (Vickers, 1970). Another group of models in psychology and information theory, known as diffusion models (e.g., Ratcliff, 2006), assumes that a decision is made when the difference between the evidence for a dominant option and the evidence for the other alternative reaches a threshold. The LCA model (Usher & McClelland, 2001) is a biologically inspired model similar to diffusion models. It assumes that noisy information is integrated through time from a starting point toward one of the two decision boundaries. In a standard RT experiment, when the accumulated information crosses a threshold, a response is triggered. In a response signal experiment, a response is required at a specific time or even before activation reaches the threshold. As noted by Ratcliff (2006), in the LCA model, each response has an accumulator with a decay rate and mutual inhibition from the other accumulator. The LCA model, without between-trial variability, shows errors to be slower than correct responses. At the time of a response cue, either a decision has been made or it has not. In a fast trial and at cue presentation, either decision is made based on partial information or by a guess. Ratcliff (2006) showed that the latter case fits the data better than the former, consistent with the current model.

Chapter 5: Discussion

Review of the current findings

The experimental findings

The main finding of the behavioural data in Experiment 1 was a PCE, i.e., better performance for congruent compared to incongruent trials, in the masked condition with both non-illusory and illusory lines. However, in the unmasked condition, there was no priming effect. The prime and target lines were different in two aspects. First, the prime lines had arrows both in illusory and non-illusory conditions. Second, the lengths of the two parts of the lines were different, even in the congruent condition. Therefore, unlike most previous studies, here the PCE was found without including repeated stimuli in the congruent condition. The fMRI results showed a widely spread activation for the unmasked condition compared to the masked and a higher activation for the illusory compared to non-illusory condition (caused mainly by the unmasked illusion).

Experiment 2 tested the symbolic representation using numerals and arbitrary assignment of symbols to numbers. In this experiment participants were faster in the incongruent than in the congruent trials in the masked condition, showing an NCE. Experiment 3 consisted only of masked trials. It revealed that distance plays a role in numerical decision-making with recently learned symbols. This effect had already been found in comparison and priming with Arabic numerals and words for number. This experiment tracked the NCE effect to an additive role of distance and target type, as only one distance level (close prime and close target) reached significance in this experiment. When the distance of both prime and target was close to the reference number *five*, and the target type was symbol, a significant NCE was found. Experiment 4 revealed that another important factor relevant to the target strength plays a role, namely the predictability of the target. Predictability (by cueing the target type) strongly attenuated the PCE and NCE.

Explaining the experimental findings

In the masked condition in Experiment 1, the prime (both illusory and non-illusory) affected the target and caused a PCE. This is similar to the results of previous studies that have employed other stimuli, such as colours and colour words (Marcel, 1983), shapes (Neumann & Klotz, 1994), numbers (Dehaene et al., 1998), and arrows (Eimer & Schleghecken, 1998). This PCE shows that illusory and non-illusory line length can create priming, similar to numerical magnitude (Dehaene et al., 1998). However, this PCE was not found in the unmasked condition, presumably because participants found the prime irrelevant to the task and ignored it. They were not able to ignore the prime in the masked condition, because of the presence of the mask. Previously it has been shown that using contextual strategies is possible in the unmasked but not the masked trials (Cheesman & Merikle, 1984). Higher brain activation in the unmasked condition compared to the masked in Experiment 1 supports this idea.

The main fMRI results were a widely distributed activation for the unmasked condition compared to the masked, similar to the effect of reportability in the attentional blink (e.g., Feinstein et al., 2004; Kranczioch et al., 2005). The results also showed brain activations as an index of the unmasked illusion, found in the IFG and dl-PFC, proposed to be involved in inhibition and control (e.g., Aron et al., 2004; Brass et al., 2005). The involvement and even necessity of these areas do not rule out the role of other areas in those processes, and their higher activations compared to other areas do not imply that they are sufficient for a given function (for a discussion see, Sohrabi & Brook, 2005). Most cognitive processes are dependent on interconnecting areas throughout the brain. However, some areas have a more crucial role, because, for example, they have connections with a wide range of input and associative areas.

The paradoxical result in Experiment 2 and 3, i.e., a significant NCE in the masked condition (numerals priming symbols mapped to numbers), might be due to the low strength of the symbol that made the NCE when it was the target. Symbols recently mapped to numbers have weaker representation than numerals, which are over-learned stimuli (i.e., having strong representation, relatively). Recently learned symbols could involve a less straight or weaker representation in terms of both semantic representation and perceptuo-motor processing. The difference could be due to frequent exposures to, or early learning of, numerals compared to symbols recently mapped to numbers (see Appendix F, Part 2 and 3). This negative effect or NCE may also be due to delay or difficulty in the processing of the symbol target that temporarily has been memorized. This effect could cause an endogenous delay or semi-SOA that led to the negative priming in the masked condition. The effect may be related to the difference in two kinds of representations, well-learned versus recently memorized stimulus-response associations, and their interactions with the timing of stimulus presentation. An NCE already has been shown using long mask-target SOA, as discussed previously (mainly using arrow stimuli). Here, this effect was shown with short mask-target SOA (i.e., a brief mask) with numerals as prime and symbols mapped to numbers as target.

As supported by Experiment 3, another reason for an NCE to occur in the masked condition is the distance factor. The distance and type factors had an additive effect. Previous studies have mainly used repeated types (numeral prime and numeral target) or Arabic and word encoding of numbers, both being strongly represented. This could be a reason for not finding an NCE similar to the one found here (Experiment 2 and 3). Based on the match of representation strength framework, the representation type (here, symbol) and representation magnitude (here, close distance) together can cause this type of NCE.

The stronger NCE in the masked trials in Experiment 2, compared to Experiment 3, may have been caused by the presence of unmasked trials, as the two types of trials were mixed together, causing changes in attentional responses. In the unmasked condition a non-significant PCE was found that was larger than the unmasked condition in Experiment 1. One reason for this result may be that the prime in this experiment was not so completely irrelevant as to be ignored easily, because it could help in predicting the target type even in a single trial (the numeral prime followed by a symbol target and the symbol prime followed by a numeral target).

As we just said in connection with distance and target type, a weak target representation increased NCE and a strong target representation increased PCE. Inclusion of the predictability factor in Experiment 4 again supported the role of target strength. The target type (numerals or symbols mapped to numbers) could be predicted by the relevant cue, therefore, NCE (supposed to occur with close numeral prime and close symbol target) decreased and was no longer significant (while it was significant in Experiment 3). As shown by the model, target strength was increased in a variety of ways. In the model, symbol type was given a weaker connection weight than numeral type, similar to close vs. far distance. The cuing of the target type is assumed to increase the target strength and hence to decrease the NCE. As supported by the model, it seems that the attentional modulation by the cue in this experiment enhanced target processing by compensating for the refractory period and decreased the prime processing by creating a refractory period for it, leading to a decrease in NCE and even in PCE, respectively.

Findings from the model

The model simulated several behavioural results, including the role of the prime and target strength, masking effect (the difference between masked and unmasked), degradation effect, relation of mask to the prime and target, prime duration effect, prime-target SOA, and other effects. The attentional response mode for the prime simulated the relevant and irrelevant prime (in the unmasked condition) by higher and lower attentional responses to the prime, respectively. The conflict caused by the incongruent prime and target changed the attentional response to the target and played a main role in changing PCE to NCE (by interacting with the refractory period). This conflict was higher in the unmasked than the masked condition, paralleling the higher brain activation in the unmasked compared to masked condition in Experiment 1.

When both prime and target were weak, an NCE was found even with a short mask. When the prime or the target or both were strong, a PCE was found. However, when the mask-target interval was long, an NCE was found. This NCE was found for weak and strong stimuli but there was an interaction between mask-target SOA and the strength of prime and target. A strong prime caused a long lasting PCE initially, but caused more activations and hence a stronger refractory period that later led to an increase in NCE. The cue attention to the prime and the target increased and decreased the NCE, respectively, by increasing the match of strength representation. However, when the cue came long before the prime, it caused a refractory period and weakened the prime representation, hence decreased priming effects. The degradation of the stimuli decreased activation of, and competition between, alternative units, therefore turned the NCE into PCE. Although the mask had no direct effects on the motor and attentional response, it played a role by acquiring meaning through excitation of the prime and target. When it was similar to the prime and target (simulated by more excitation), it increased NCE but turned NCE into PCE with further increases in excitation. Prime duration increased prime activation and caused a huge refractory period when the target came relatively late. Increasing the prime duration increased the NCE but further increases turned the NCE into PCE. In general, stronger primes (e.g., using higher weights, less degradation, relatively higher excitation from the mask, higher spatial cue) caused a long-lasting PCE initially, but caused more activations and hence a stronger refractory period that led to a large NCE later in time.

Relation to other studies

Relevant experimental paradigms

The result of the current study and other studies on masked and unmasked priming (e.g., Marcel, 1983; Dehaene, Artiges, et al., 2003; Breitmeyer et al., 2005), attentional blink (e.g., Sergent and Dehaene, 2004; Feinstein, 2004; Kranczioch et al., 2005), and binocular rivalry (e.g., Williams et al., 2004) all support similarities between priming and other attentional effects. Attentional blink has been attributed to the time needed to consolidate a stimulus in short-term memory. It has been shown frequently in the attentional blink paradigm, as described in Chapter 1, that about half a second has to pass before being able to report another stimulus. It is thought that this bottleneck phenomenon occurs at the time of response selection especially when there are competitive task responses (Pashler, 1994a, b). Learning and strategy can reduce this bottleneck but neither the nature of the bottleneck nor its reduction by practice or over-learning has been explained (Marois & Ivanoff, 2005, but see, Nieuwenhuis, Aston-Jones, & Cohen, 2005; Nieuwenhuis, Gilzenrat, et al., 2005). In this thesis, the dynamics of the attentional resource as a main basis for the attentional limitation was related to the priming effect. Conflict reduced the refractory period of the attentional resource and this played a role in the priming direction in the model. The relationship between conflict and attention in other cognitive processes has been studied previously (e.g., McClure et al., 2005). However, previous studies have not investigated the conflict within a trial (between prime and target).

Attentional control occurs during a top-down interaction of PFC with other areas especially the brainstem, but it is not clear if attention is necessary for consciousness and if it precedes or follows consciousness (Maia & Cleeremans, 2005; Koch & Tsuchiya, 2007; but see Dehaene, Changeux, Naccache, Sackur, & Sergent, 2006). Dehaene et al.

(2006) argued that attention is necessary to bring strong stimuli to the level of conscious report, otherwise the stimuli remain in a "preconscious" state with no access to consciousness.

It is a difficult task to attend to more than one object at a time. This effect is known to be a result of the psychological refractory period or bottleneck because cognition has a limited capacity (e.g., Pashler, 1994a, b). Recent neurophysiological and modelling studies have shown the relationship between this bottleneck and the refractoriness of LC activities because of its self-inhibitory mechanism (Aston-Jones et al., 1994; Usher et al., 1999; Aston-Jones, & Cohen, 2005; Gilzenrat, et al., 2002; Nieuwenhuis, Gilzenrat, et al., 2005).

The role of target strength in NCE shows similarity between priming and attentional blink especially the role of attentional resources in these two phenomena. It has been shown that strong targets skip the attentional blink (e.g., Nieuwenstein et al., 2005). Similarly, in the current experimental paradigm and model, the NCE was not found with a stronger target, i.e., numeral versus symbol, and cued versus non-cued. Further evidence was found in the model where the stronger target was simulated by a stronger connection and/or attention, or cuing. The effect of cue on the target in the current model and experiment (Experiment 4) decreased NCE. Similarly Nieuwenstein et al. (2005) found that cuing the target reduces the attentional blink. Furthermore, the NCE found in the current simulations (5a, b) of Eimer and colleague's paradigm did not happen in short prime-target SOAs (where PCE occurred) similar to the absence of attentional blink in the short interval between T1 and T2, known as lag 1 sparing. By contrast, in longer SOAs, the size of NCE and the RT in general decreased, similar to the U-shaped curve in the attentional blink (see Chapter 4).

Moreover, as shown by the model and consistent with previous experimental studies using Eimer and colleagues' paradigm, a strong prime (i.e., arrow) in a short prime-target SOA condition enhances the performance on the target (causing a large PCE), but at a longer SOA, it decreases the performance on the target (causing a large NCE). Interestingly, this effect also occurs with unmasked primes (see Simulation 11) if the prime is relevant to the task when it is explicitly told to the participants (Jaśkowski, 2007). This effect is also similar to the fact that an attentional blink mainly occurs with relevant primes, especially because the prime is usually reportable though it is masked briefly. The model showed that when there is a higher attentional response to a prime, it causes a stronger refractory period, and hence a larger NCE. These findings support the involvement of a similar attentional process in priming and attentional blink (see next section).

Other relevant models

The model is similar to some other previous neural models, especially those used to simulate the Attentional Blink (AB). In the early days, some theorists claimed that classical connectionist models were structured more like brain mechanisms than other models. These theorists initially ignored the importance of top-down and recurrent interactive connections (e.g., Rumelhart & McClellands, 1986), which are considered to be the prerequisite for consciousness (e.g., Baars, 1988; Crick & Koch, 1998; Dehaene & Naccache, 2001; Maia & Cleeremans, 2005). However, recent models try to take into account the top-down control and modulation in the brain (e.g., Cohen, Braver, & O'Reilly, 1996; Botnivick et al., 2001), still not having much to do with consciousness (but for conscious reportability as in AB, see Mathis & Mozer, 1996; Dehaene et al., 2003; Nieuwenhuis, Gilzenrat, Holmes, & Cohen, 2005). These computational models, as the developers have noted, even the most relevant models (e.g., Dehaene et al., 2003, but see Tononi, 2004) still relate to the accessibility to consciousness, not to its neural basis or its nature. A promising approach for further progress would be a combination of these methods to explore consciousness and relevant issues.

Using a neuron level neural network model, Dehaene et al. (2003) simulated conscious accessibility in tasks such as AB. As mentioned earlier, participants in AB often fail to consciously report the stimuli. Dehaene et al. employed a network consisting of single compartment spiking neurons, in a hierarchy similar to the biological model of cortical organization with both bottom-up and top-down connections (bi-directional). They compared human data from their AB experiment and data from the model and found that it was able to simulate this bottleneck processing effect, showing that target stimuli cannot be processed simultaneously.

The global workspace models of consciousness (Dehaene et al. 2003; Baars, 1988, 1997), and similar models of cognitive control (Cohen & Huston, 1994; Cohen et al., 1990; Botvinick et al., 2001) are based on interactive biased competition in which a group of neurons win, leading to a global and widely distributed state in a moment (Maia & Cleeremans, 2005), but as their developers accept, they simulate the accessibility or reportability of consciousness not the very nature of consciousness *per se*.

Nieuwenhuis, Gilzenrat, et al. (2005) employed a computational model (Gilzenrat et al., 2002) and showed that refractoriness in attentional activity might be the cause of a deficit in processing a second target and therefore the blink in AB. This model can simulate missing the target when it falls in the refractory period of the attention, resulting from a system-level dynamic interaction between processing components, as with the model in Chapter 4, not at the neural level employed by Dehaene et al. (2003). Their model investigated the accessibility to consciousness (or the reportability of stimuli) in AB (see also, Mathis & Mozer, 1996; Dehaene et al., 2003) but shares mechanisms with the current priming paradigm. In these models (especially Nieuwenhuis, Gilzenrat, et al., 2005) blink for the second target occurs at lag 2 (after 100 ms from the first target) and no blink occurs at lag 1 (if the second target is presented during 100 ms after the first target), related to NCE and PCE in the current model, respectively.

In the current model, as described in Chapter 4, the mask activation was always higher than the prime activation because it came after the prime (and therefore interrupted the prime) and it was of longer duration. Therefore, it is the mask that is seen clearly and can be reported consciously. However, because the mask was not task-relevant, it was supposed to have no direct effects on the attentional response.

Overview of the results based on the match of representational strength

I suppose that the difference between masked and unmasked conditions is due to paying attention to the prime if it is relevant and ignoring it if it is irrelevant. In priming experiments, participants are asked to respond to the target, however, they apply the task instruction to the prime as well, as shown by the priming effects. In the unmasked condition, the prime is not interrupted by the mask. In this case, it is possible for participants to pay attention to the prime (making it stronger) or ignore it (making it weaker) based on the contextual information or instruction (as shown by Jaśkowski, 2007, see Simulations 1, 2, and 11).

The current model and experiments showed that other factors can increase the representation strength. These factors include salient physical features such as long duration, less degradation, brightness, and so on, and similarly, semantic features such as notation (e.g., Arabic vs. symbol encoding) and numerical magnitude and all increase PCE and NCE at short and long prime-target SOAs, respectively. The current experimental findings and the modelling results also illustrated that the non-linear relationships between representation strength and priming are mainly due to their interaction with the dynamics of attentional resource and its refractory period. In addition to the mentioned factors, a crucial factor is the timing of the presentation of stimuli. Mask and target need to be presented at specific temporal points with regard to the prime. These timing factors (in general, the prime-target SOA) interact with other factors in a dynamic way due to the limitations of cognitive resources (e.g., memory decay and the refractory period in attention). Generally, factors that increase the strength of the prime lead to a greater PCE at short and a greater NCE at longer prime-target SOAs. A weak prime causes smaller PCE but causes NCE to appear earlier than that caused by a stronger prime.

A mask can cause interruption, competition, and interference in prime. The role of the mask depends on its relation or similarity to the prime and the target (see

Simulation 7b). On the one hand, if the mask is irrelevant, its interruption effect can decrease the strength of the prime, including the strength caused by drawing attention. This can lead to a small or no PCE, and even an NCE, especially if the target is weak or presented after a long interval. On the other hand, if the mask is relevant, it can increase prime activation in the brain, causing a PCE with short, and an NCE with long prime-target SOA. An effective mask leads to an NCE when the prime-target SOA is relatively long. In contrast it leads to a PCE if partial masks or no mask is used, especially with short prime-target SOA.

Another factor that affects priming patterns is top-down attention, for example cuing the prime or target. The target being predictable increased target strength, thereby decreasing NCE. Therefore, as shown by the current experiments and simulations, attention to the prime or target has a role in the match of representation strength, similar to other aforementioned factors. But like other attentional resources, attention by cueing has a modulatory (non-linear) effect rather than an additive (or linear) one.

Therefore, all the above-mentioned factors can be understood as, or related to, the match of representation strength, which can be used as a unifying framework to explain PCE and NCE. While in the model representation strength is simulated by the connection weights between input and representation layers for the prime and target separately, the match of representation strength refers to the overall strength of the representation after being affected by attention, which is also affected by the joint prime and target activations (and hence the prime-target SOA) and congruency. The match of representation strength affects the decision presumably through an abstract value-based scale (modeled as competing neural firing) that is independent of the format of the stimuli (nonsense symbols, numerals, or lines) and even the type of task to be done (line-length comparison or numerical comparison). Like other magnitude comparison tasks, number comparison obeys Weber's law, which states that the threshold for discriminating two stimuli depends on their magnitude. The number magnitude seems to be represented in an abstract way regardless of the type (format or notation) of the stimuli, whether they are dot patterns, Arabic numerals, or number words (e.g., Buckley & Gillman, 1974; Dehaene et al., 1998; Koechlin et al., 1999). In this thesis, the effect of notation or type of magnitude was investigated and modeled by assuming that symbols are learned by linking them to abstract meaning (here magnitude), such as other categorization and learning processes. This suggests that the processing of symbols depends on their representational strength. It seems that not only numbers are represented on a mental scale, but also all representations that can somehow be valuated for the task goal are represented in a way that can be compared with a given reference, depending on the task. This valuational system seems to be amodal, being independent of whether input is auditory or visual, for instance (e.g., West, Ward, & Khosla, 2000). As shown by West et al., physical features of stimuli can be subjectively scaled by numerical values with training. Upon the training, participants can generalize their mental scale to new levels of stimuli features, and to different domains such as the subjective utility of money (West & Ward, 1998) and the subjective loudness or brightness (West et al., 2000).

Limitations and future work

There are some limitations in the current study. The sample size in Experiment 1 was eight. This sample size is good for fMRI results but it is small for behavioural results. The sample size for other experiments was ten, again a small one for behavioural results. Another limitation is that the congruency and ratio effects in the fMRI data, and the ratio effect in the behavioural condition were not included in the analysis of Experiment 1. A longer study would be needed to control these effects. In Experiment 3 and 4, some conditions contained repetition priming, for example 1 primed 1. A study that controls this effect would be helpful in separating distance and repetition priming effects. Moreover, Experiment 4 was run on the same participants as Experiment 3. Examining the predictability effect with a fresh sample of participants is needed for a more reliable result. Another effect that is worth considering is the SNARC effect, i.e., an intrinsic relation between numbers and motor responses. As mentioned previously, smaller numbers are associated with the left response (e.g., pressing a button with the left hand) and, conversely, larger numbers are associated with the right response (e.g., pressing a button with the right hand). This effect was not investigated in the current numerical priming experiments, as they all were SNARC compatible, i.e., participants were asked to select smaller numbers with their left hand and larger numbers with their right hand.

Regarding the role of a mask, the apparent decrease in PCE found in Experiments 3 and 4, at least for numerals priming numerals (compared to numerals priming symbols), may reflect the type of mask. The fact that the mask consisted of symbols and not numerals could cause that effect, though the difference was highly variable and decreased or disappeared when t values were considered with the mean RT difference. Another factor that could cause this decrease in PCE was the time effect. Experiment 4 was conducted after Experiment 3. Because of this treatment, more studies are needed to separate the role of prediction, or cuing, from learning.

An interesting study for the future would be to find a relationship between the amount of learning or memorizing of the symbols and the direction of priming. Another factor to be considered in future studies is the interval between the prime and target in the current paradigm and to compare with the results of Eimer and colleagues' paradigm. Finally, a study to find the effect of recently learned symbols in an attentional blink paradigm is worth considering.

Regarding the model, it could be improved in many ways, for example by using a better representation of stimuli, such as separate layers for numerals and symbols (preferably through a working memory layer at least for the latter), a better weight adjustment and parameterization, and improving the timing in the model to find a better fit between the model response time and human data. To improve the model to produce a better error pattern, a larger study is needed to investigate error patterns because the current experiments were short and the number of participants was small, causing a few errors per condition. Previous studies on NCE have not reported the error RTs so more studies are needed to guide modelling of the error patterns.

Other factors that should be involved, but were not considered in the model, include: representation of the cue similar to other stimuli, interaction between different kinds of attention (e.g., an interaction between different neuro-modulators, see Yu &

Dayan, 2005), and partial conflict between targets that are a type different from the primes, i.e., trials with a numeral prime and a symbol target, where in fact NCE was found.

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Appendices

Appendix A. The methods and results of memorizing number-symbol mapping in Experiments 2 and 3.

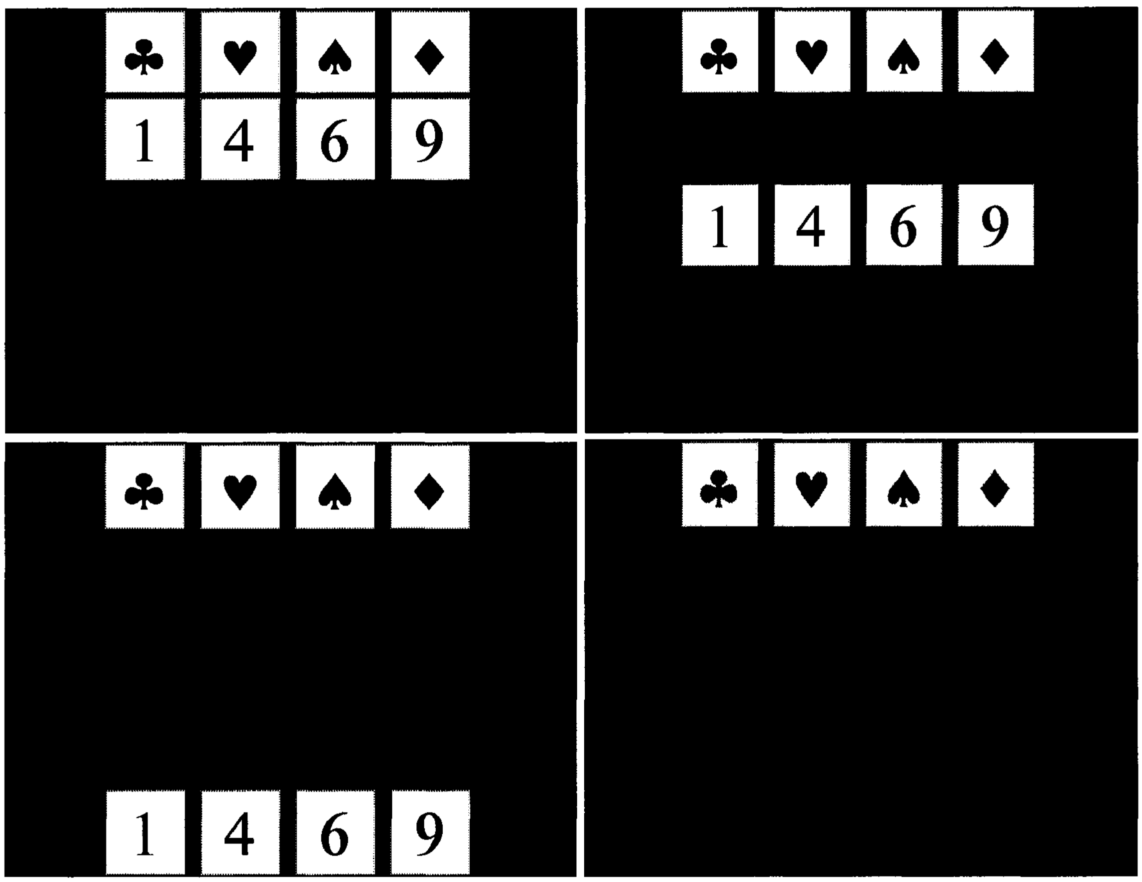

Figure 1. The memorizing (learning) phase of the number-symbol mapping. First the top-left image appears on the screen and the instruction on the mapping is provided, i.e., “you are going to relate each symbol on the top to its corresponding number at the bottom, the numeral group moves down in three 15s steps until it disappear from the screen. So, you will have 45s to memorize this, are you ready?”. Then the other images were presented in order (in three steps, making the numerals move downward). The last three steps were not presented in Experiment 2.

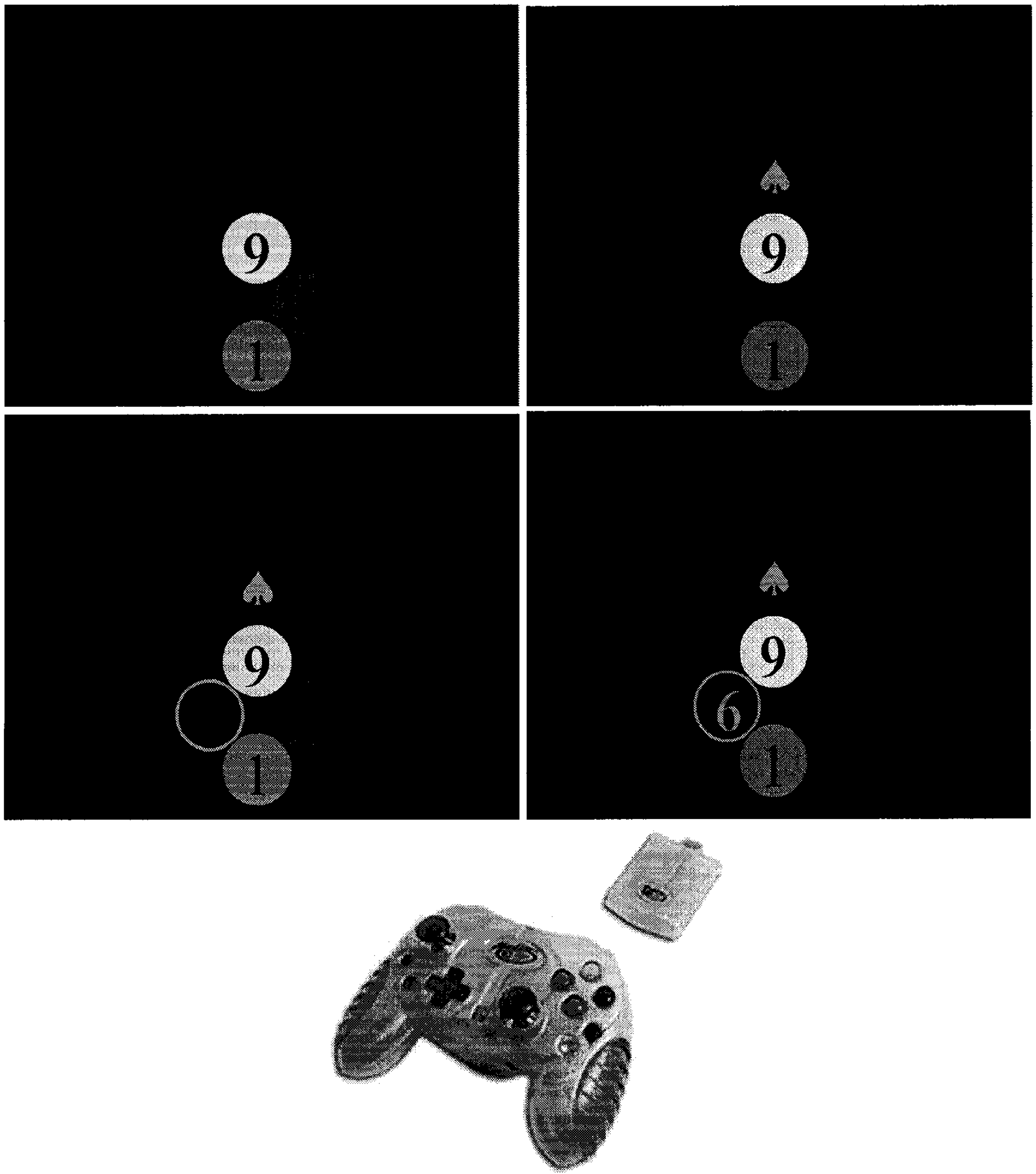

Figure 2. Top: A correct trial in the memory test phase of the number-symbol mapping (4s). A trial started with the top-left image for 1s. Then the top-right image was presented until the participant pressed a button that highlighted the selected option. Then the correct option was shown by highlighting the corresponding number (each color matched a color on a corresponding joystick button). The feedback remained on the screen for the rest of the 4s. Bottom: The corresponding buttons on the response device.

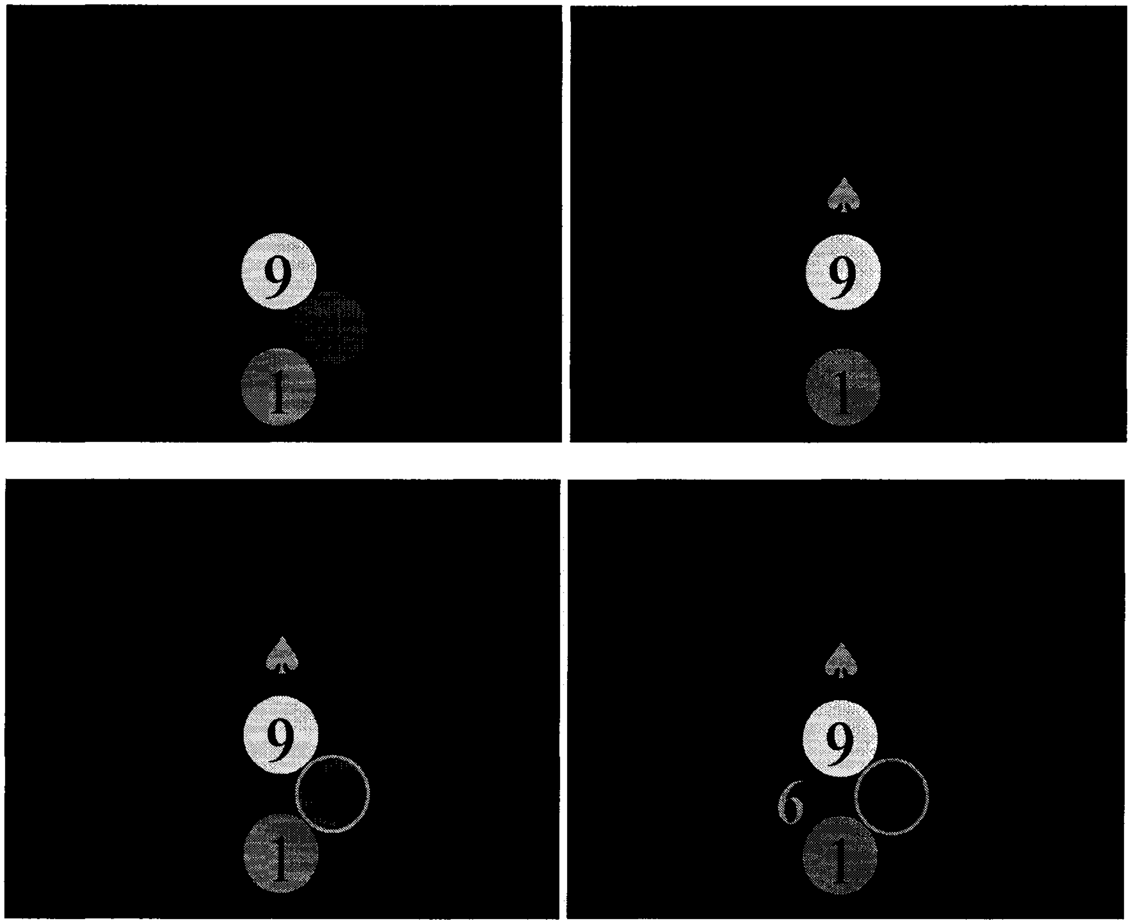

Figure 3. An incorrect trial in the memory test phase of the number-symbol mapping (4s). A trial started with the top-left image for 1s. Then the top-right image was presented until the participant pressed a button that highlighted the selected option. Then the correct option was shown by highlighting the corresponding number. The feedback remained on the screen for the rest of the 4s.

The results of training phase in Experiment 2:

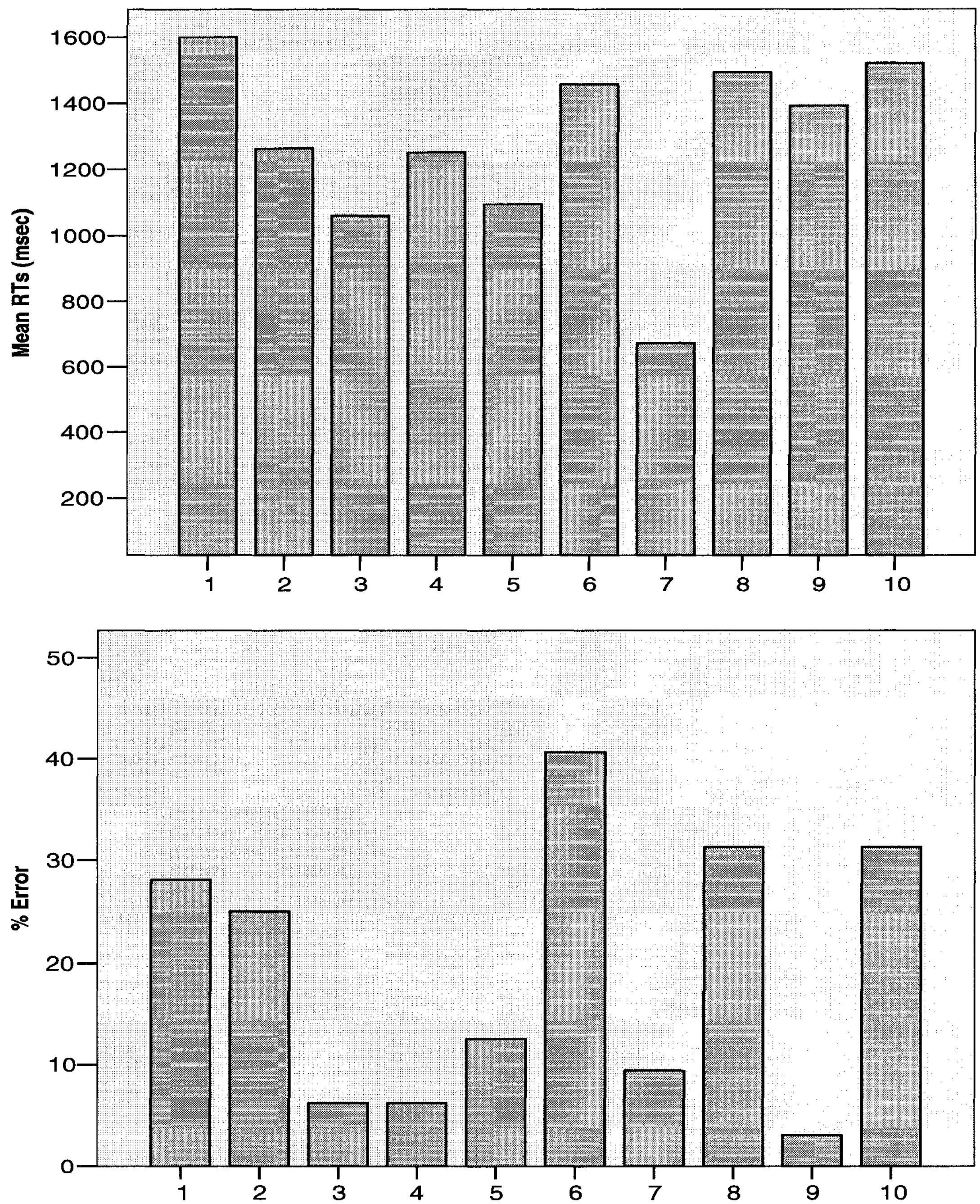

Figure 4: Experiment 2: Mean RTs (Top) and % error (bottom) in learning phase for each participant separately. Note that the errors occurred mainly in the early trials and the long RTs are due to emphasis on accuracy not speed.

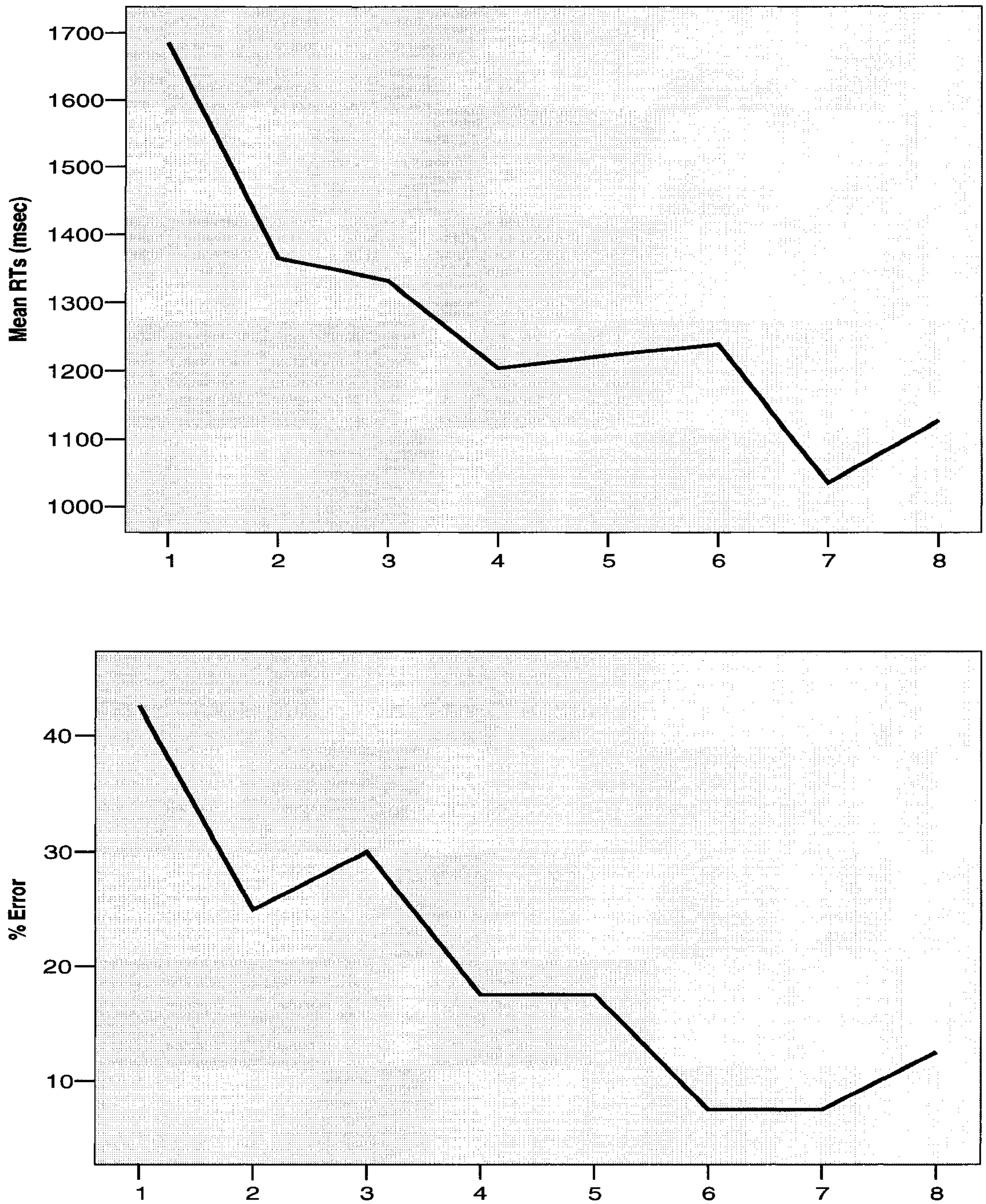

Figure 5: Experiment 2: Mean RTs (Top) and % error (bottom) in learning phase for each block separately.

The results of training phase in Experiment 3:

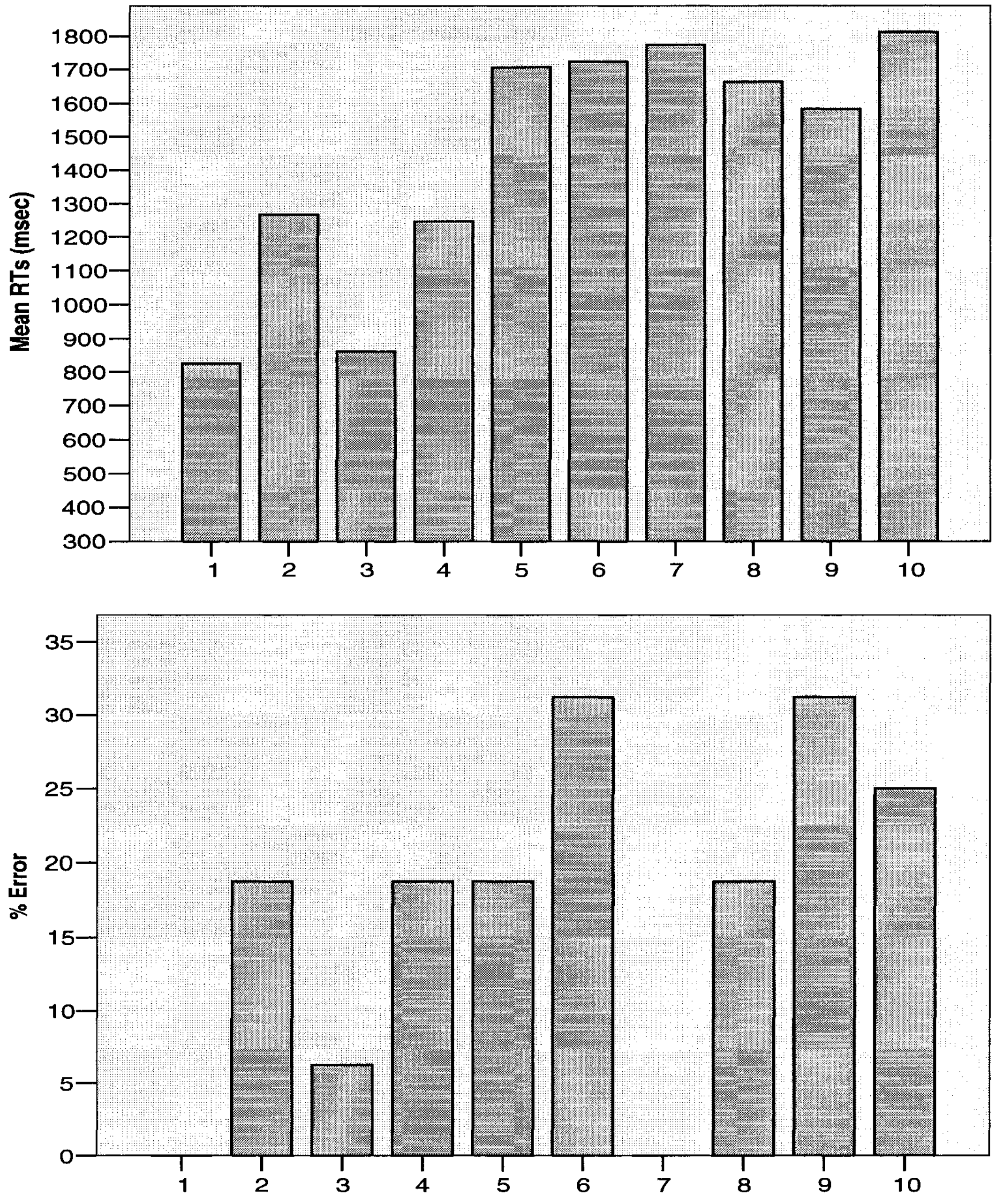

Figure 6: Experiment 3: Mean RTs (Top) and % error (bottom) in learning phase for each participant separately (less error compared to Experiment 2 shows that benefit of more time for memorizing here).

Distance effect in the training phase (Experiment 3)

With regard to the numerical distance which was controlled in Experiments 3, a repeated measure ANOVA was run on training phase RTs in four levels of distance factor (Far/Small, Close/Small, Close/Large, and Far/Large, i.e., 1, 4, 6, & 9). The results of ANOVA showed a significant distance effect (F=3.915, p=.019). These results indicate that in the number-symbol mapping, participants were faster in trials with far compared to close numerical distance from *five*. A similar result was found for errors, showing a marginally significant distance effect (F=2.603, p=.073) (Figures 7-9). It seems that they categorized the numbers according to the distance from *five* without being asked to do so in this phase.

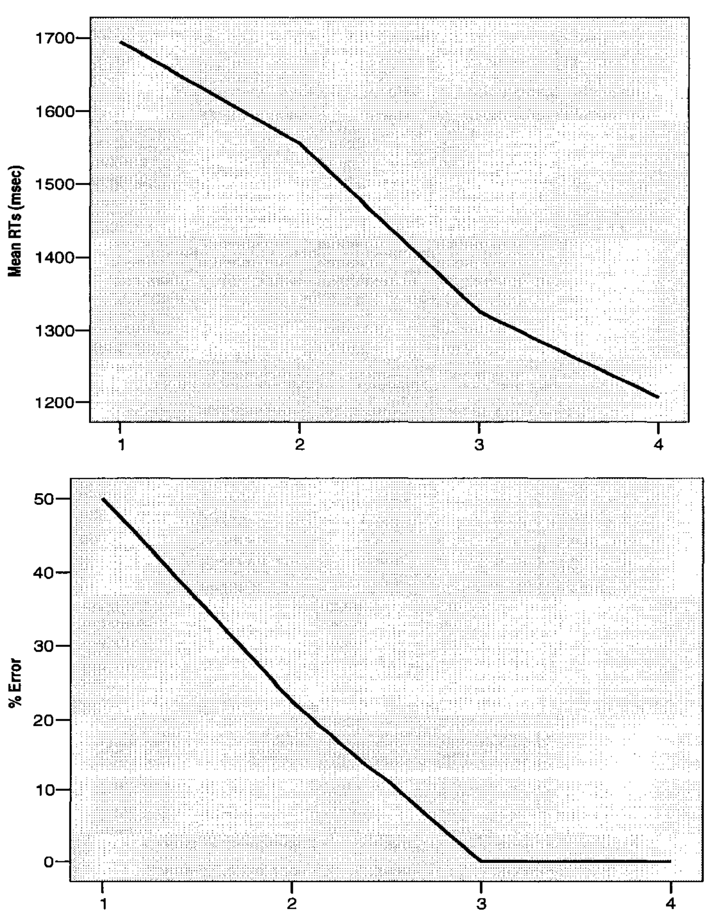

Figure 7: Experiment 3: Mean RTs (Top) and % error (bottom) in learning phase for each block separately.

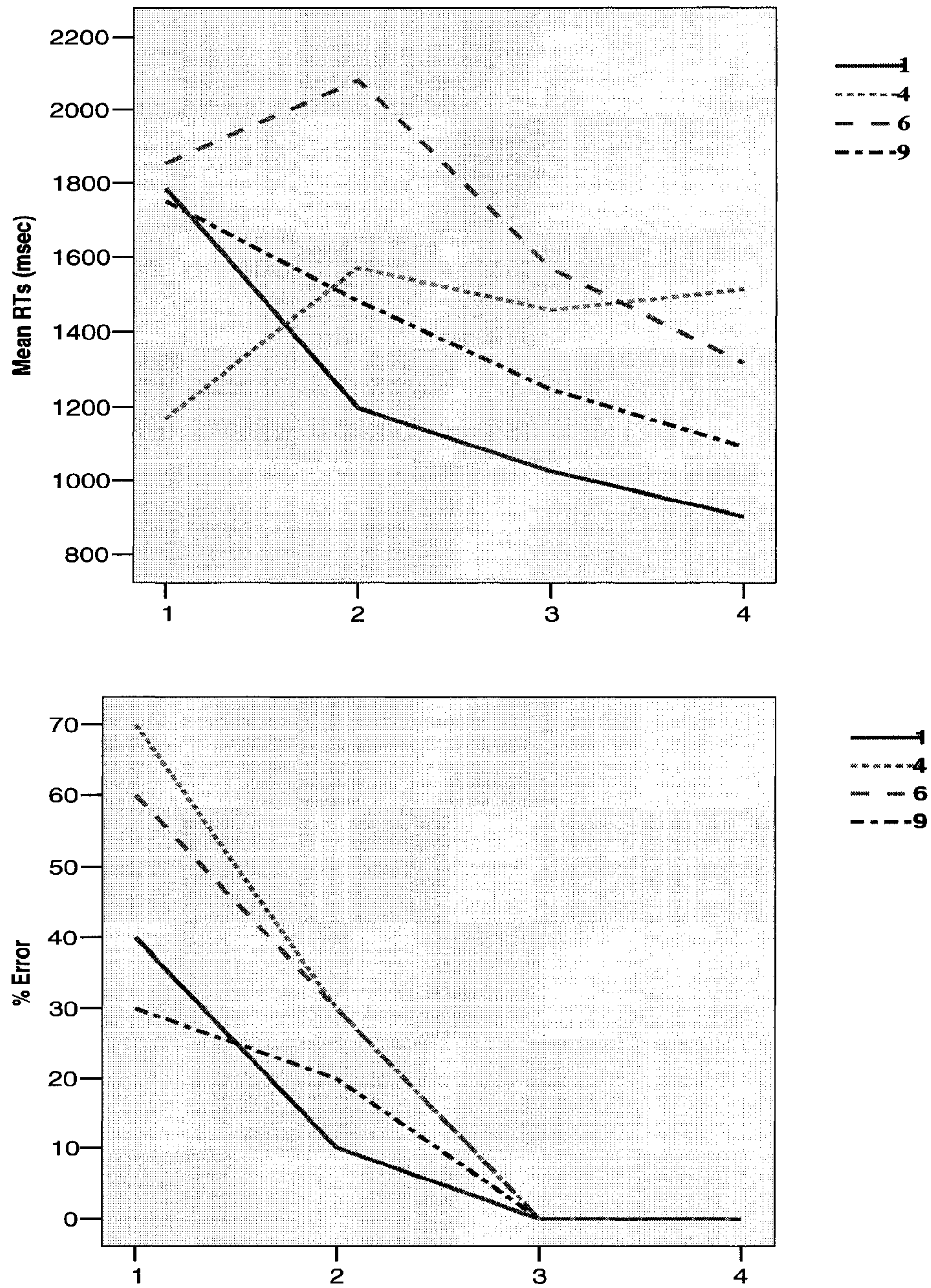

Figure 8: Experiment 3: Mean RTs (Top) and % error (bottom) in learning phase in the four distance levels, for each block separately. Both graphs show the distance effect in memorizing.

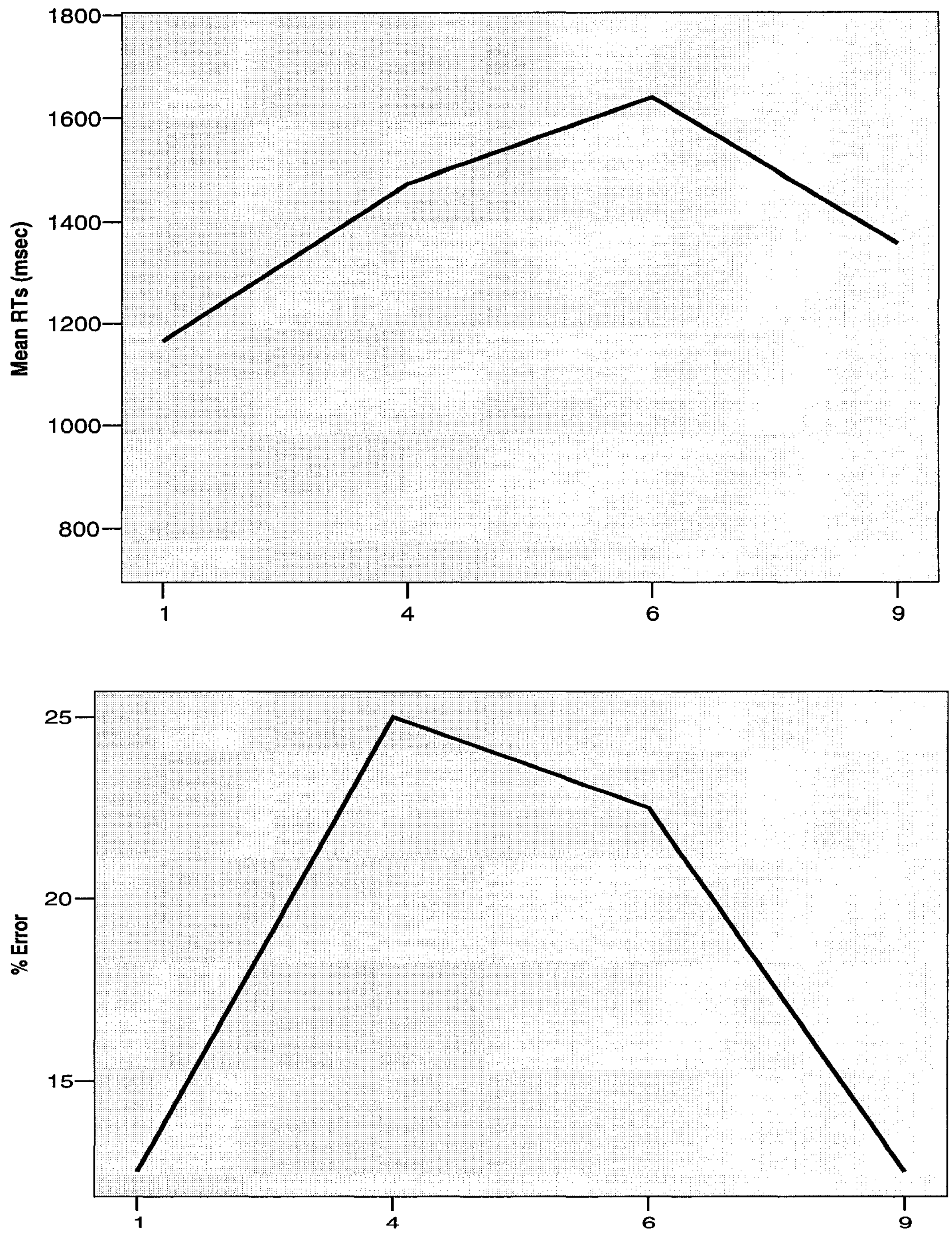

Figure 9: Experiment 3: Mean RTs (top) and % error (bottom) in learning phase in the four distance levels.

Table 1. Correlations between RTs in learning phase and priming in Experiment 3 (*= sig. at the .05 level; **= sig. at the .001 level).

Number-Number	Congruent	Close-Close	Pearson Correlation	.457
			Sig. (2-tailed)	.184
			N	10
		Close-Far	Pearson Correlation	.533
			Sig. (2-tailed)	.113
			N	10
		Far-Close	Pearson Correlation	.651*
			Sig. (2-tailed)	.042
			N	10
		Far-Far	Pearson Correlation	.726*
			Sig. (2-tailed)	.017
			N	10
	Incongruent	Close-Close	Pearson Correlation	.556
			Sig. (2-tailed)	.095
			N	10
		Close-Far	Pearson Correlation	.810**
			Sig. (2-tailed)	.005
			N	10
		Far-Close	Pearson Correlation	.493
			Sig. (2-tailed)	.147
			N	10
		Far-Far	Pearson Correlation	.870**
			Sig. (2-tailed)	.001
			N	10
Number-Symbol	Congruent	Close-Close	Pearson Correlation	.529
			Sig. (2-tailed)	.116
			N	10
		Close-Far	Pearson Correlation	.565
			Sig. (2-tailed)	.089
			N	10
		Far-Close	Pearson Correlation	.305
			Sig. (2-tailed)	.392
			N	10
		Far-Far	Pearson Correlation	.697*
			Sig. (2-tailed)	.025
			N	10
	Incongruent	Close-Close	Pearson Correlation	.079
			Sig. (2-tailed)	.829
			N	10
		Close-Far	Pearson Correlation	.745*
			Sig. (2-tailed)	.013
			N	10
		Far-Close	Pearson Correlation	.267
			Sig. (2-tailed)	.455
			N	10
		Far-Far	Pearson Correlation	.763*
			Sig. (2-tailed)	.010
			N	10

Table 2. Correlations between RTs in learning phase and priming in Experiment 4 (*= sig. at the .05 level; **= sig. at the .001 level).

Number-Number	Congruent	Close-Close	Pearson Correlation	.241
			Sig. (2-tailed)	.503
			N	10
		Close-Far	Pearson Correlation	.449
			Sig. (2-tailed)	.193
			N	10
		Far-Close	Pearson Correlation	.577
			Sig. (2-tailed)	.081
			N	10
		Far-Far	Pearson Correlation	.467
			Sig. (2-tailed)	.174
			N	10
	Incongruent	Close-Close	Pearson Correlation	.495
			Sig. (2-tailed)	.146
			N	10
		Close-Far	Pearson Correlation	.642*
			Sig. (2-tailed)	.046
			N	10
		Far-Close	Pearson Correlation	.426
			Sig. (2-tailed)	.220
			N	10
		Far-Far	Pearson Correlation	.343
			Sig. (2-tailed)	.331
			N	10
Number-Symbol	Congruent	Close-Close	Pearson Correlation	-.332
			Sig. (2-tailed)	.349
			N	10
		Close-Far	Pearson Correlation	.512
			Sig. (2-tailed)	.130
			N	10
		Far-Close	Pearson Correlation	.309
			Sig. (2-tailed)	.385
			N	10
		Far-Far	Pearson Correlation	.832**
			Sig. (2-tailed)	.003
			N	10
	Incongruent	Close-Close	Pearson Correlation	-.048
			Sig. (2-tailed)	.894
			N	10
		Close-Far	Pearson Correlation	.564
			Sig. (2-tailed)	.090
			N	10
		Far-Close	Pearson Correlation	-.176
			Sig. (2-tailed)	.627
			N	10
		Far-Far	Pearson Correlation	.577
			Sig. (2-tailed)	.081
			N	10

Appendix B. Distance effect in the priming phase.

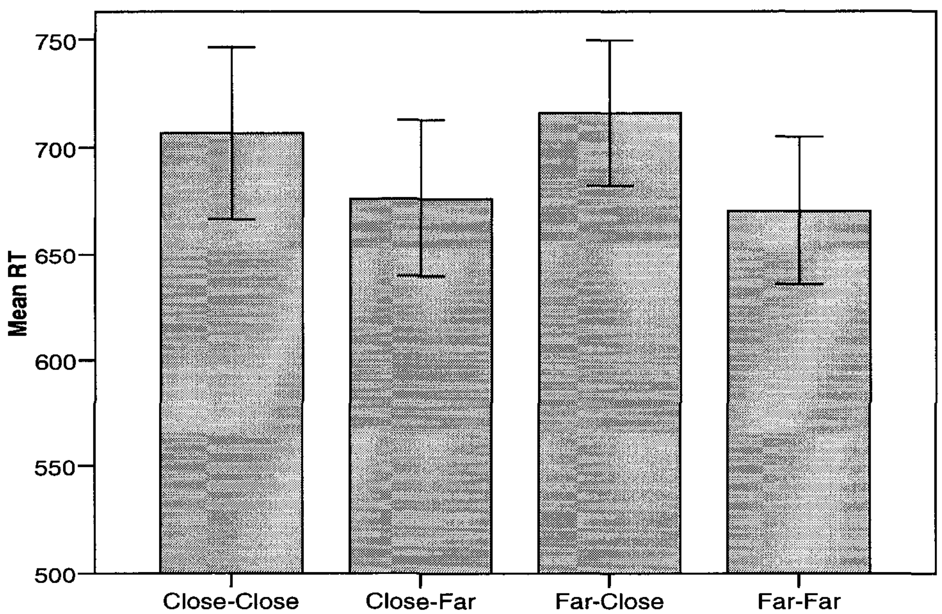

Figure 1. Distance effect was mainly caused by target distance (in Experiments 3 and 4 together).

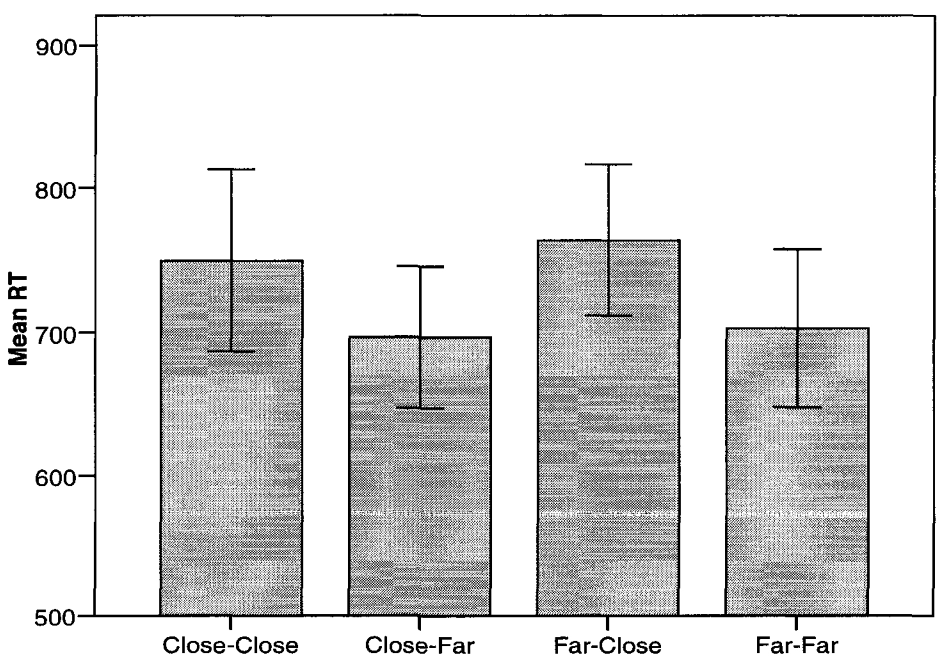

Figure 2. Distance effect mainly was mainly caused by target distance. (Experiment 3).

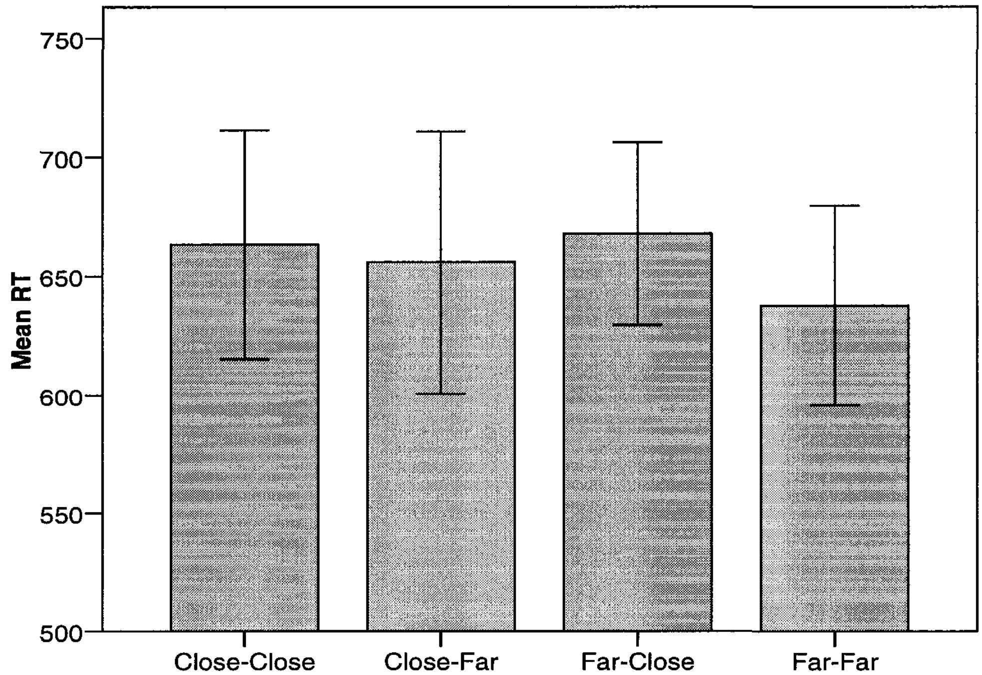

Figure 3. Distance effect mainly was mainly caused by target distance (Experiment 4).

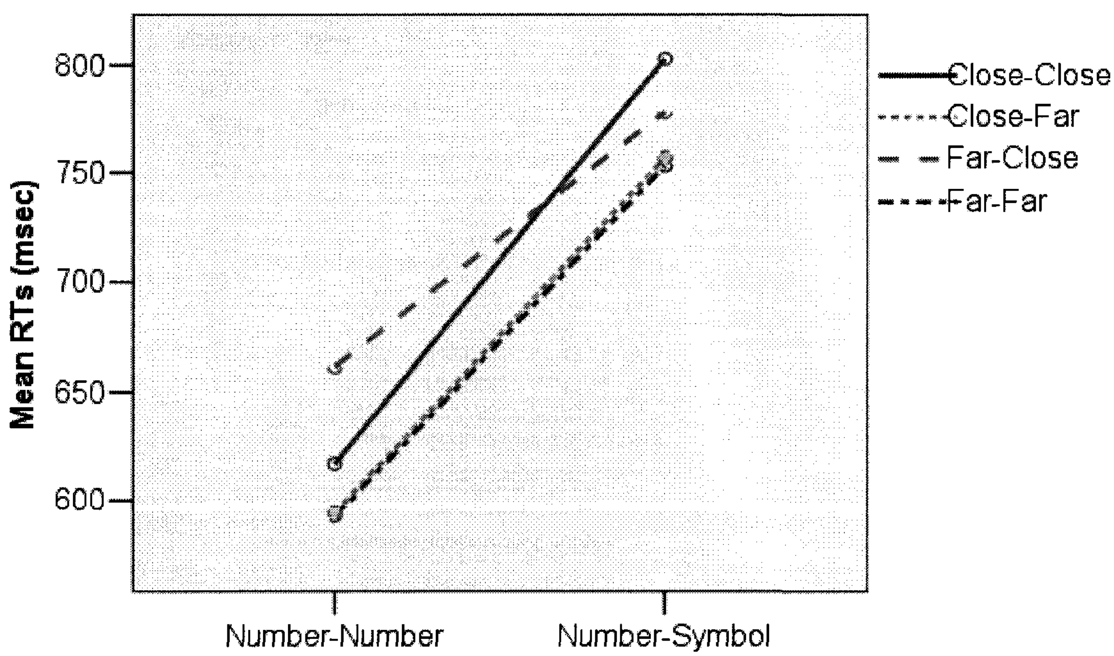

Figure 4. The interaction between Type and Distance (Experiments 3 and 4 together).

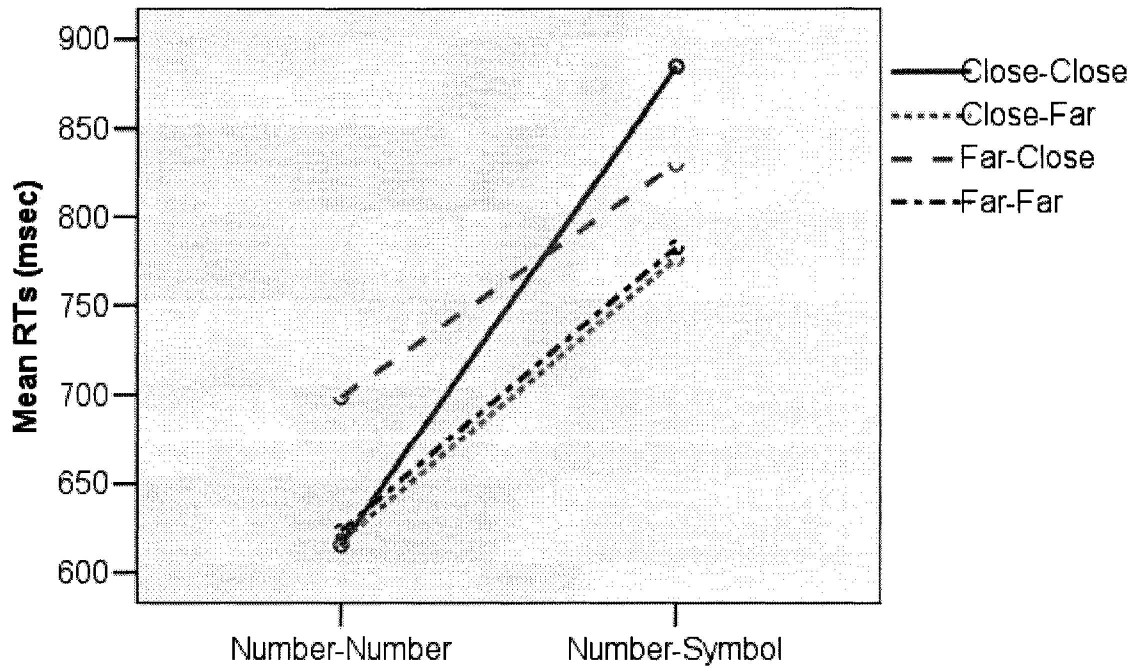

Figure 5. The interaction between Type and Distance (Experiment 3).

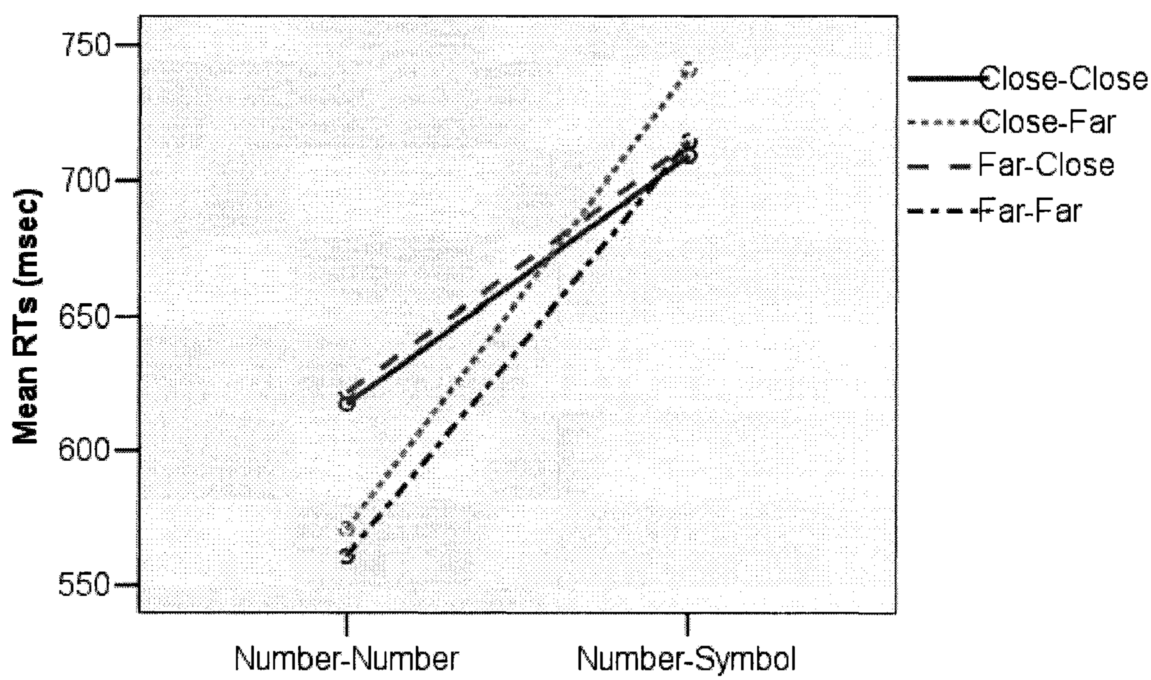

Figure 6. The interaction between Type and Distance (Experiment 4).

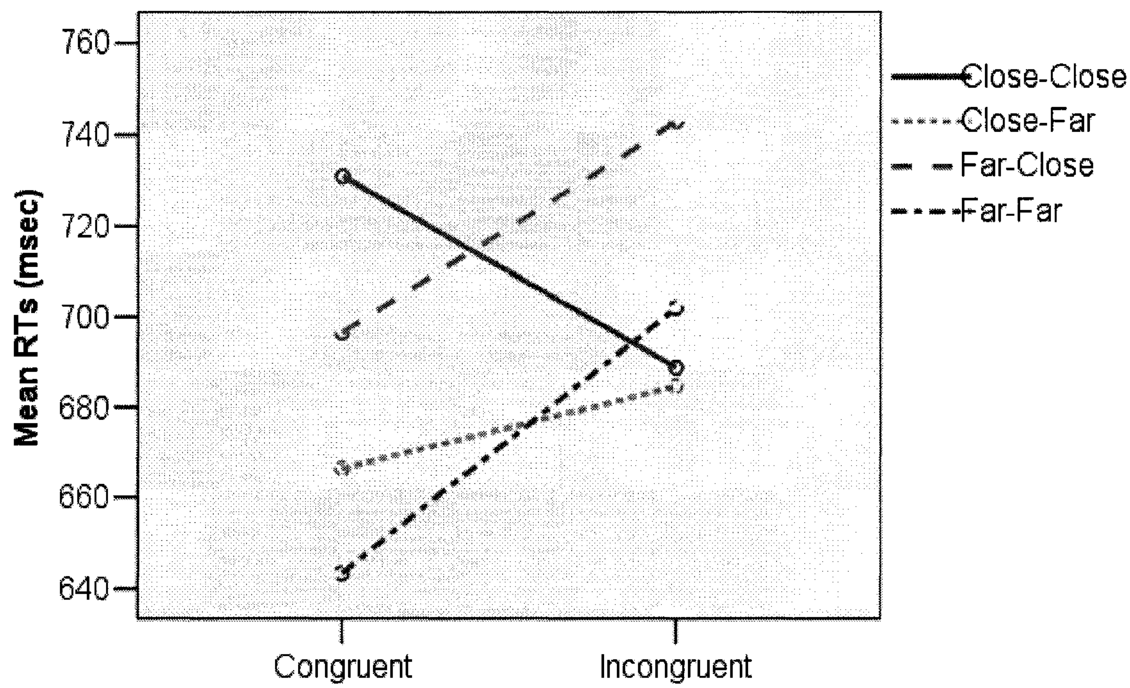

Figure 7. The interaction between Congruency and Distance (Experiments 3 and 4 together).

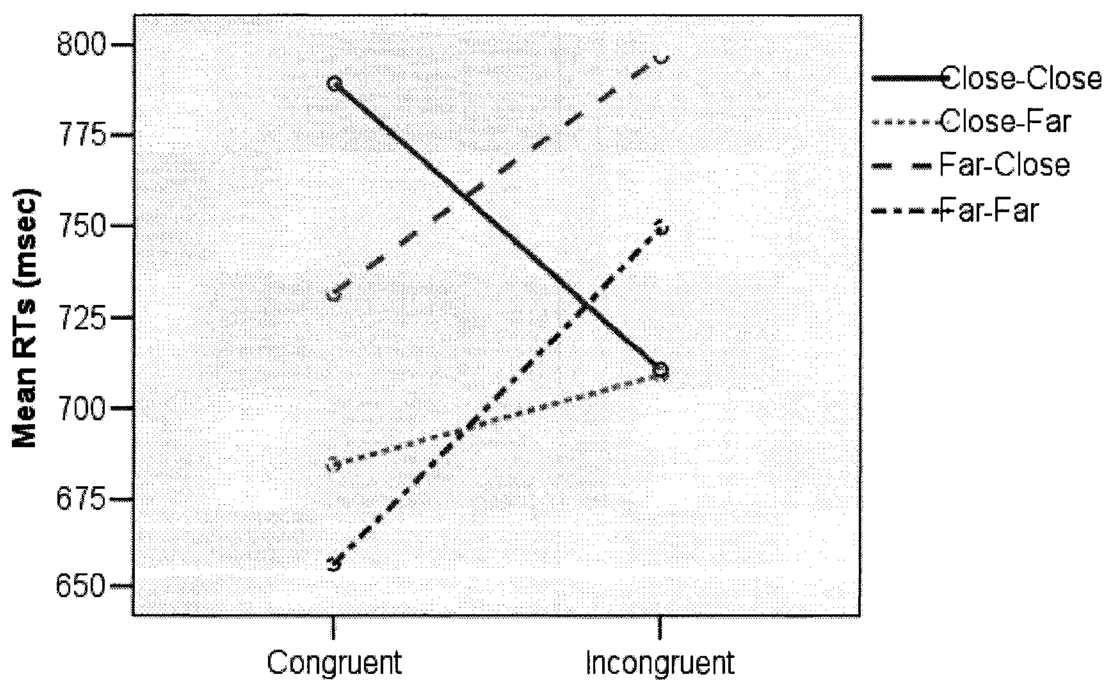

Figure 8. The interaction between Congruency and Distance (Experiment 3).

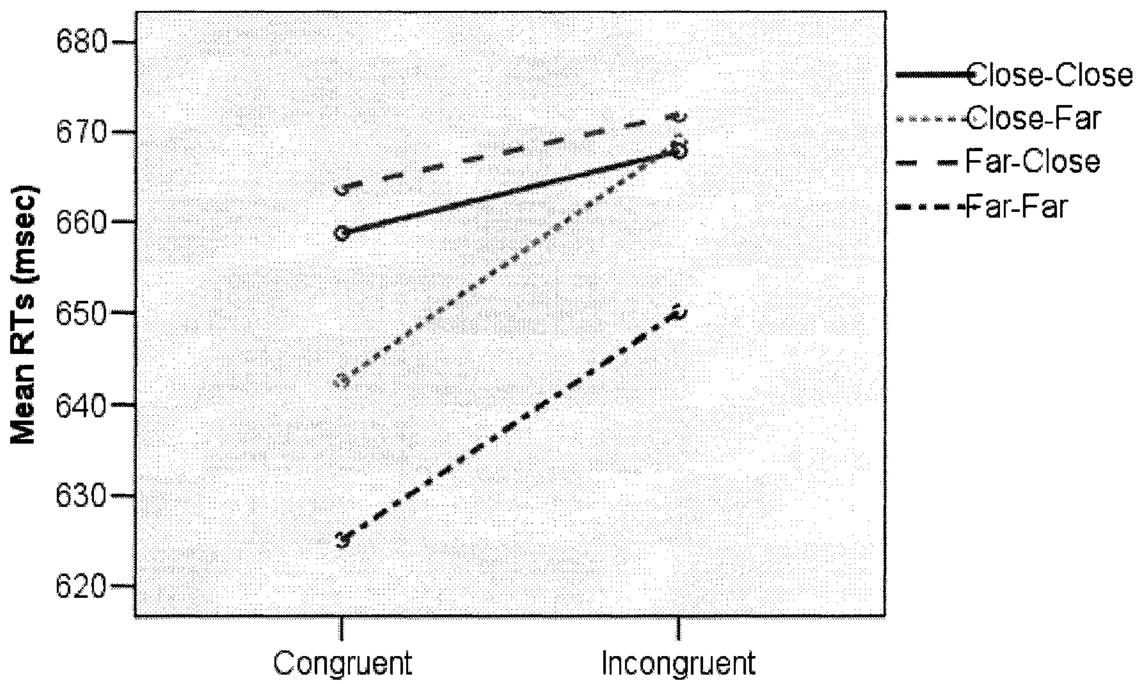

Figure 9. The interaction between Congruency and Distance (Experiment 4).

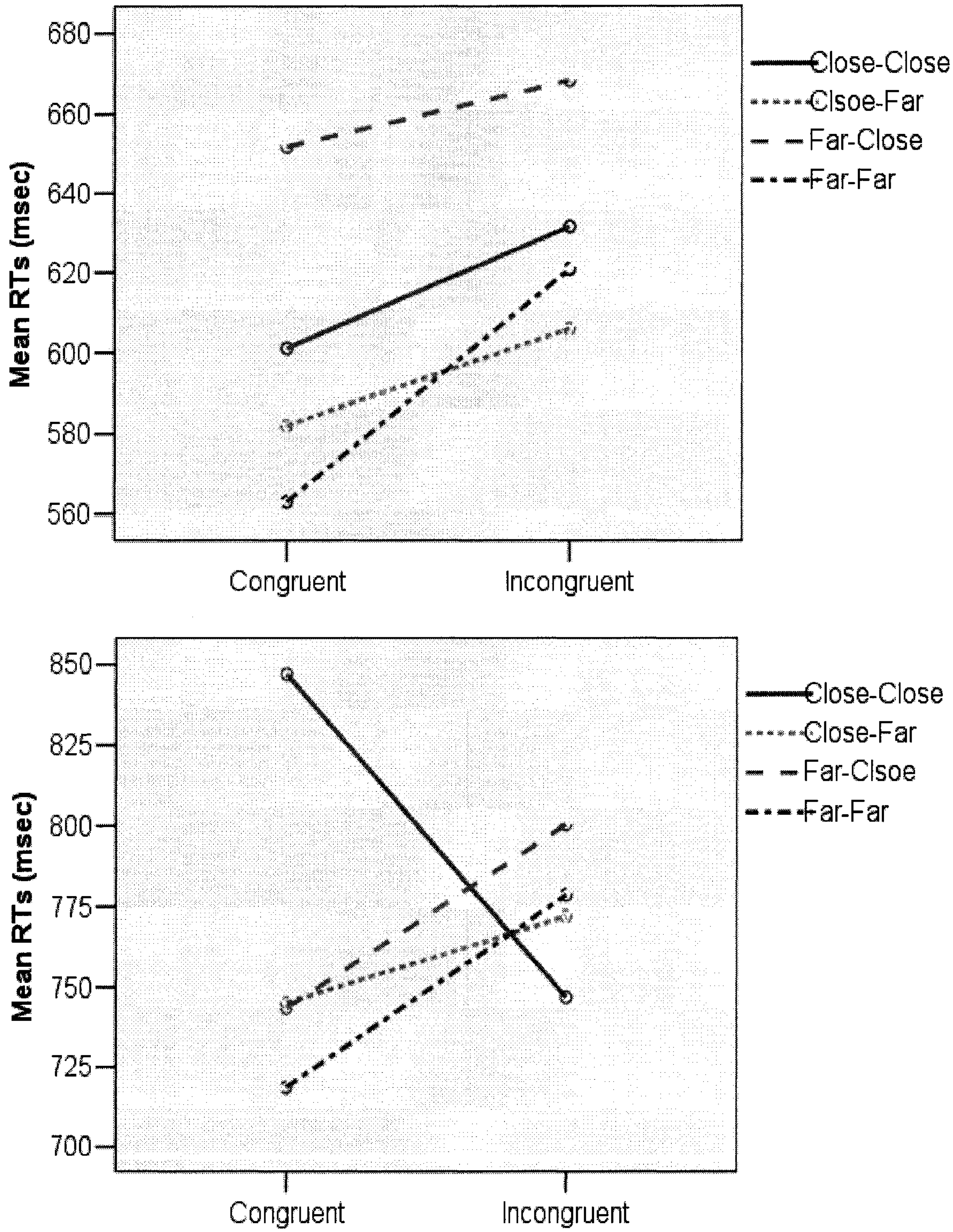

Figure 10. The interaction between Congruency and Distance in Experiments 3 and 4 together, for Number-Number (top) and Number-Symbol (bottom) Type.

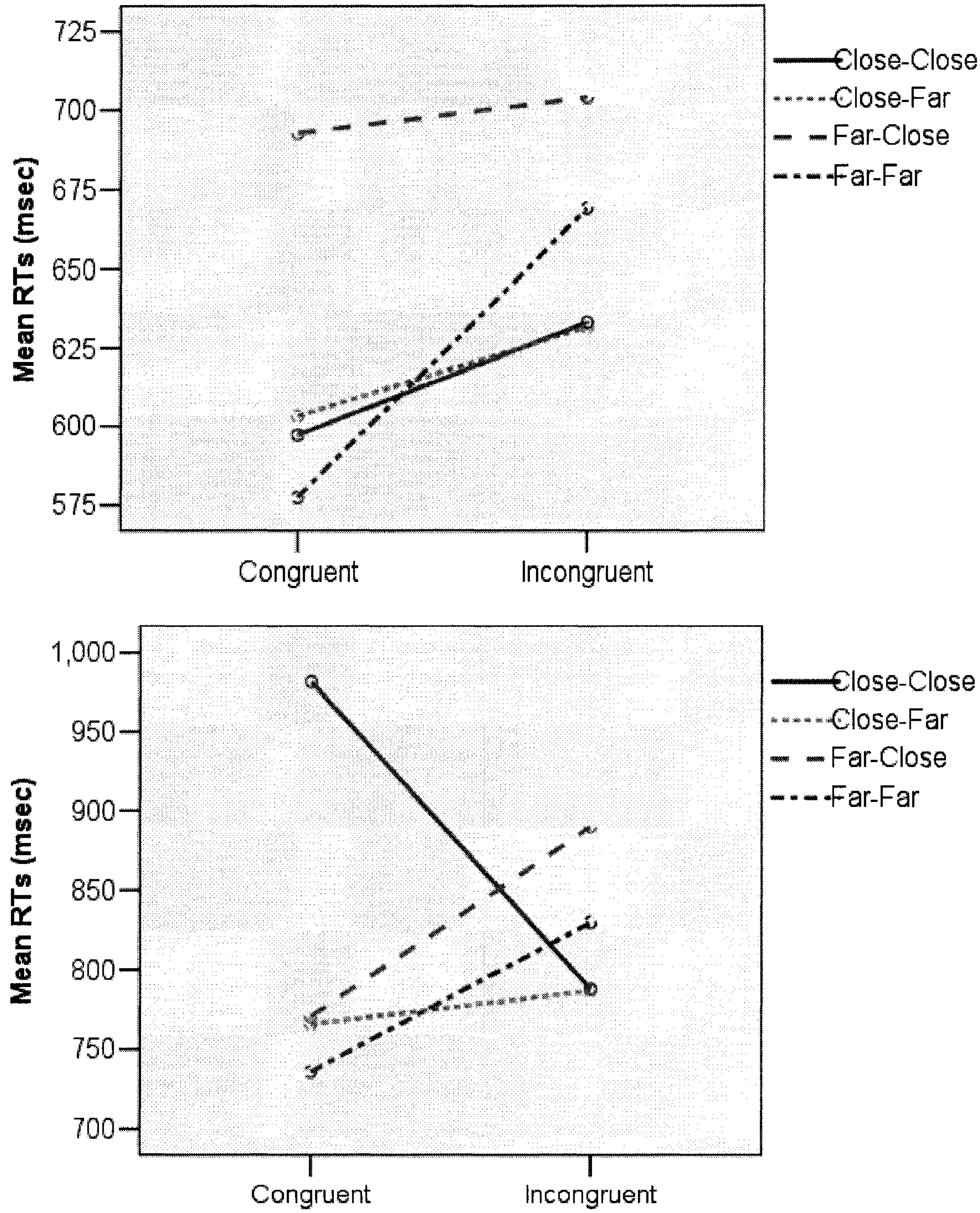

Figure 11. The interaction between Congruency and Distance in Experiment 3, for Number-Number (top) and Number-Symbol (bottom) Type.

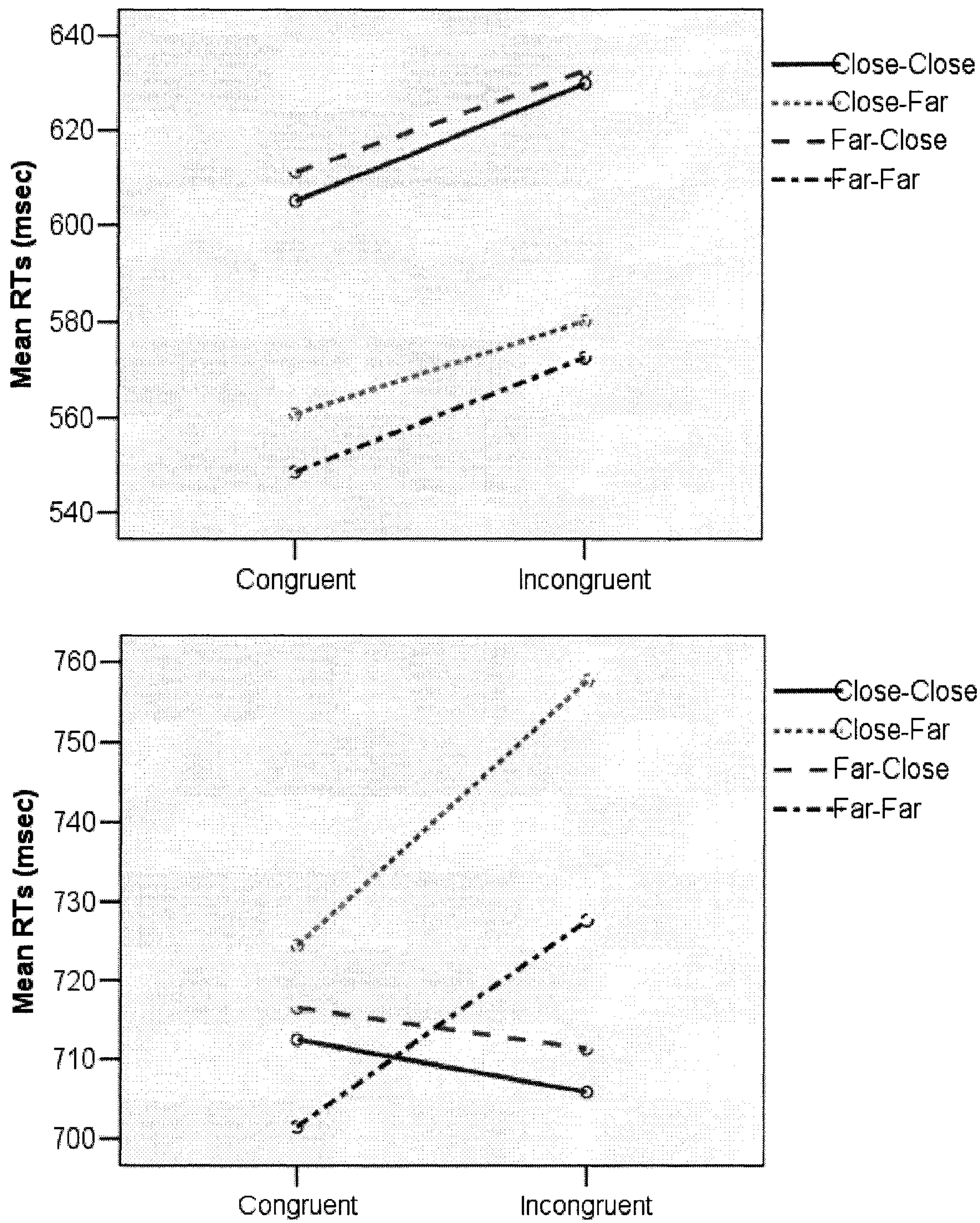

Figure 12. The interaction between Congruency and Distance in Experiment 4, for Number-Number (top) and Number-Symbol (bottom) Type.

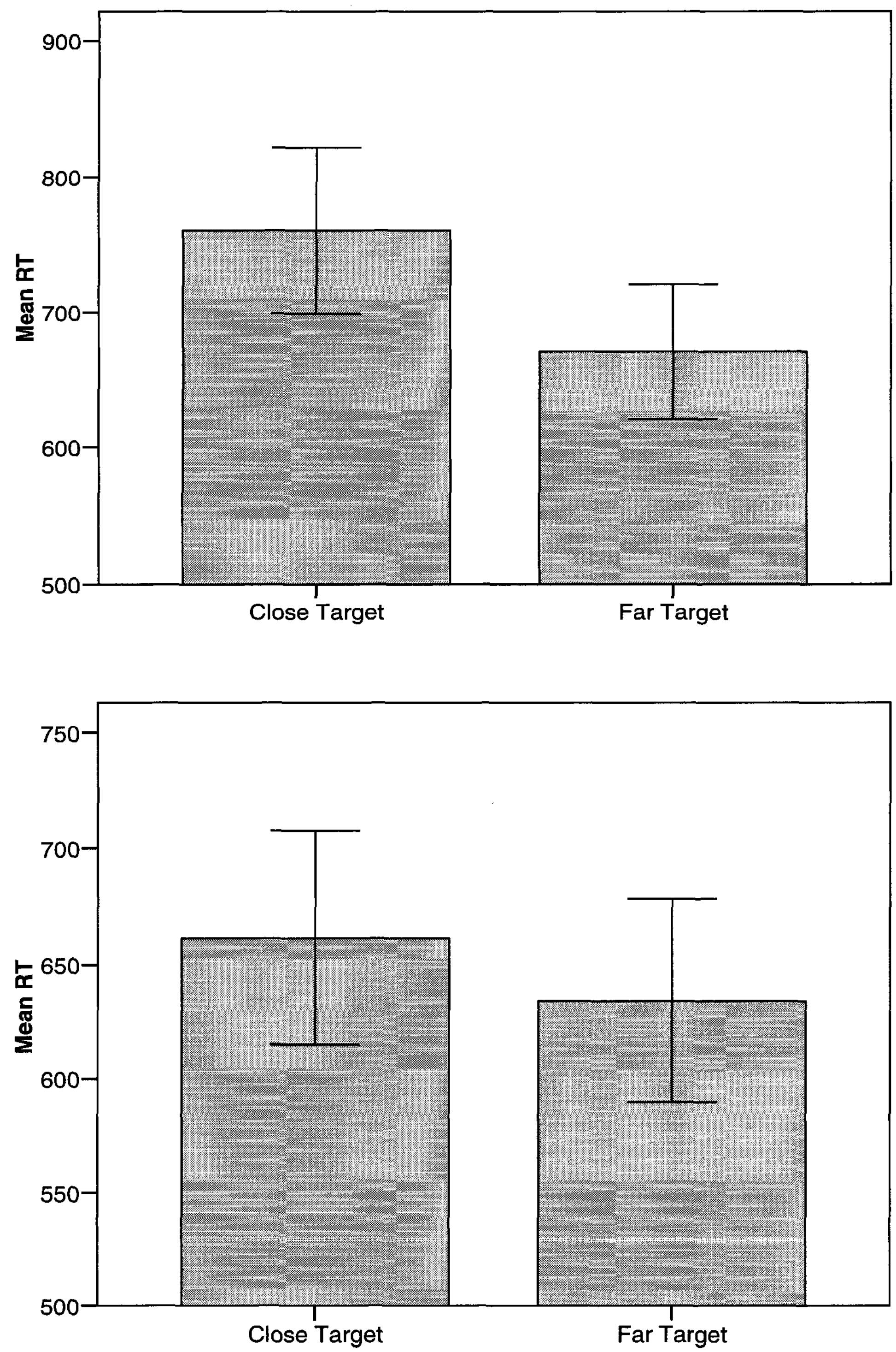

Figure 13. The target Distance effect in the Congruent condition in Experiment 3 (top) and Experiment 4 (Bottom).

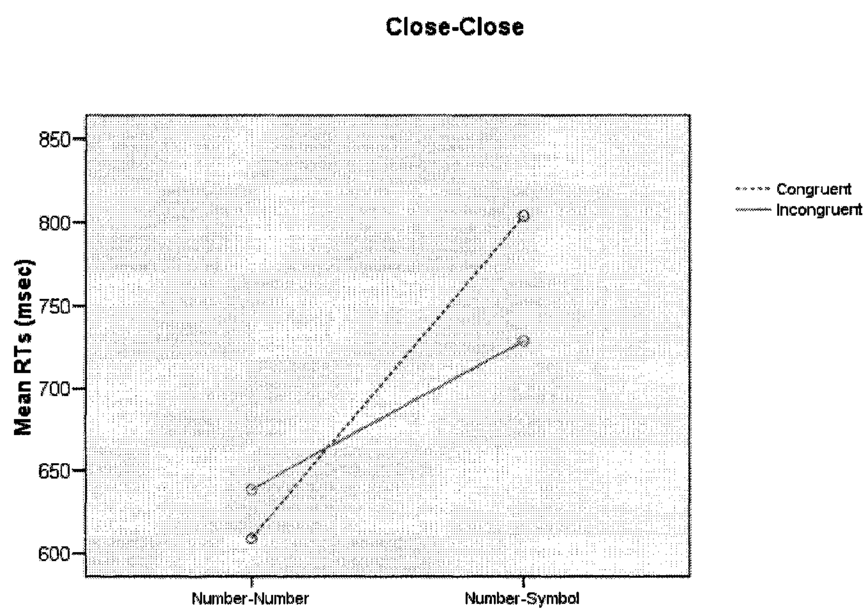

Figure 14. RTs in Experiment 3 after data trimming (400 ms <RT<1100 ms).

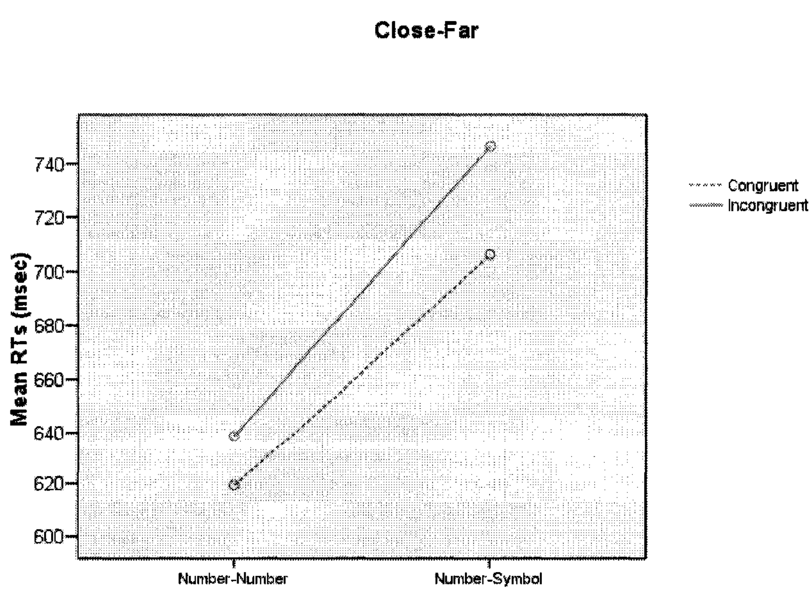

Figure 15. RTs in Experiment 3 after data trimming (400 ms <RT<1100 ms).

Far-Close

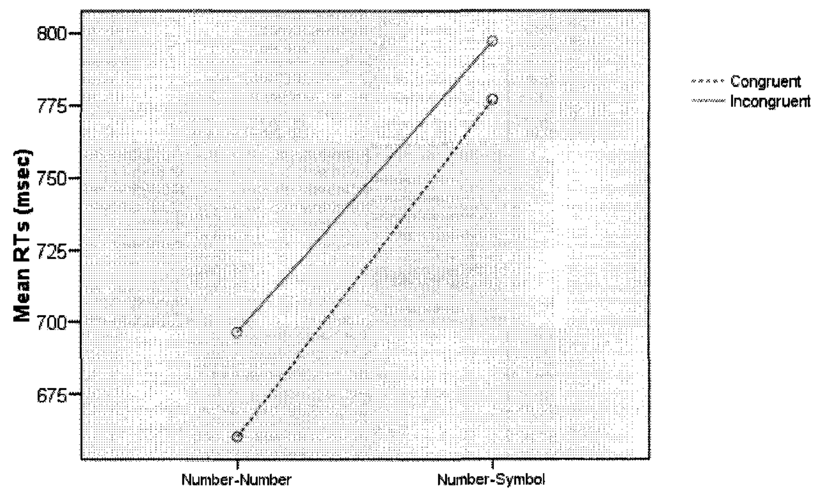

Figure 16. RTs in Experiment 3 after data trimming (400 ms <RT<1100 ms).

Far-Far

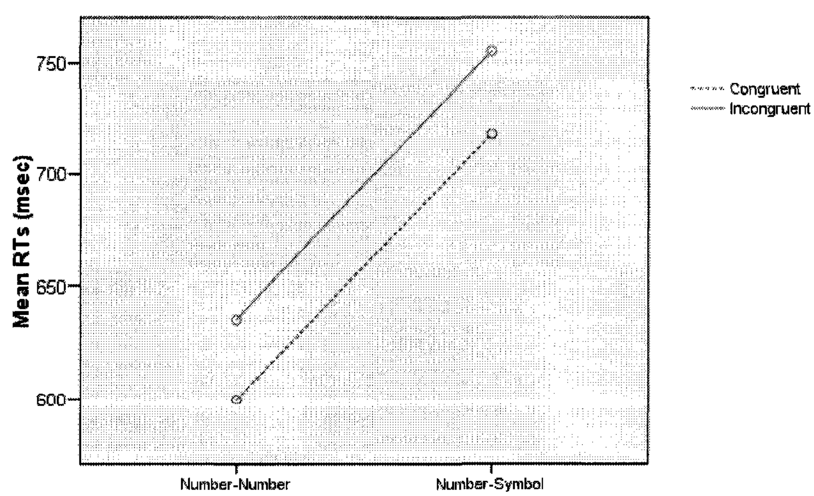

Figure 17. RTs in Experiment 3 after data trimming (400 ms <RT<1100 ms).

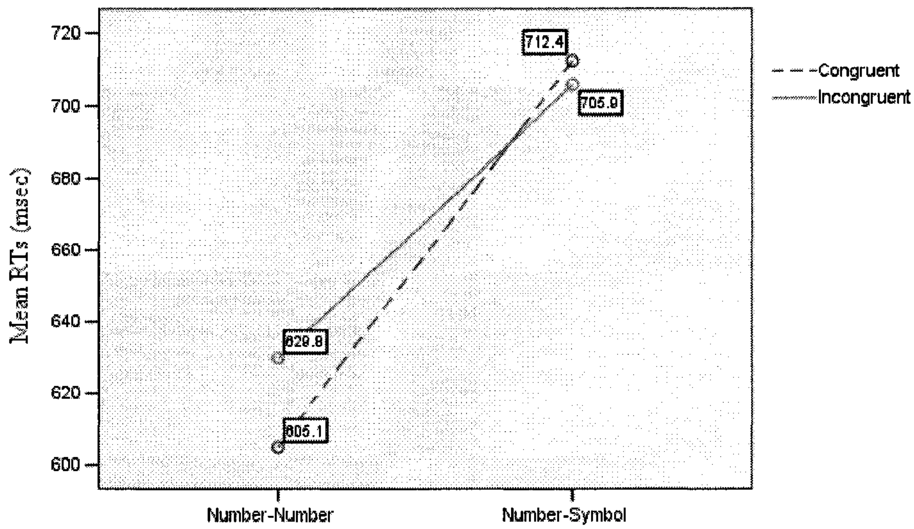

Figure 18. Non-significant PCE in Experiment 4 at Close Prime-Close Target distance in Number–Number (t=1.375, p=.202) and in Non-significant NCE Number Prime-Symbol Target (t=.*191*, p=.853).

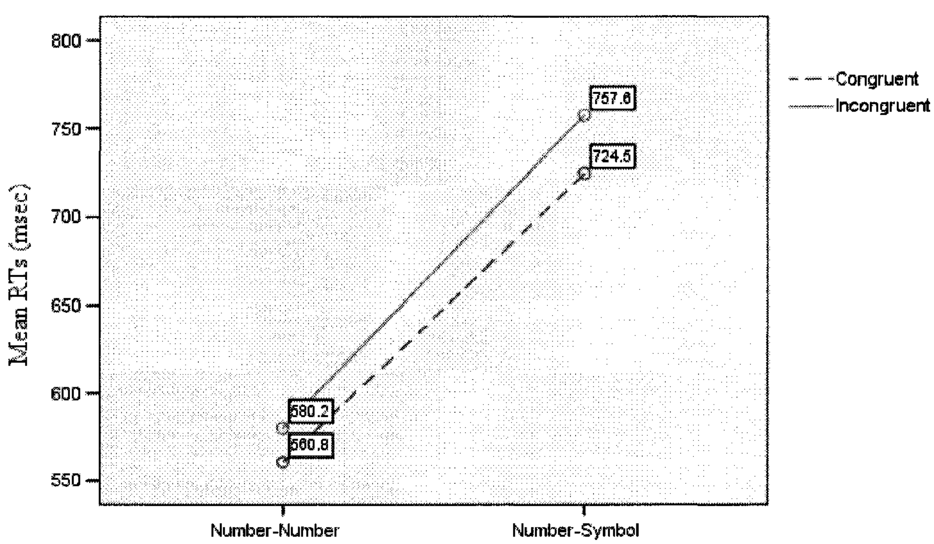

Figure 19. Non-significant PCE in Experiment 4 at Close Prime-Far Target distance both in Number–Number (t=1.048, p=.322) and in Number–Symbol (t=.*452*, p=.552).

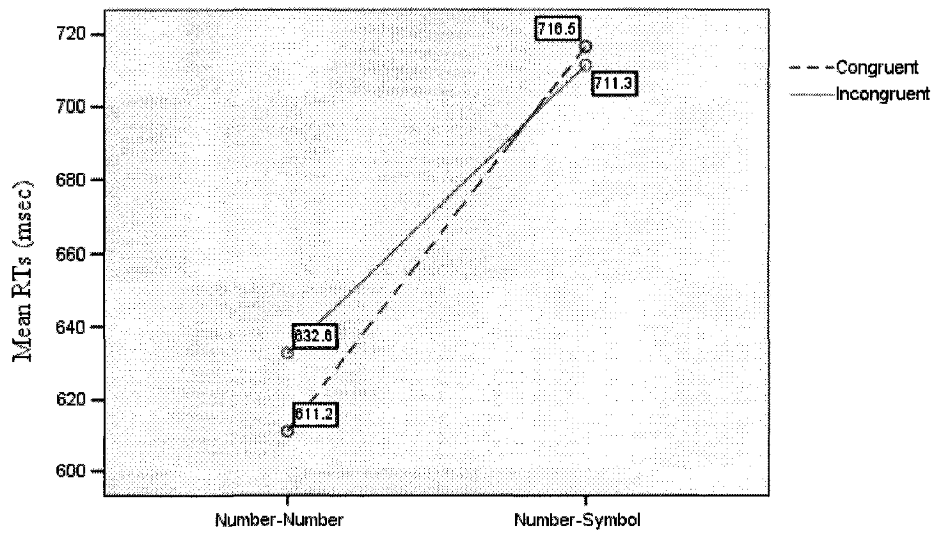

Figure 20. In Experiment 4 at Far Prime-Close Target distance, the priming was a Non-significant PCE in Number–Number (t=.778, p=.109) and a Non-significant NCE in Number Prime- Symbol Target (t=*.133*, p=.897).

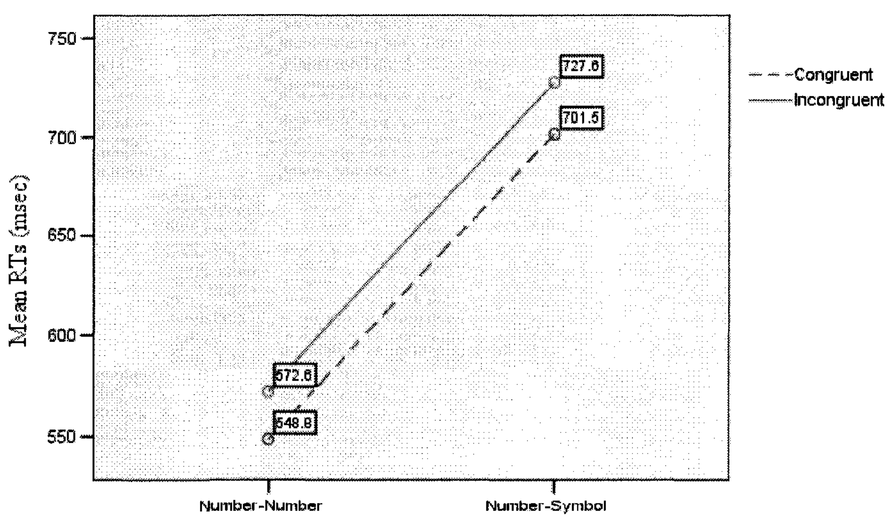

Figure 21. Marginally significant PCE in Experiment 4 at Far Prime-Far Target distance both in Number–Number (t=1.846, p=.098) and in Number–Symbol (t=*1.081*, p=.308).

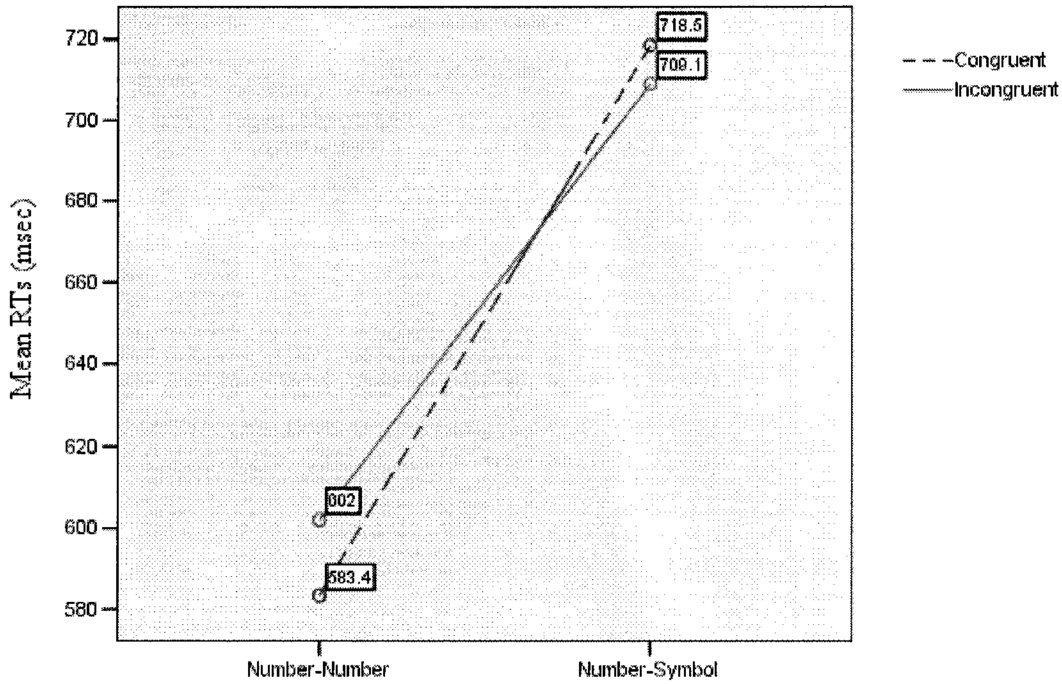

Figure 22. In Experiments 3 and 4 together, regardless of Distance, a PCE was found for Number-Number and an NCE was found for Number-Symbol.

Appendix C. Mean Error RTs and Error percentages in the experiments.

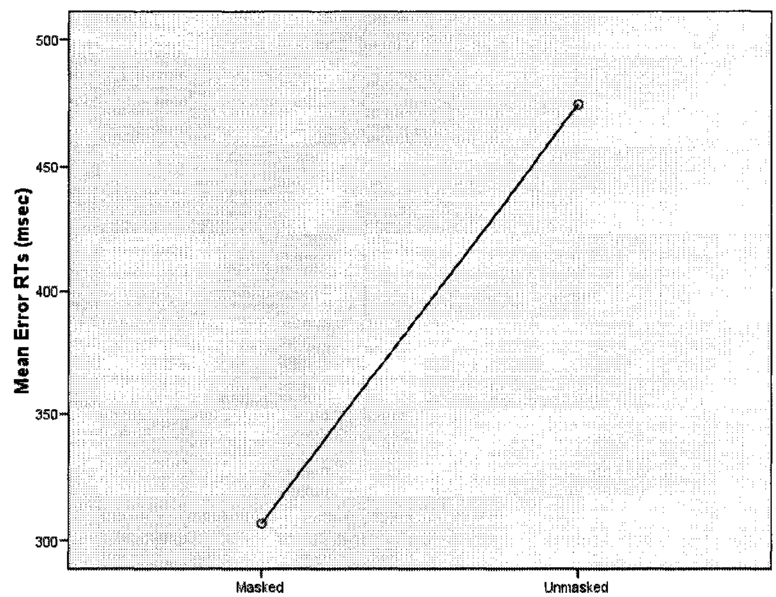

Figure 1. Experiment 1: Mean error RTs in the masked and unmasked trials.

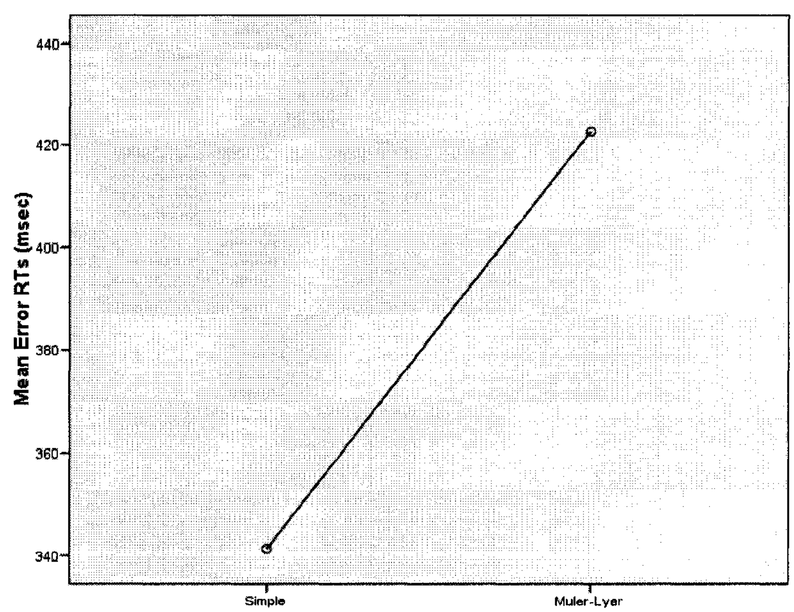

Figure 2. Experiment 1: Mean error RTs in the congruent and incongruent trials.

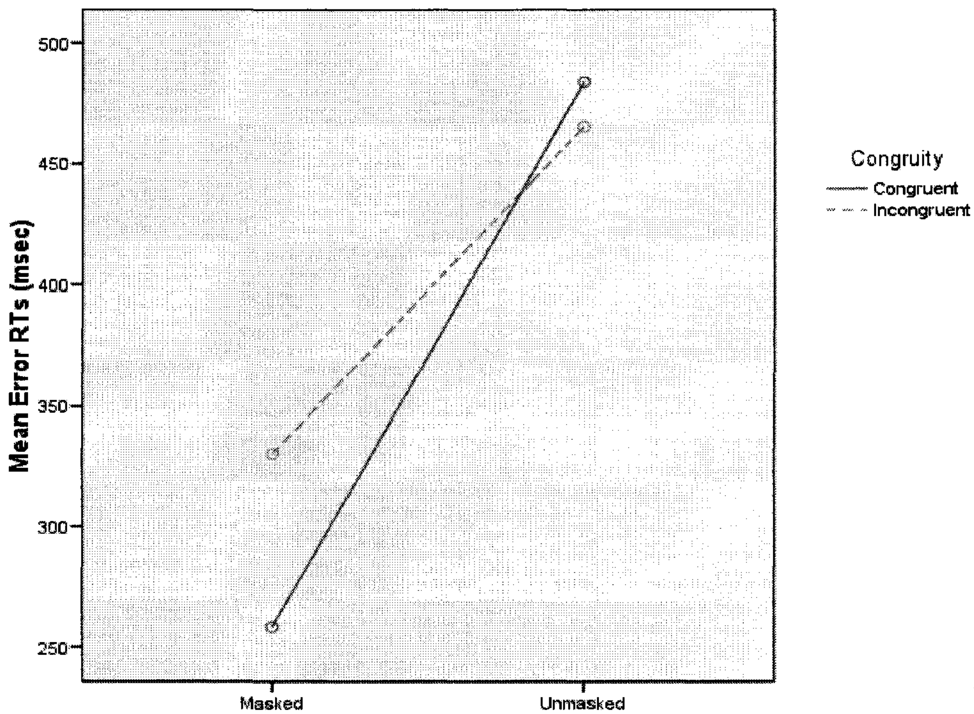

Figure 3. Experiment 1: Mean error RTs in the masking by congruency interaction.

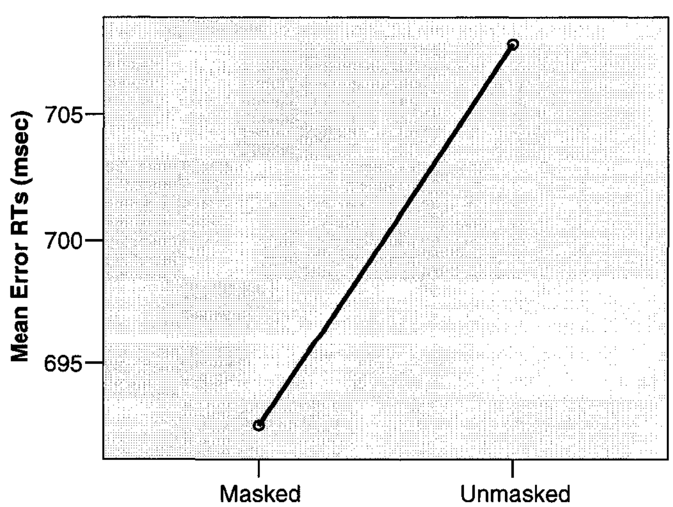

Figure 4. Experiment 2: Mean error RTs in the masked and unmasked trials.

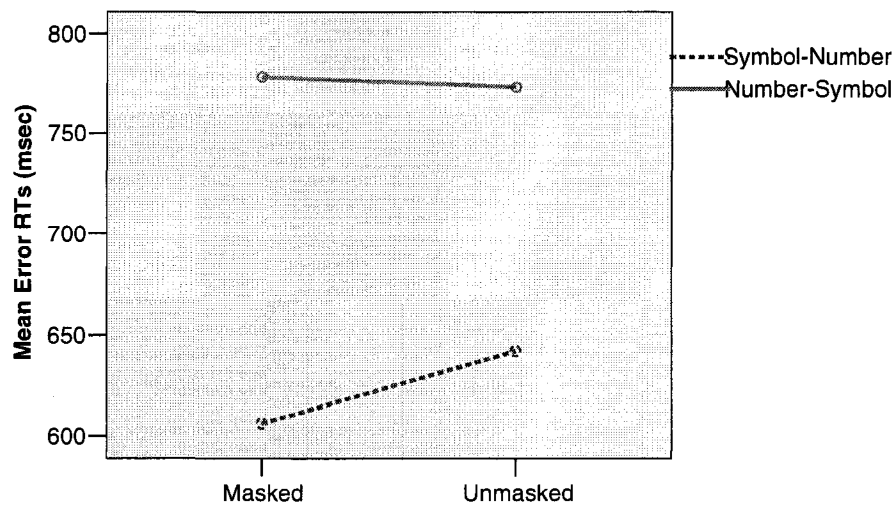

Figure 5. Experiment 2: Mean error RTs in the masking by type interaction.

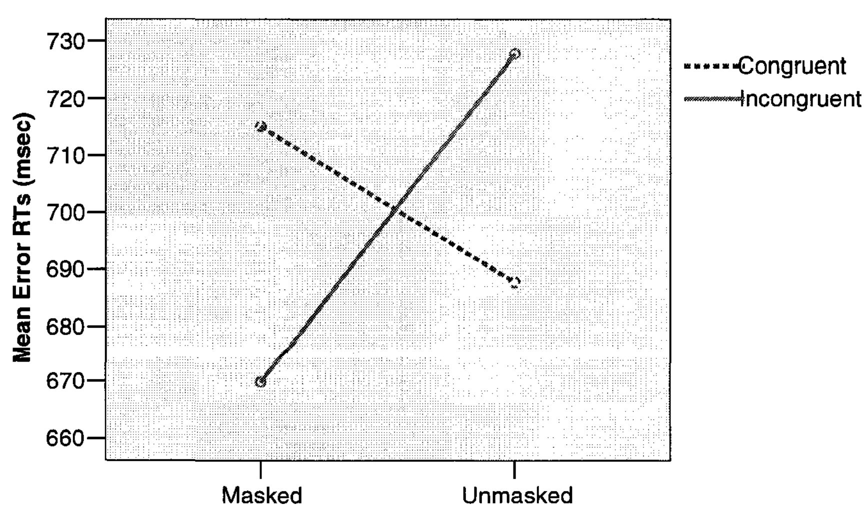

Figure 6. Experiment 2: Mean error RTs in the masking by congruency interaction.

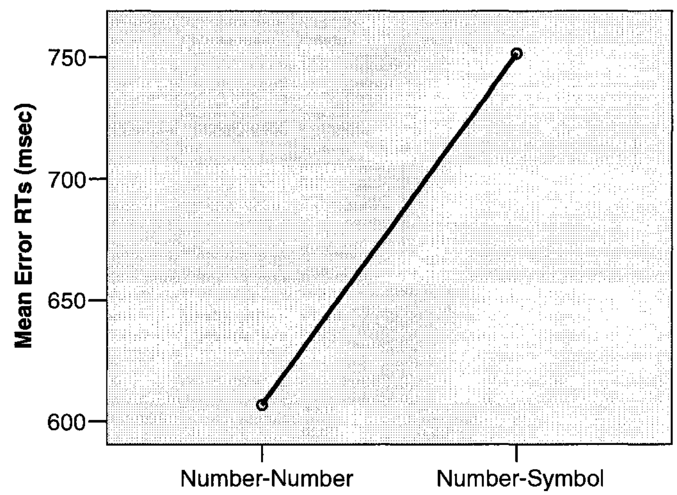

Figure 7. Experiments 3 and 4 together: Mean error RTs in the Number-Number and Number-Symbol trials.

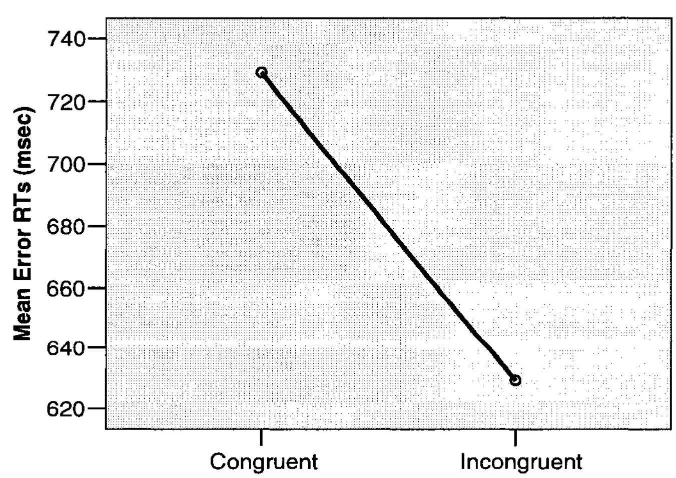

Figure 8. Experiments 3 and 4 together: Mean error RTs in the congruent and incongruent trials.

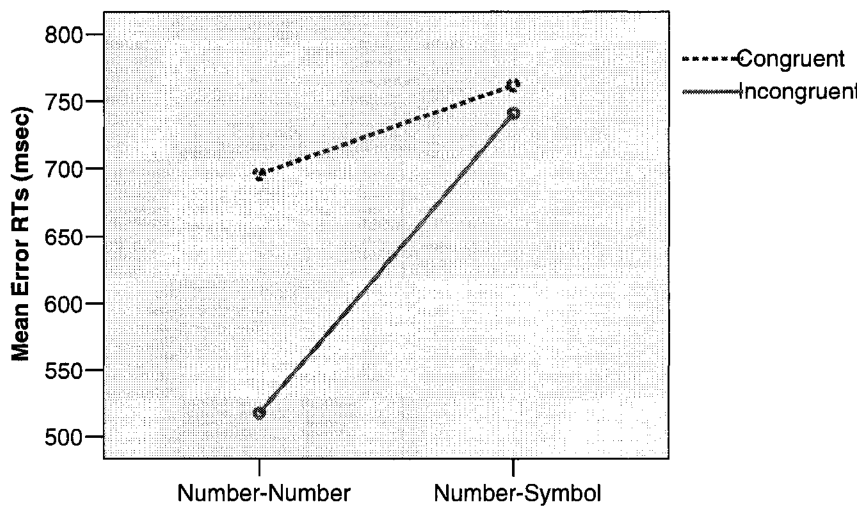

Figure 9. Experiments 3 and 4 together: Mean error RTs in the type by congruency interaction.

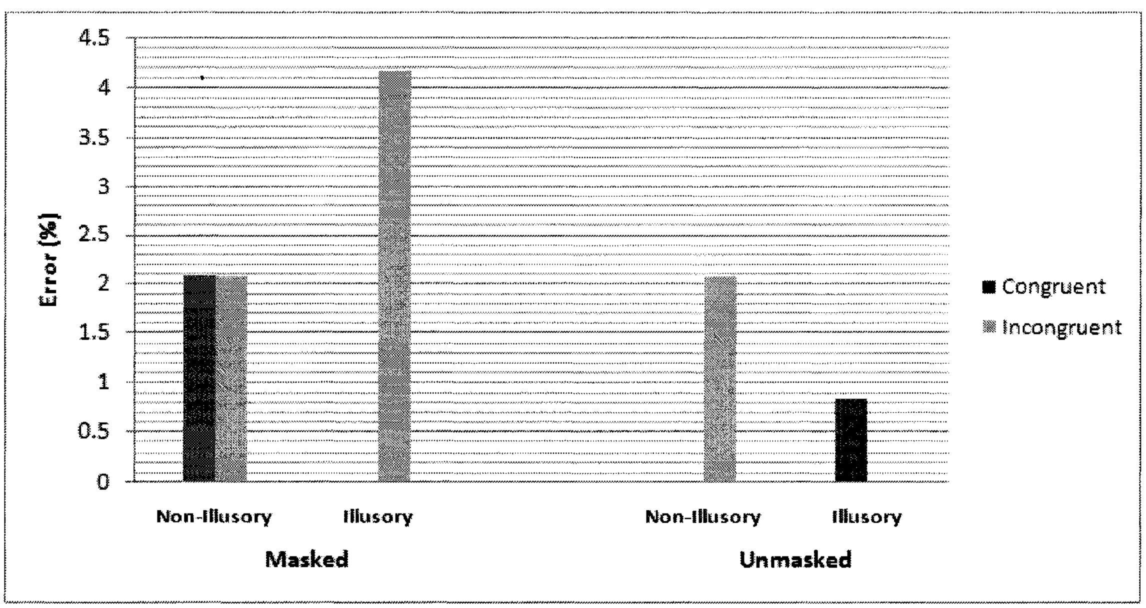

Figure 10. Error percentages in Experiment 1.

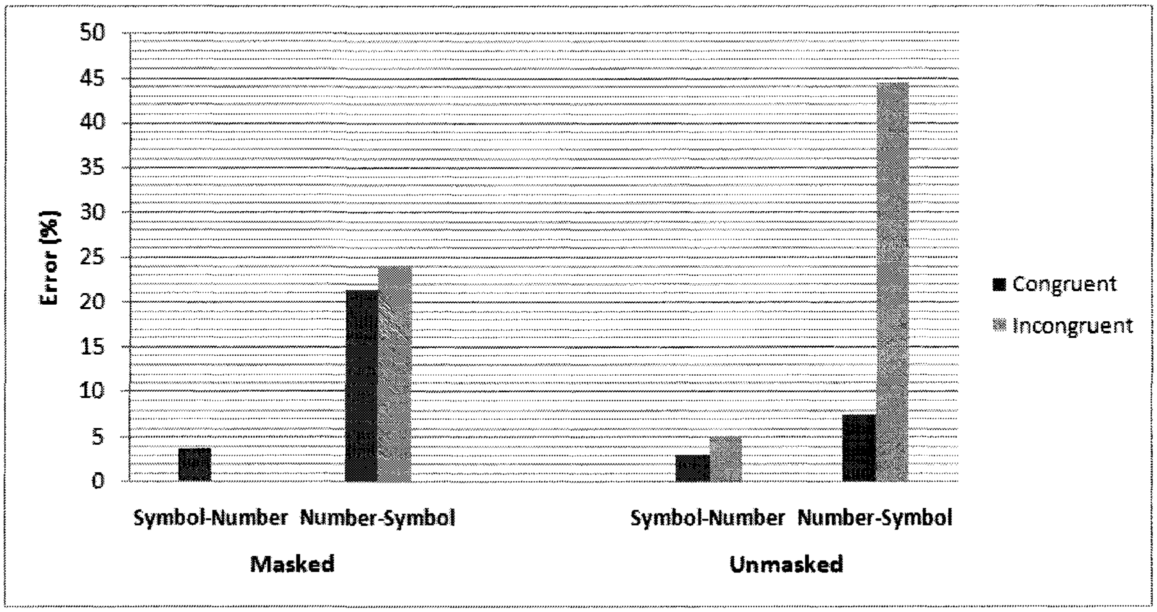

Figure 11. Error percentages in Experiment 2.

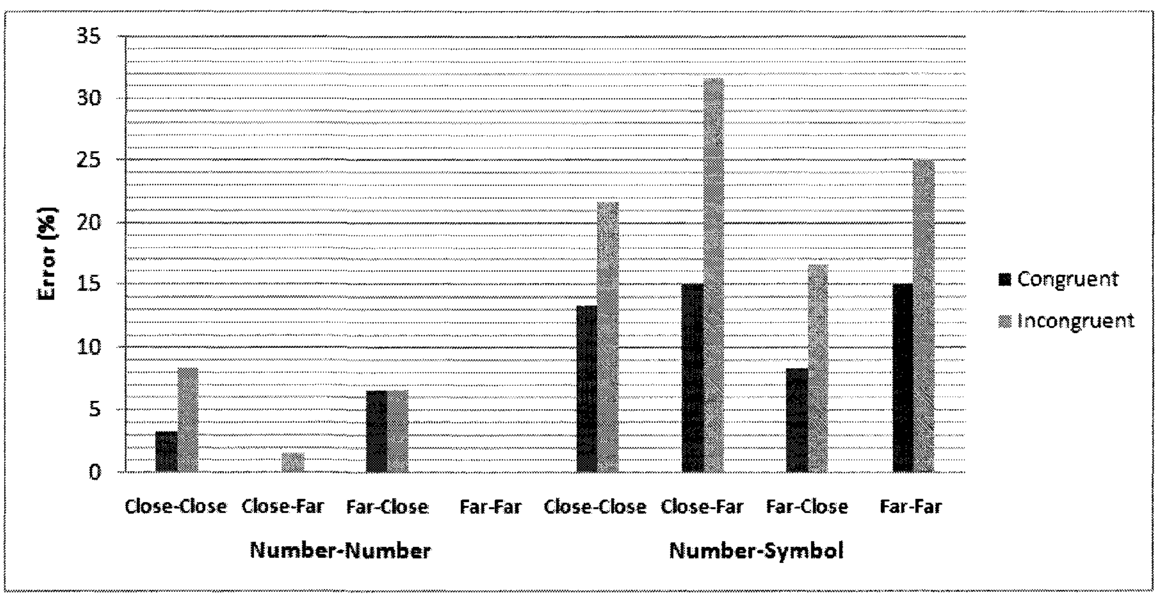

Figure 12. Error percentages in Experiment 3.

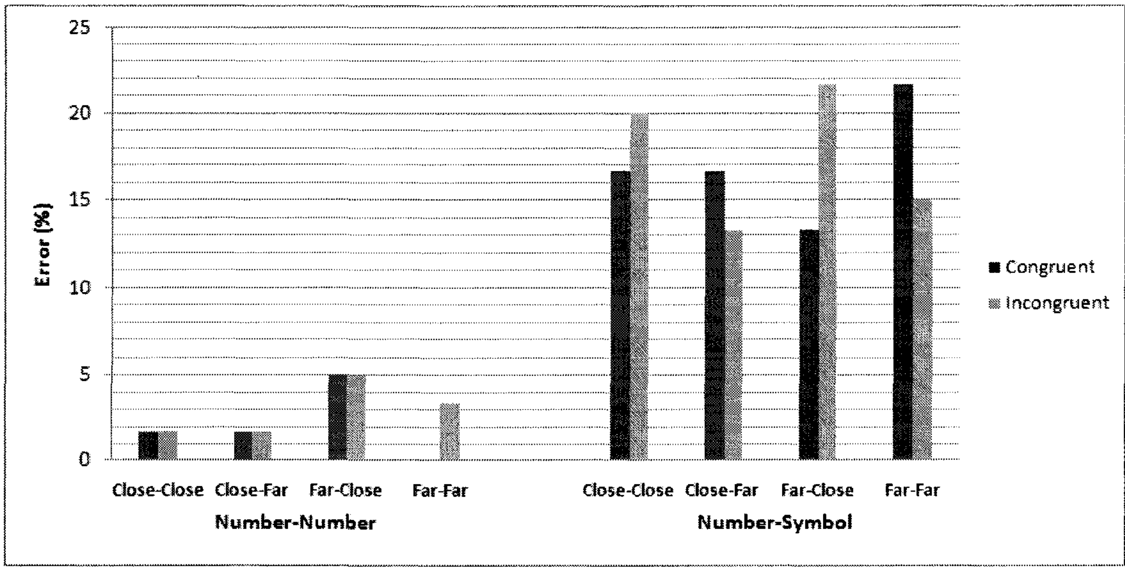

Figure 13. Error percentages in Experiment 4.

Appendix D. Model's behavior in a trial for different conditions (L-R=Left - Right; vt=X_t; NE=G_t; F-Mask=Mask; OU=CL; AR=AA; Fix=Fixation point; vACh=ACh of OA).

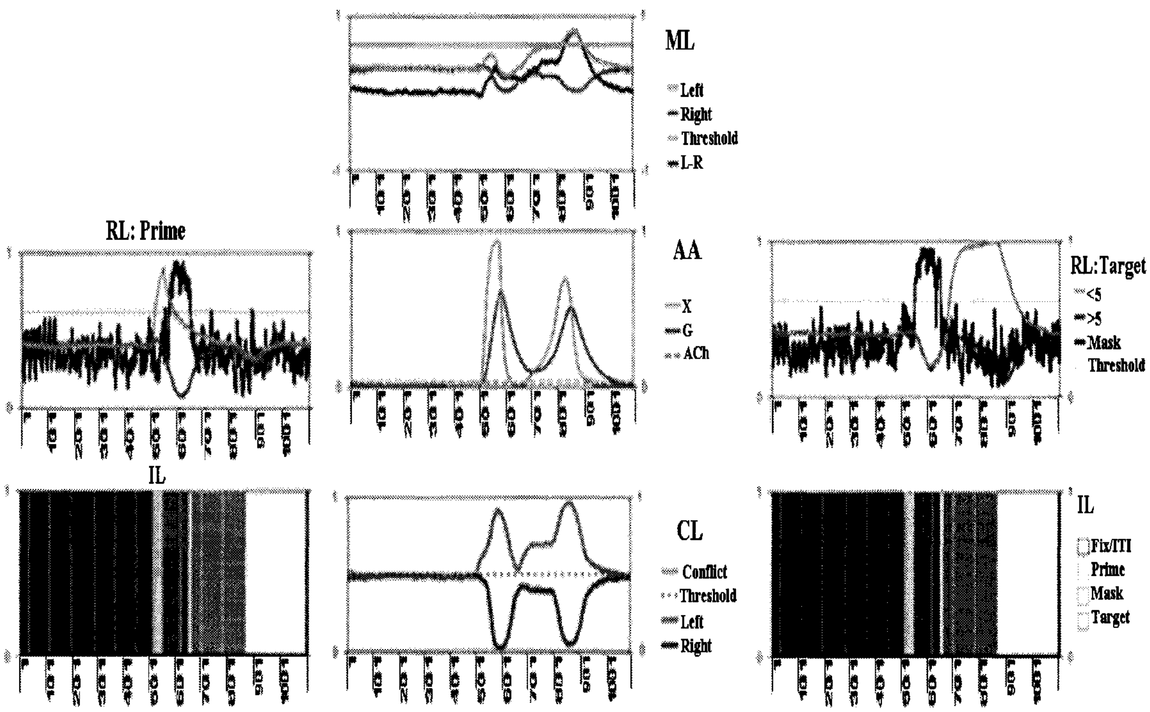

Figure 1. The activities in all layers in a congruent trial in prime-target strength 3-3 and 125 mask-target SOA that crosses the threshold after 779 cycles.

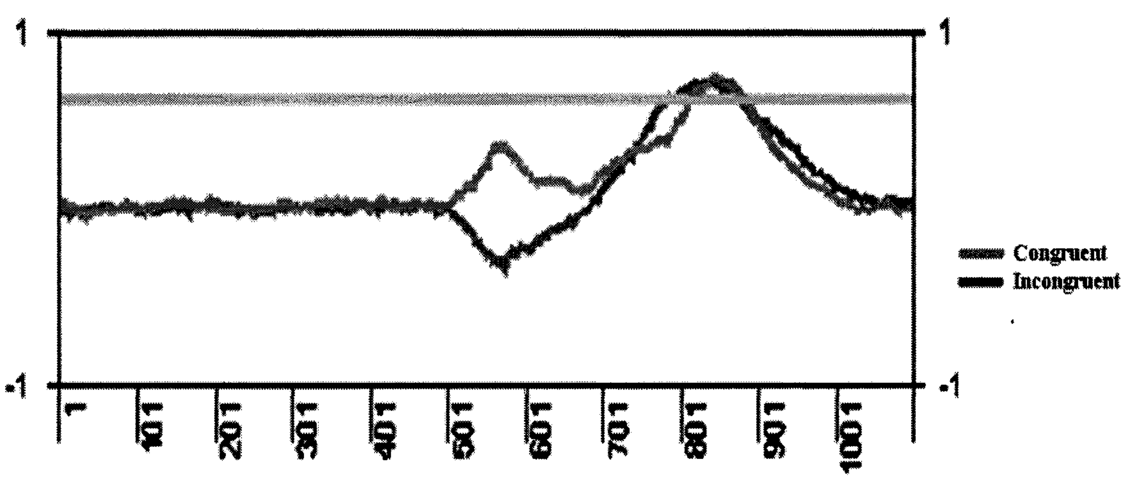

Figure 2. The activation differences of the Left vs. Right ML units in a congruent and an incongruent trial (see Figure 1 and 4-5).

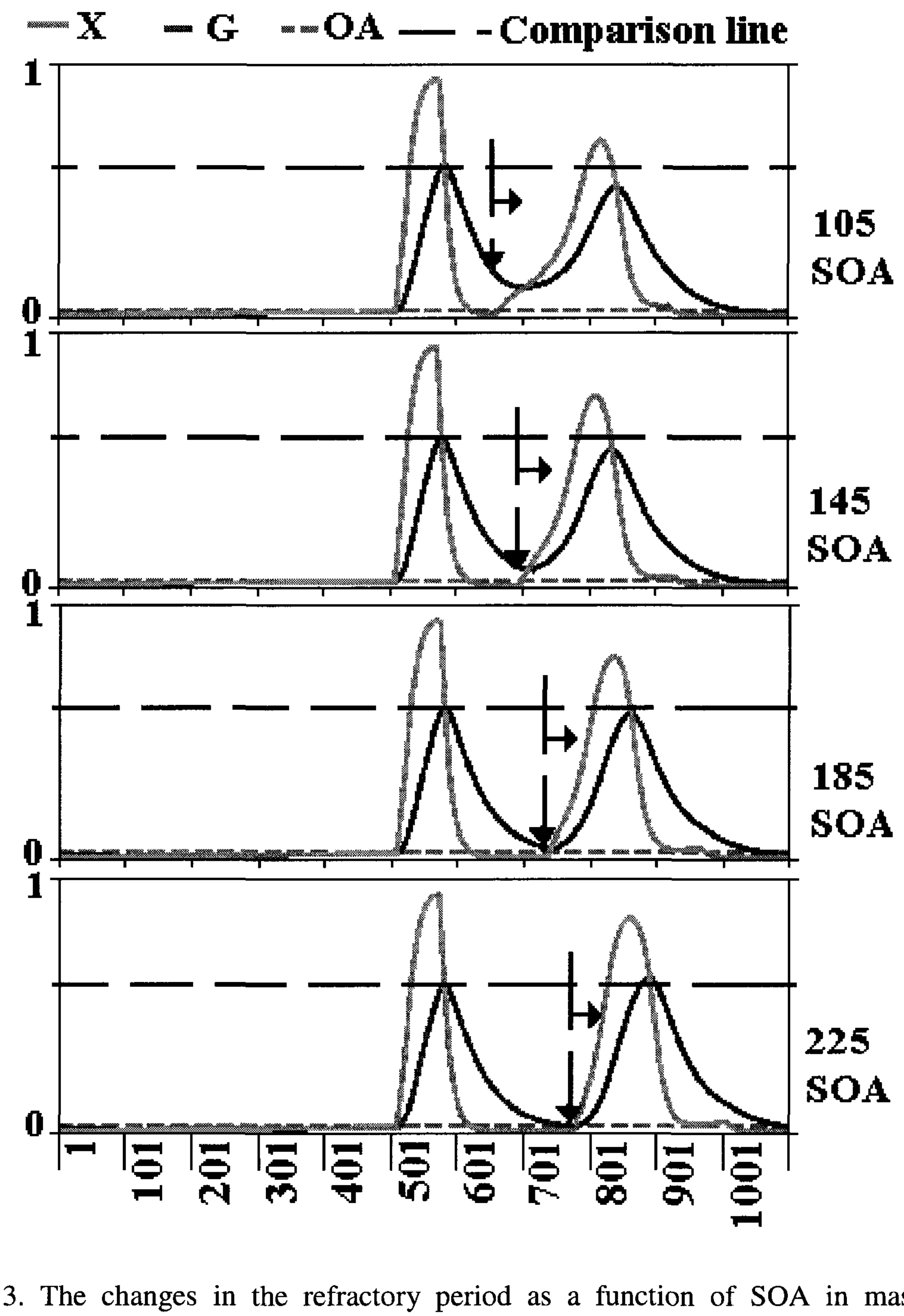

Figure 3. The changes in the refractory period as a function of SOA in masked congruent trials and prime-target strength 3-3 for mask-target SOAs105, 145, 185, and 225.

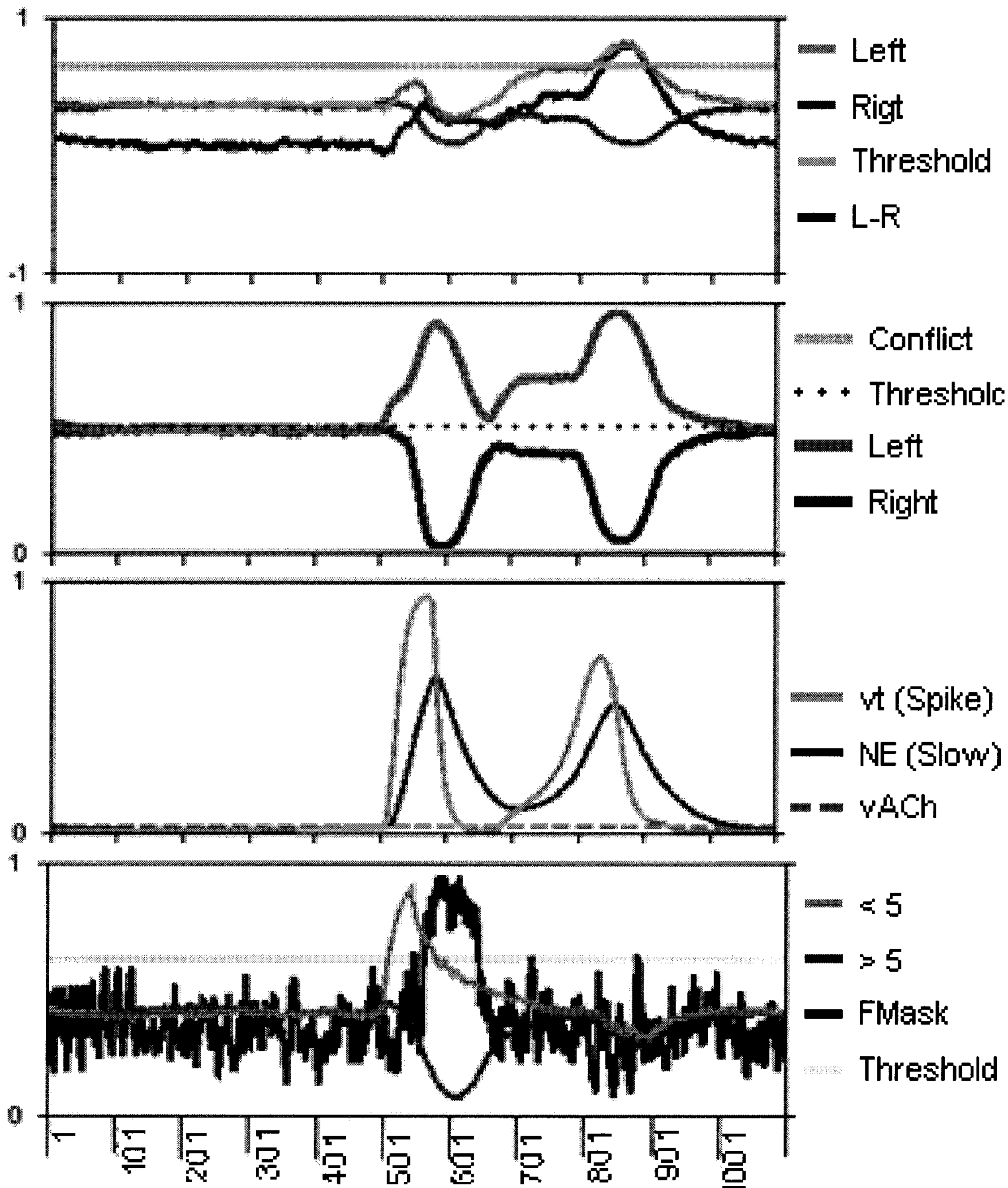

Figure 4. A congruent trial in prime-target strength 3-3 and 125 mask-target SOA that crosses the threshold after 779 cycles (the same as the one in Figure 1) (from the top, ML, CL, AA, RL-prime, but RL-target and IL are not shown).

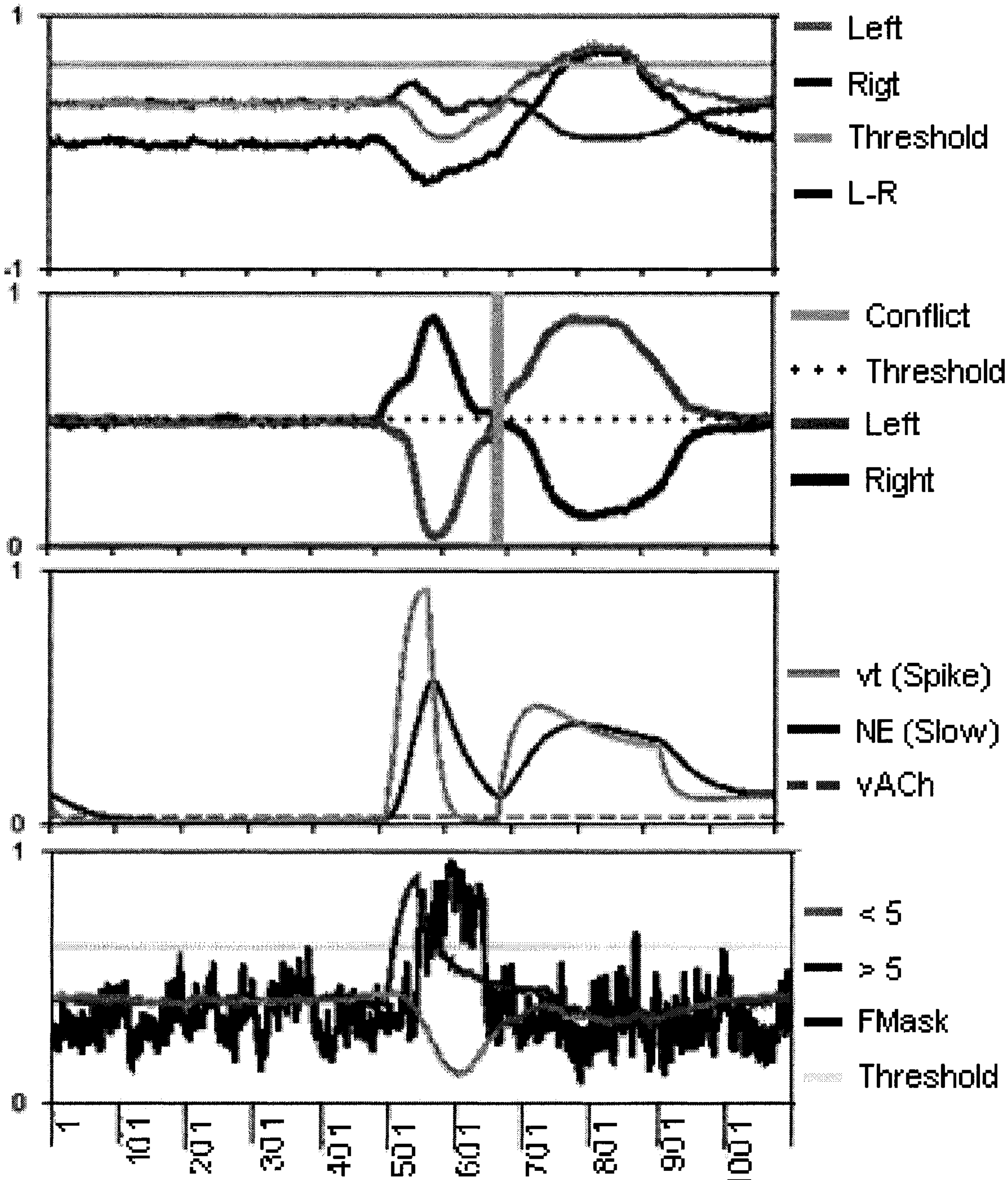

Figure 5. An incongruent trial with the same condition in Figure 4 that crosses the threshold after 762 cycles (from the top, ML, CL, AA, RL-prime, but RL-target and IL are not shown).

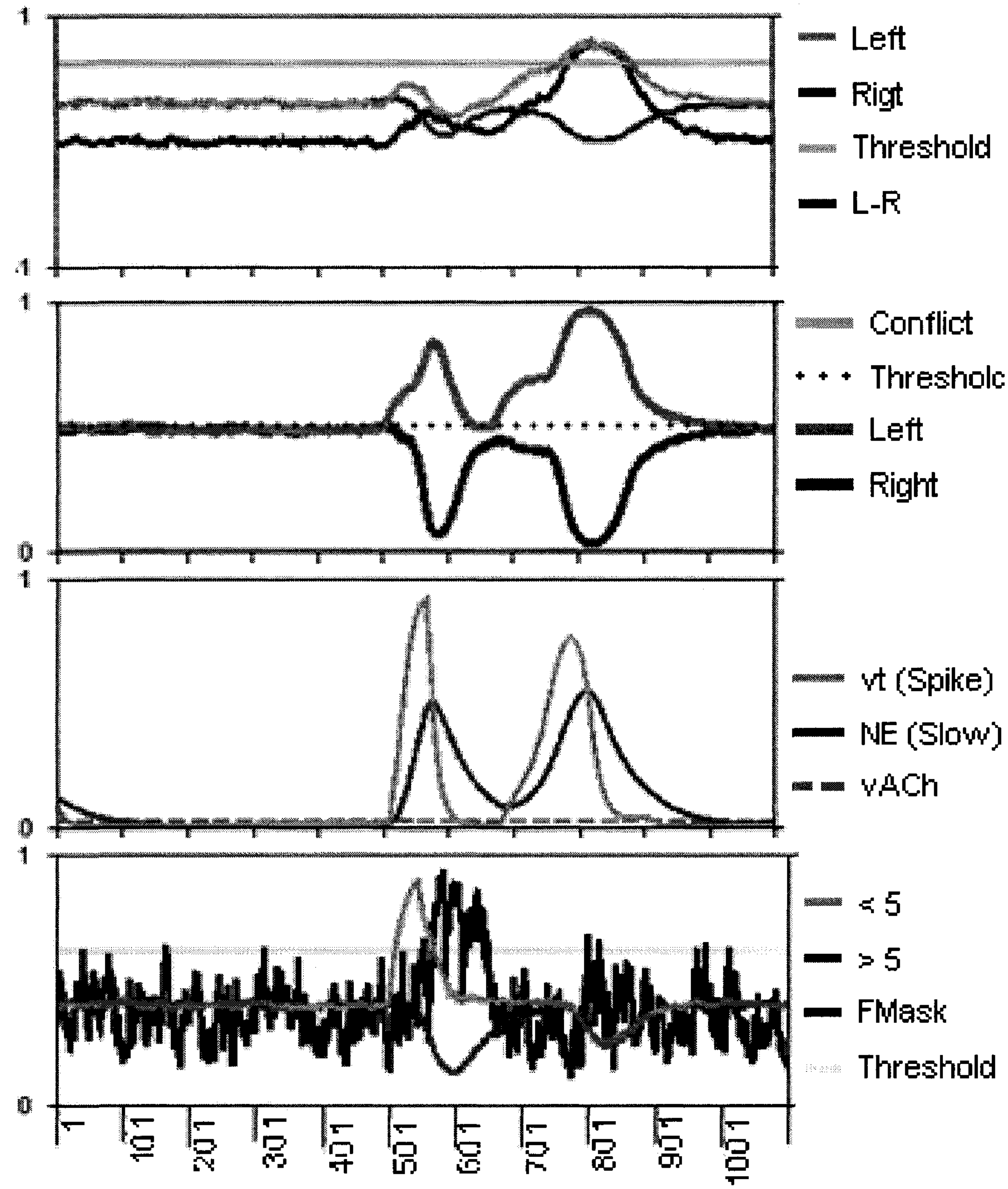

Figure 6. A congruent trial in prime-target strength 3-3 and 125 mask-target SOA with low (.65) mask similarity that crosses the threshold after 772 cycles (from the top, ML, CL, AA, RL-prime, but RL-target and IL are not shown).

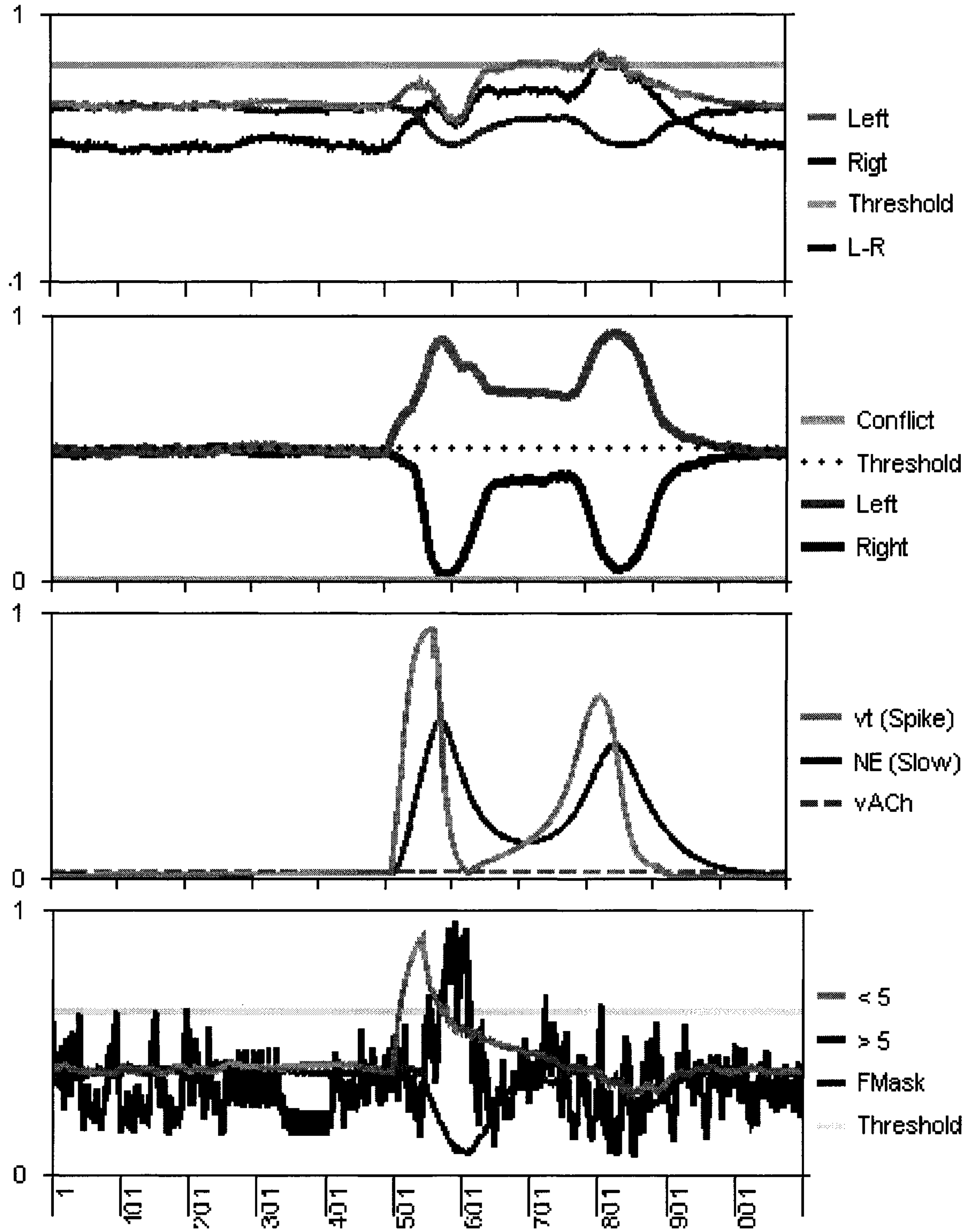

Figure 7. A congruent trial in prime-target strength 3-3 and 71 mask-target SOA that crosses the threshold after 698 cycles (from the top, ML, CL, AA, RL-prime, but RL-target and IL are not shown).

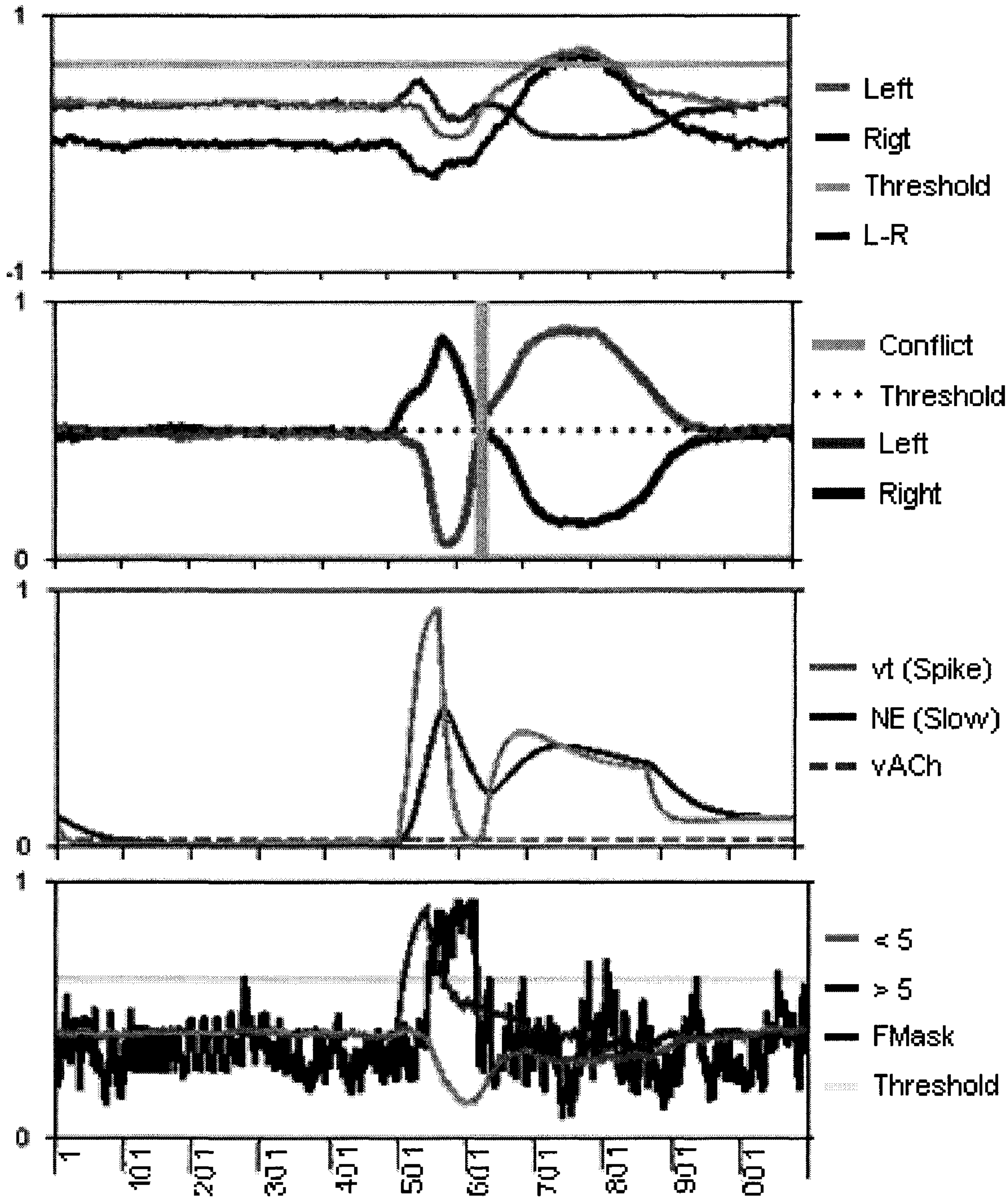

Figure 8. An incongruent trial in prime-target strength 3-3 and 71 mask-target SOA that crosses the threshold after 721 cycles (from the top, ML, CL, AA, RL-prime, but RL-target and IL are not shown).

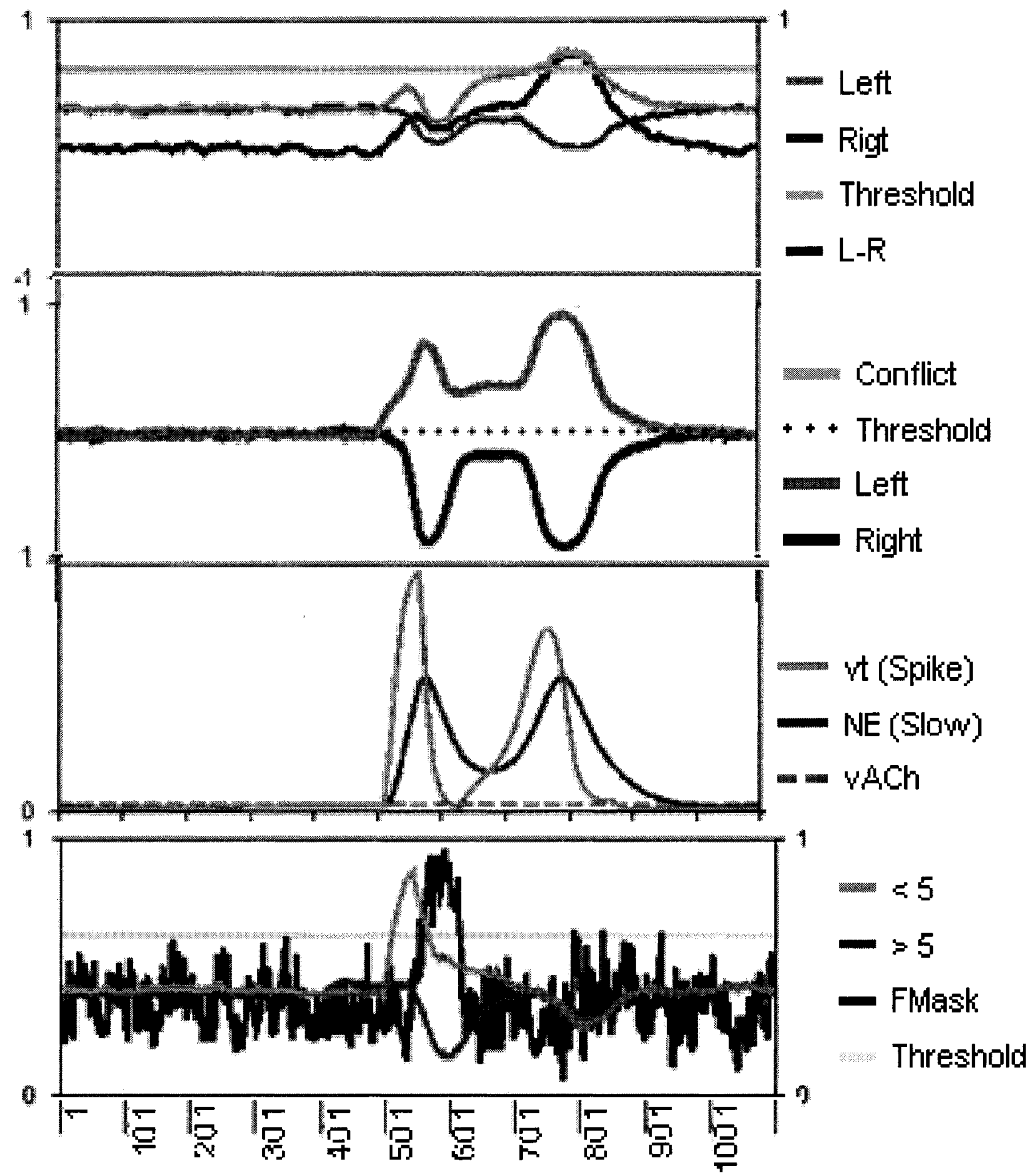

Figure 9. A congruent trial in prime-target strength 2.5-2 and 71 mask-target SOA that crosses the threshold after 744 cycles (from the top, ML, CL, AA, RL-prime, but RL-target and IL are not shown).

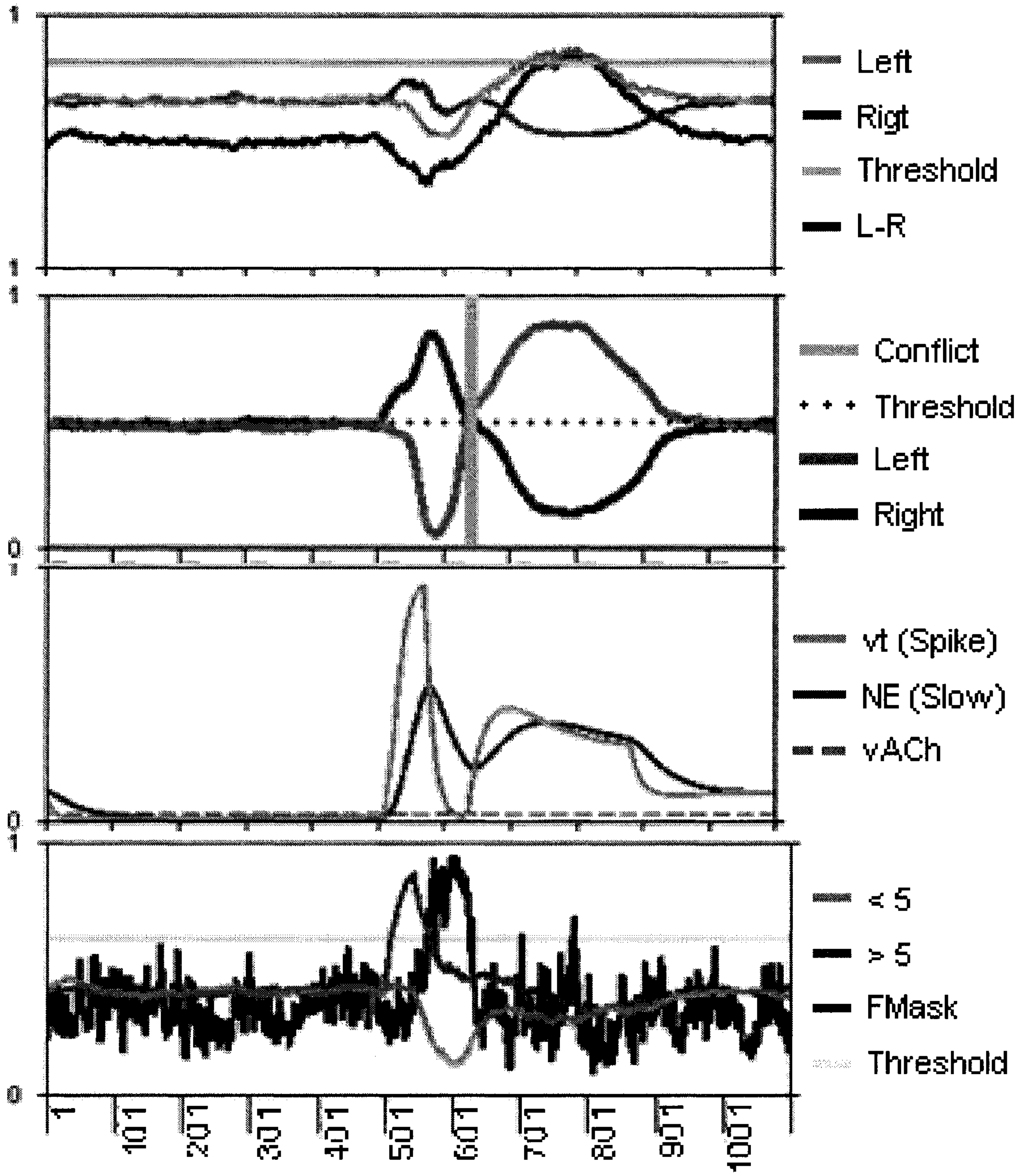

Figure 10. An incongruent trial in prime-target strength 2.5-2 and 71 mask-target SOA that crosses the threshold after 727 cycles (from the top, ML, CL, AA, RL-prime, but RL-target and IL are not shown).

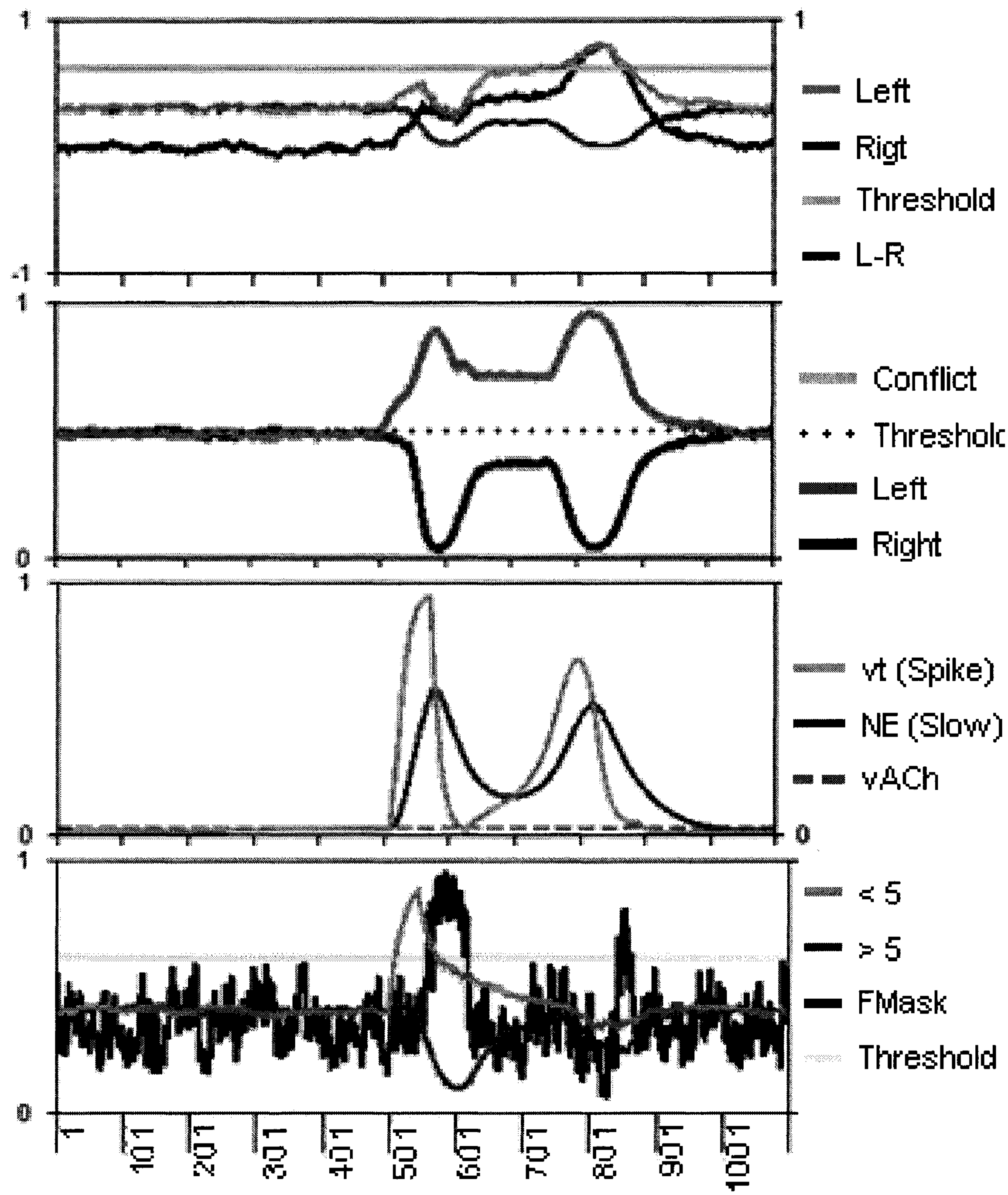

Figure 11. A congruent trial in prime-target strength 2.5-3 and 71 mask-target SOA that crosses the threshold after 702 cycles (from the top, ML, CL, AA, RL-prime, but RL-target and IL are not shown).

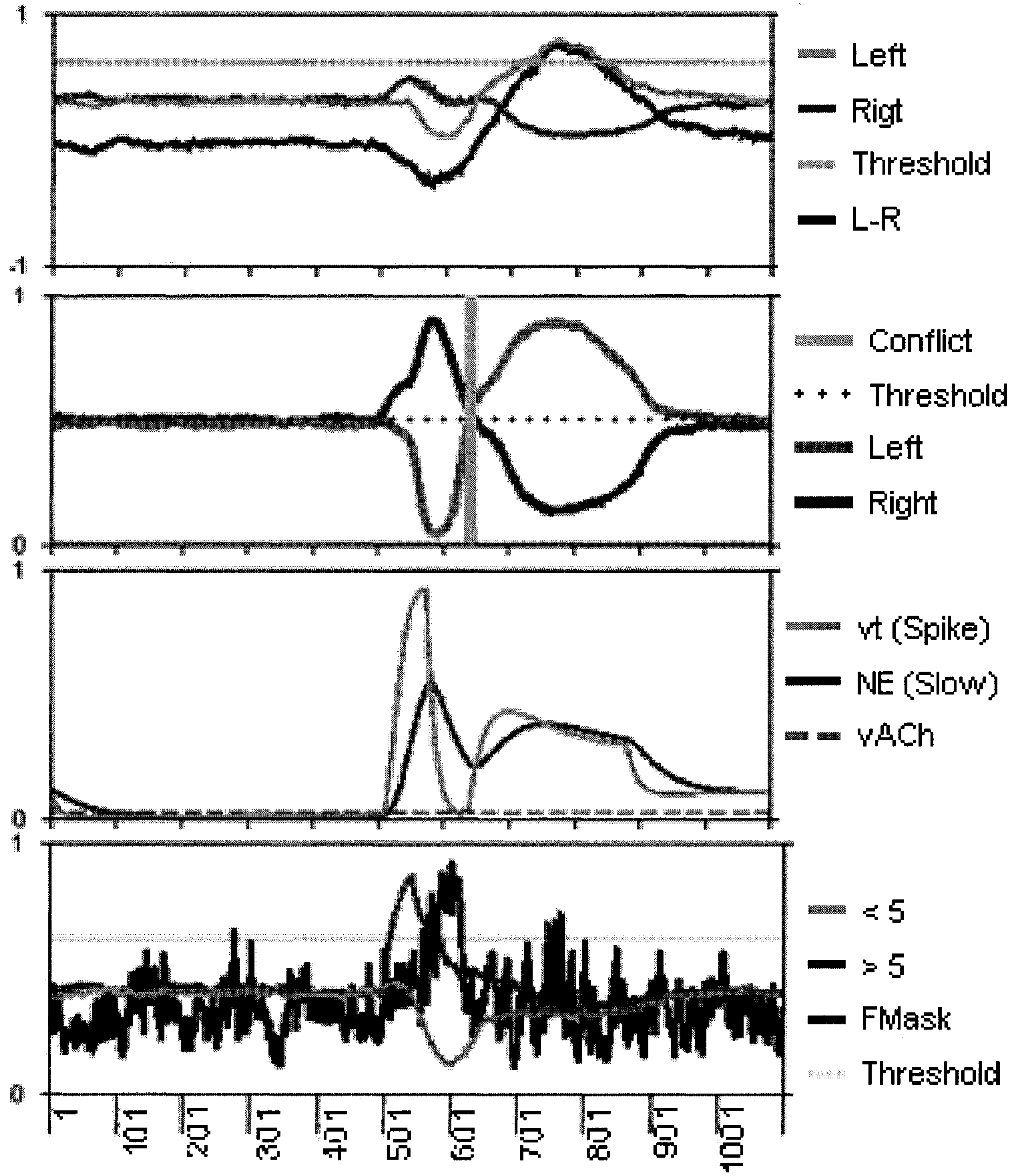

Figure 12. An incongruent trial in prime-target strength 2.5-3 and 71 mask-target SOA that crosses the threshold after 719 cycles (from the top, ML, CL, AA, RL-prime, but RL-target and IL are not shown).

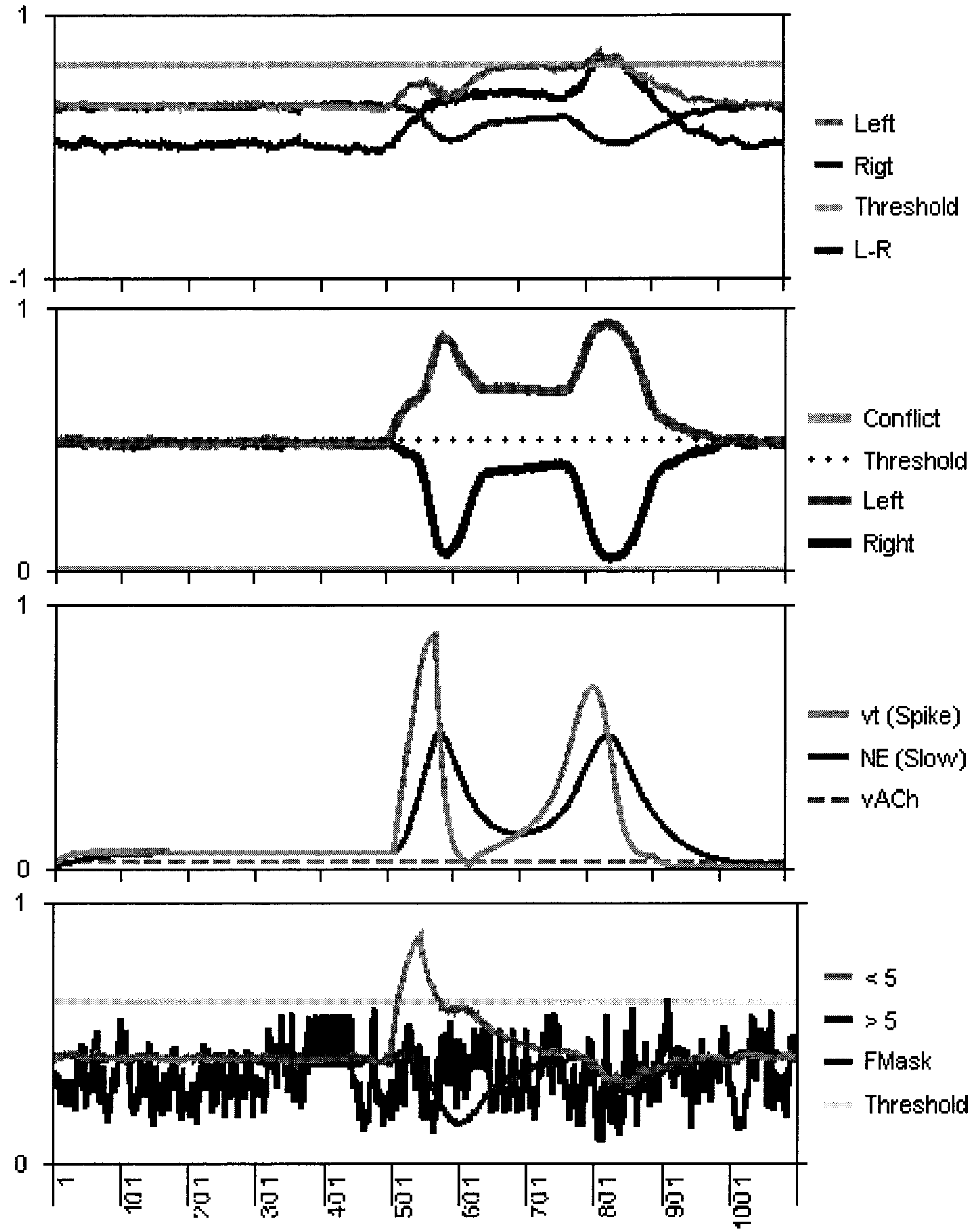

Figure 13. An unmasked congruent trial with a slightly relevant prime in prime-target strength 2.5-2 and 71 mask-target SOA that crosses the threshold after 722 cycles (from the top, ML, CL, AA, RL-prime, but RL-target and IL are not shown).

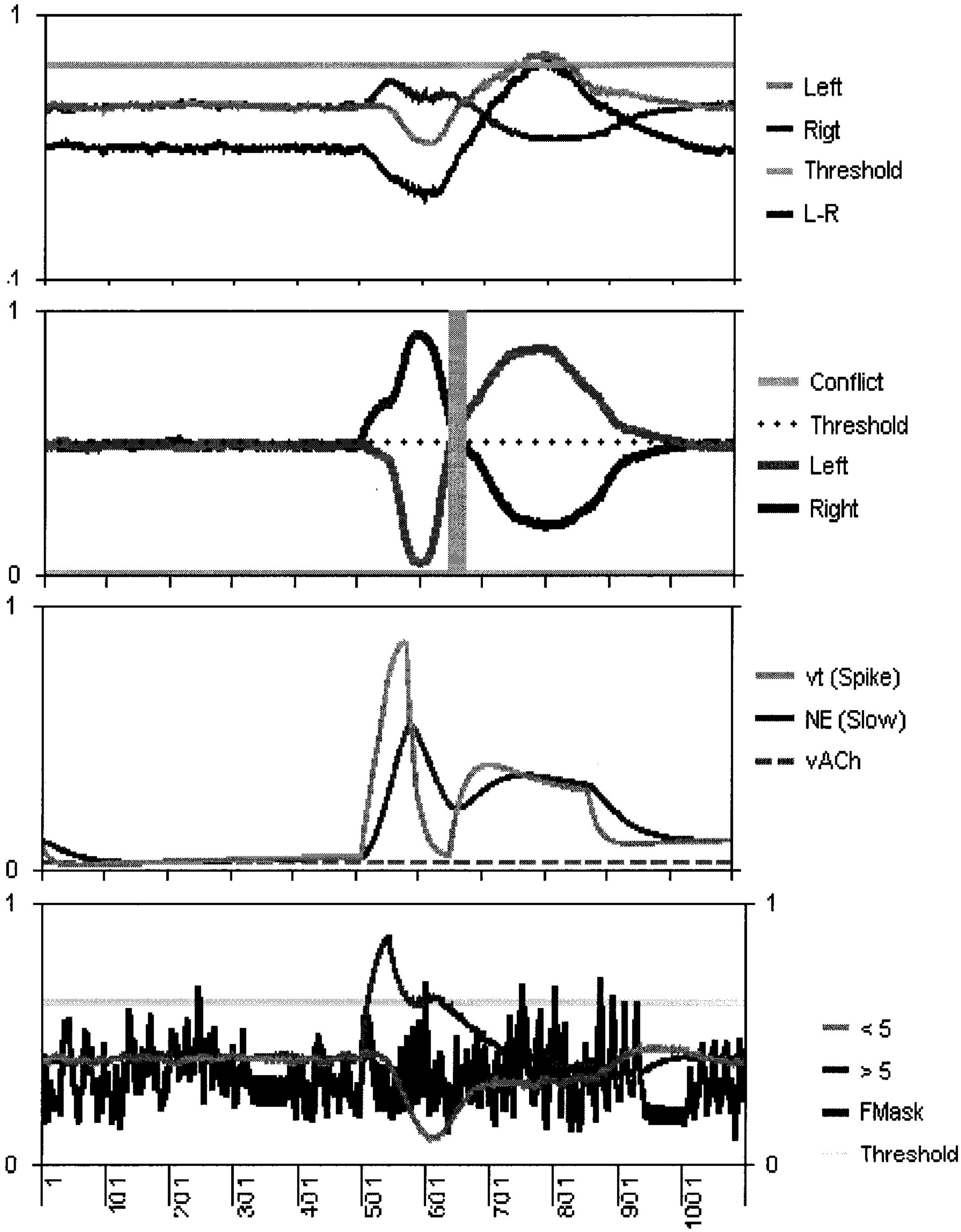

Figure 14. An unmasked incongruent trial with a slightly relevant prime in prime-target strength 2.5-2 and 71 mask-target SOA that crosses the threshold after 745 cycles (from the top, ML, CL, AA, RL-prime, but RL-target and IL are not shown).

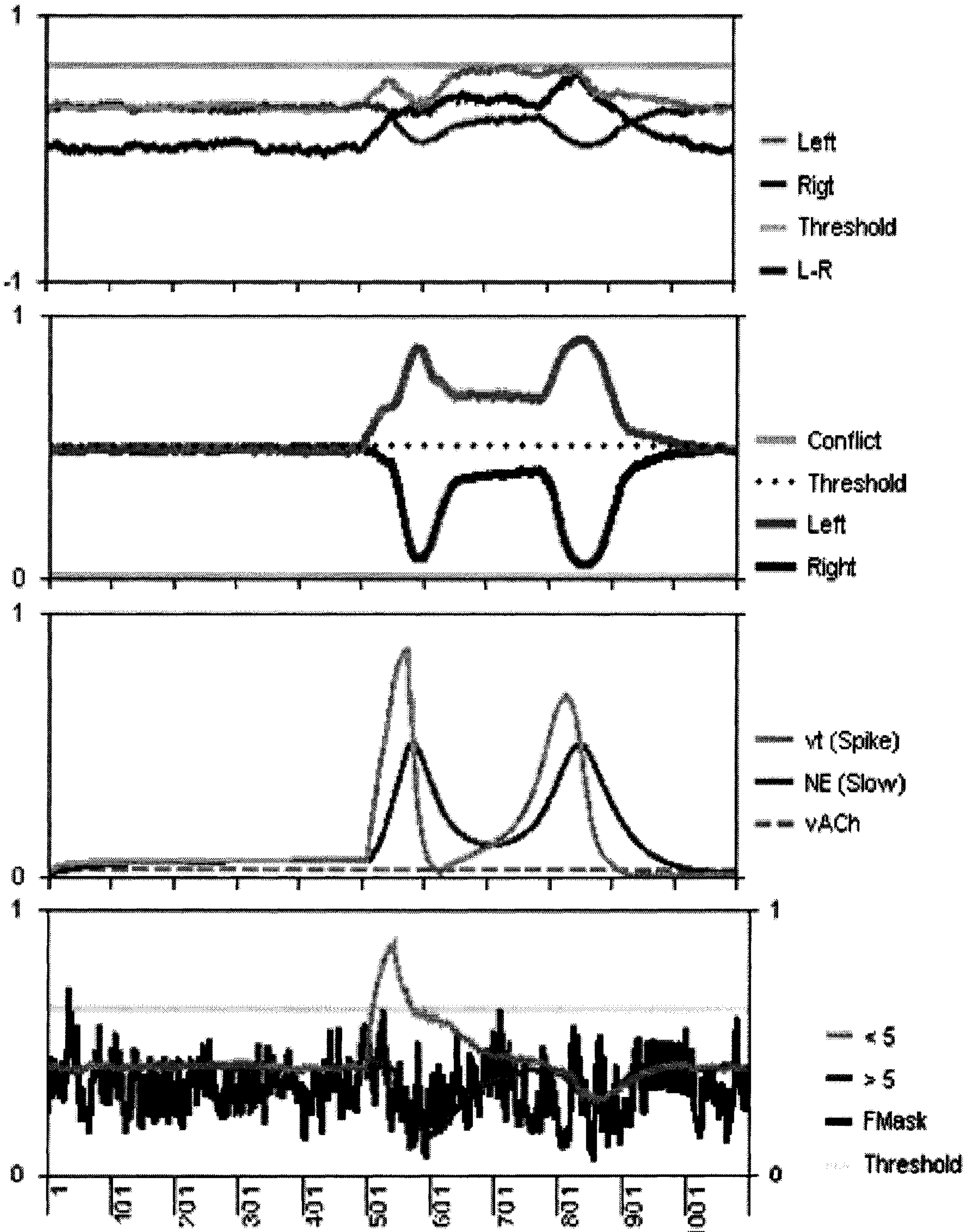

Figure 15. An unmasked congruent trial with irrelevant prime in prime-target strength 2.5-2 and 71 mask-target SOA that crosses the threshold after 735 cycles (from the top, ML, CL, AA, RL-prime, but RL-target and IL are not shown).

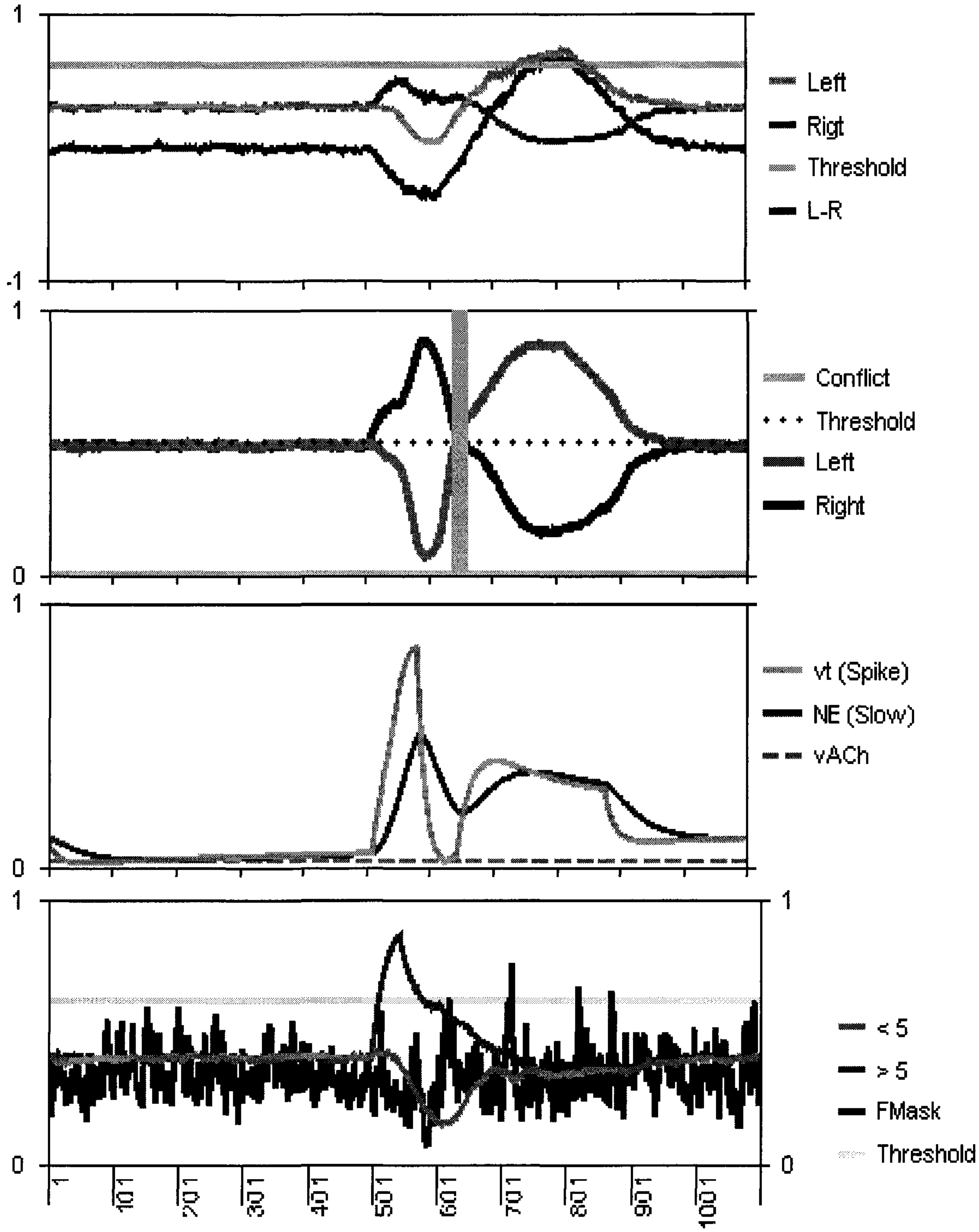

Figure 16. An unmasked incongruent trial with irrelevant prime in prime-target strength 2.5-2 and 71 mask-target SOA that crosses the threshold after 738 cycles (from the top, ML, CL, AA, RL-prime, but RL-target and IL are not shown).

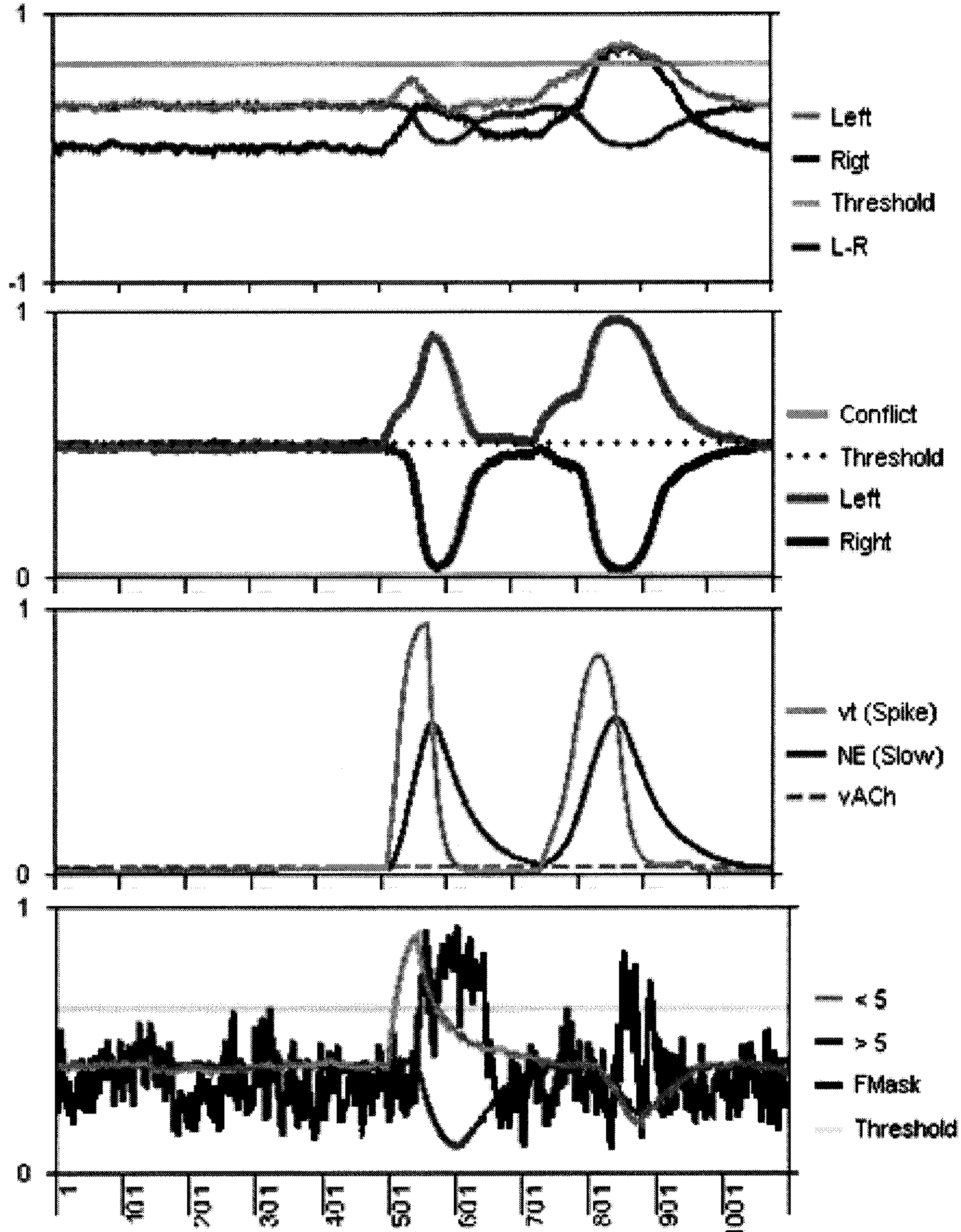

Figure 17. A masked congruent trial in prime-target strength 3-3 and 234 prime-target SOA that crosses the threshold after 819 cycles (from the top, ML, CL, AA, RL-prime, but RL-target and IL are not shown).

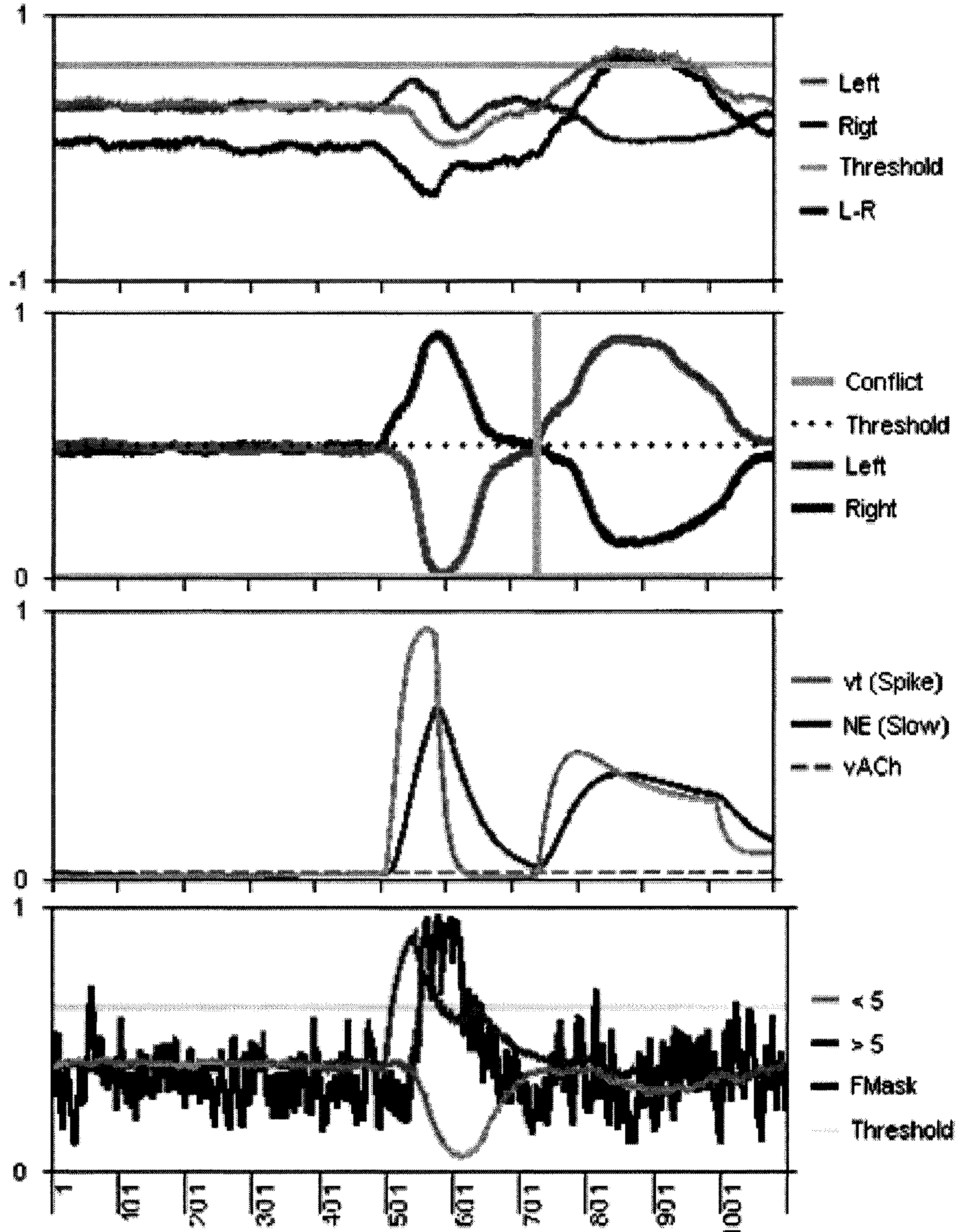

Figure 18. A masked incongruent trial in prime-target strength 3-3 and 234 prime-target SOA that crosses the threshold after 818 cycles (from the top, ML, CL, AA, RL-prime, but RL-target and IL are not shown).

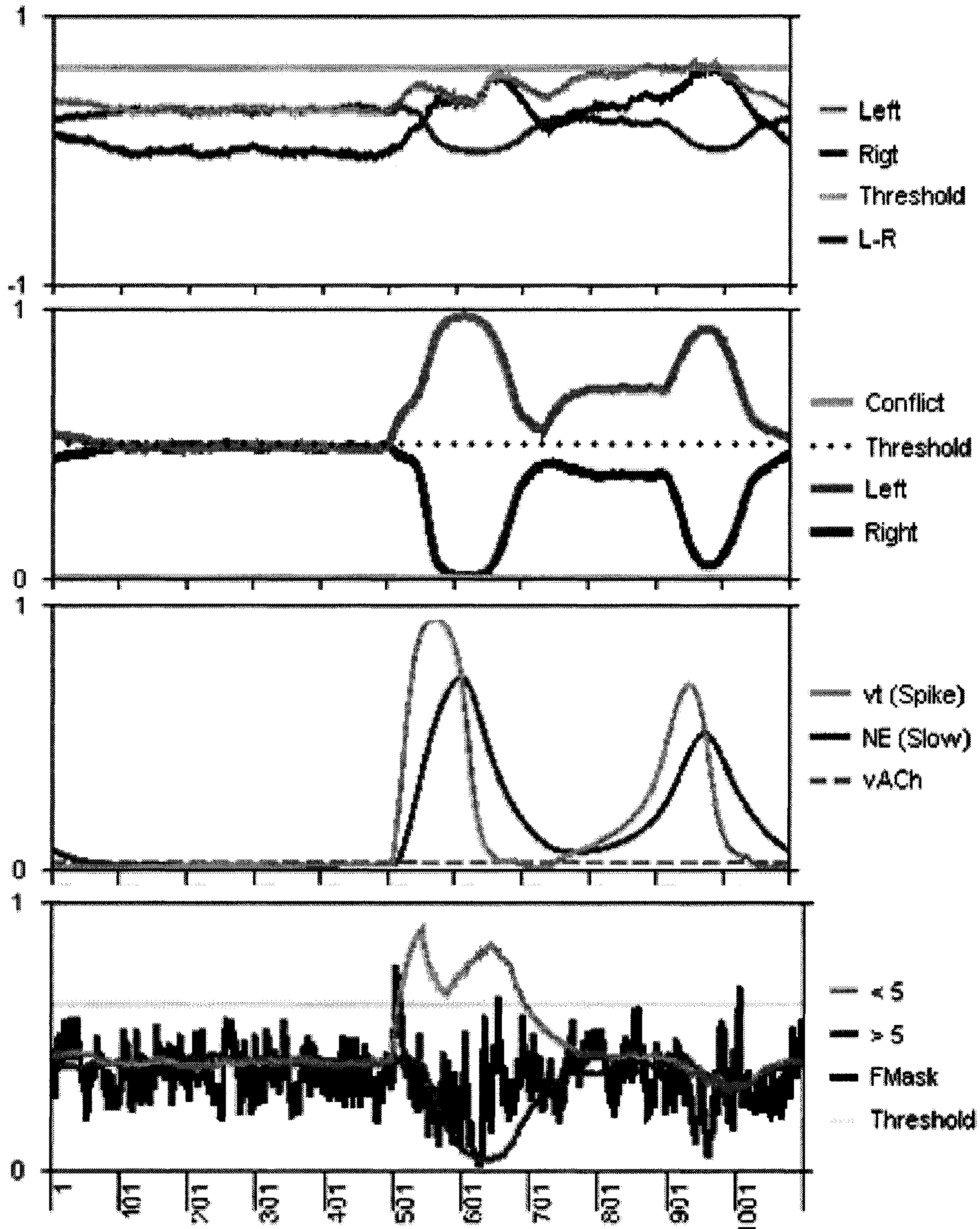

Figure 19. An unmasked congruent trial with relevant prime in prime-target strength 3-3 and 234 prime-target SOA that crosses the threshold after 876 cycles (from the top, ML, CL, AA, RL-prime, but RL-target and IL are not shown).

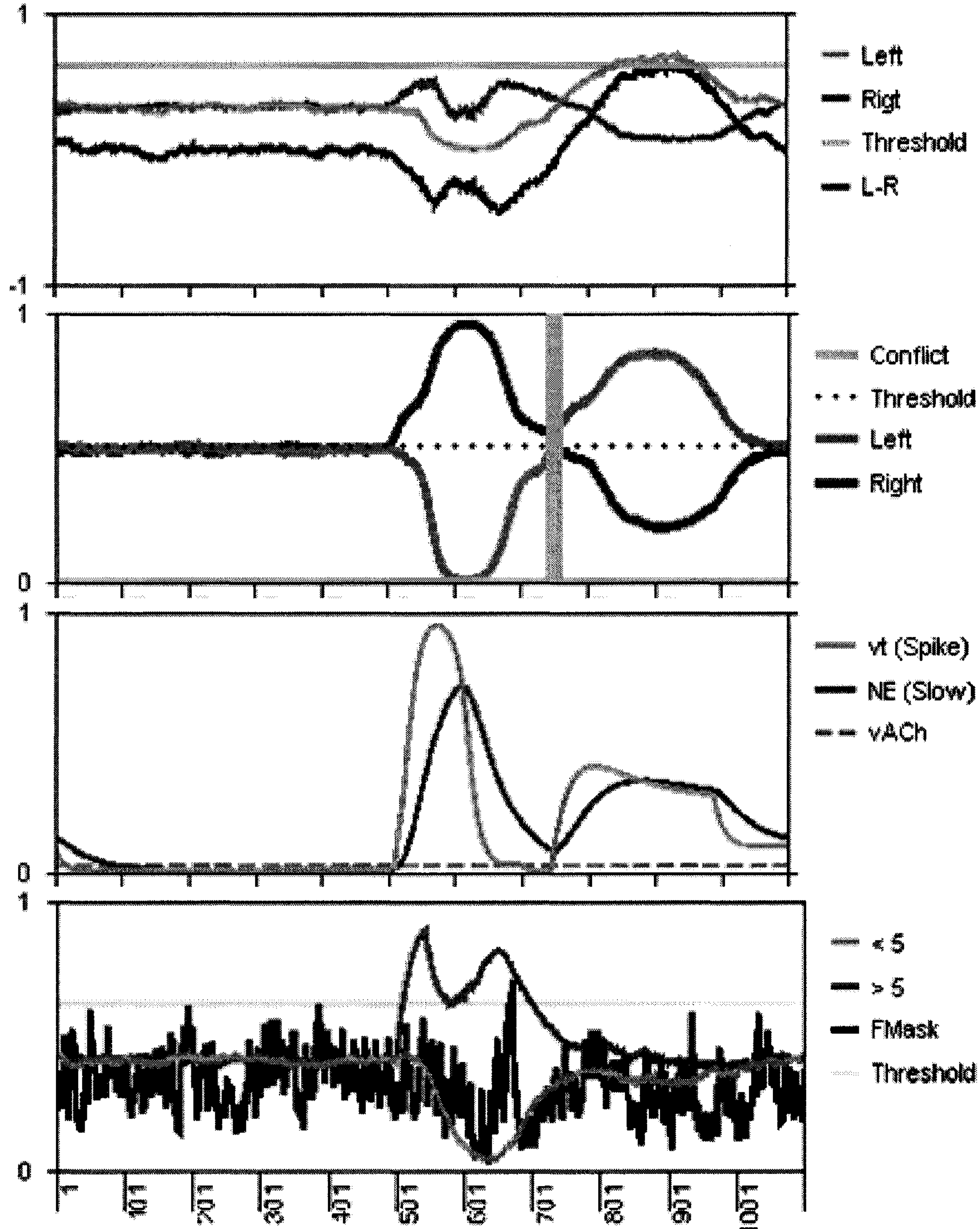

Figure 20. An unmasked incongruent trial with relevant prime in prime-target strength 3-3 and 234 prime-target SOA that crosses the threshold after 840 cycles (from the top, ML, CL, AA, RL-prime, but RL-target and IL are not shown).

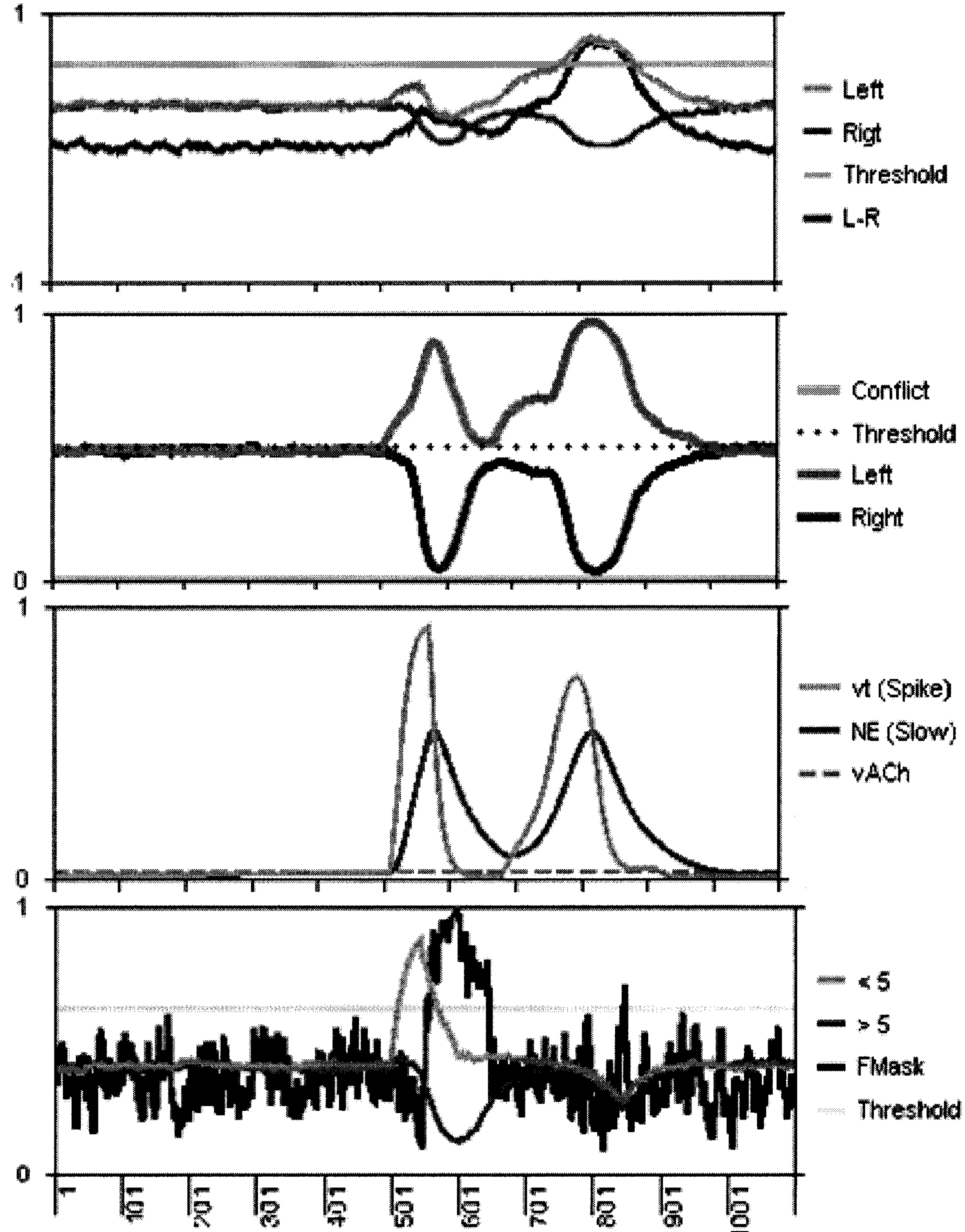

Figure 21. A congruent trial in prime-target strength 2.5-2.5 and 125 mask-target SOA that crosses the threshold after 774 cycles (from the top, ML, CL, AA, RL-prime, but RL-target and IL are not shown).

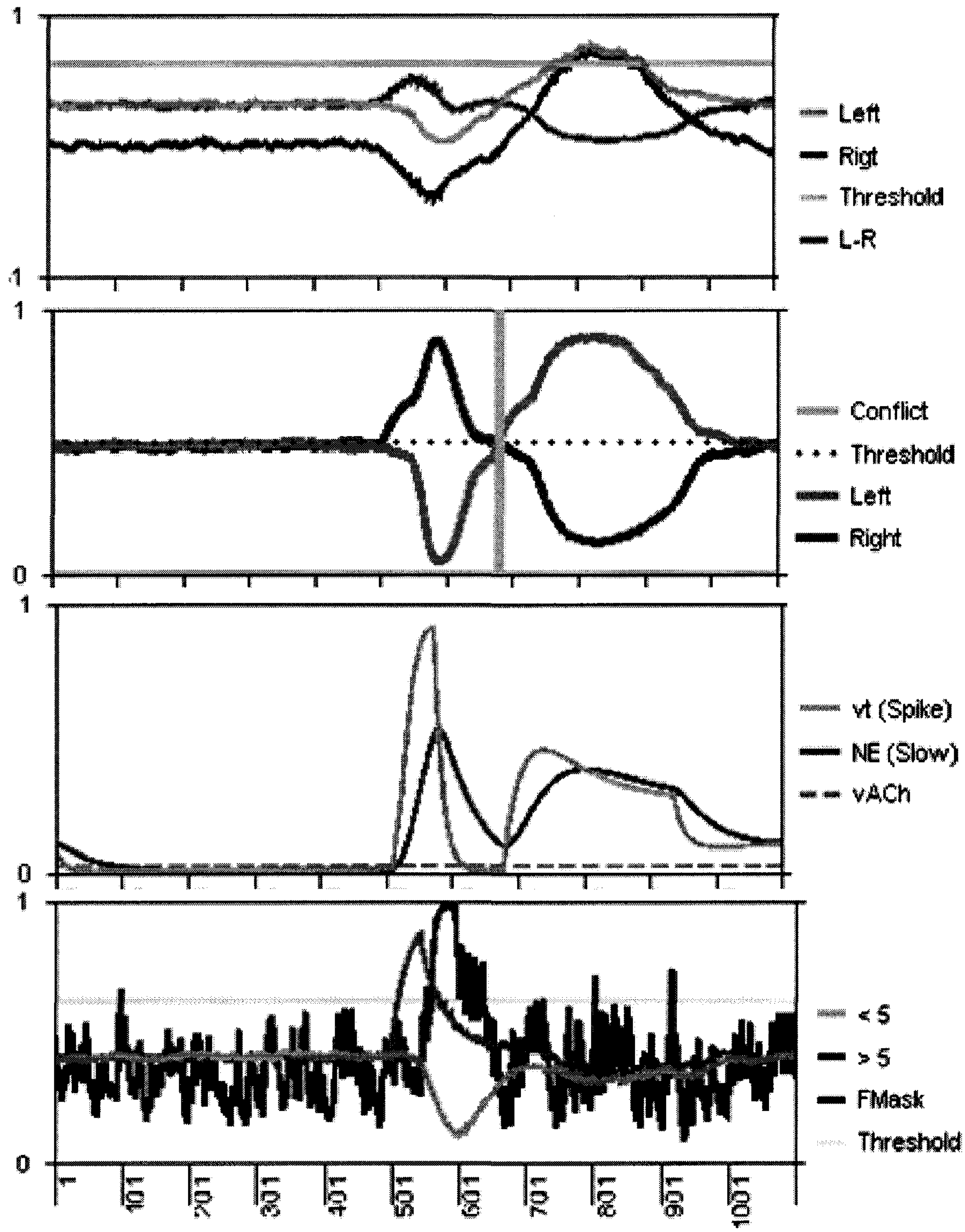

Figure 22. An incongruent trial in prime-target strength 2.5-2.5 and 125 mask-target SOA that crosses the threshold after 764 cycles (from the top, ML, CL, AA, RL-prime, but RL-target and IL are not shown).

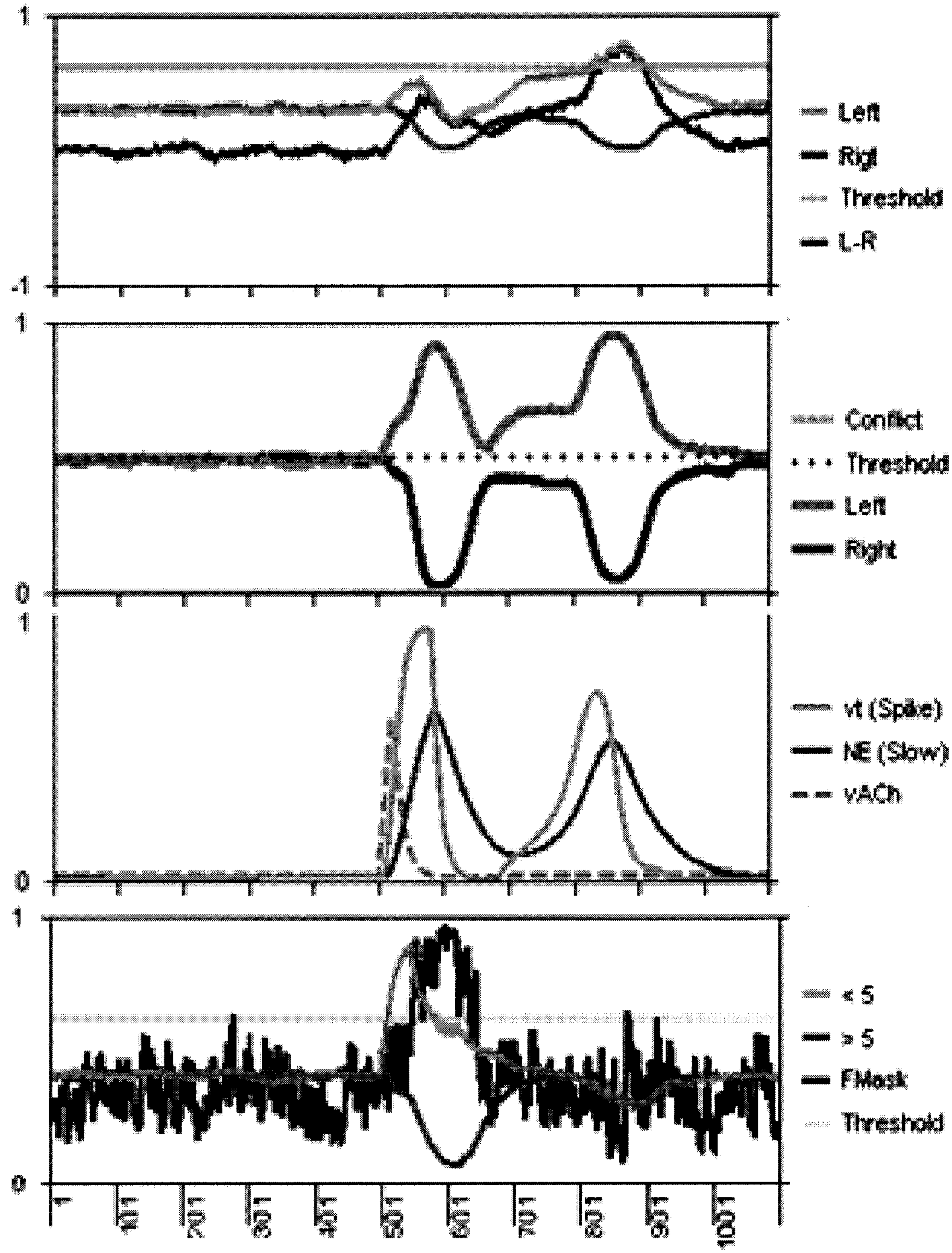

Figure 23. The effect of attention to the prime on a masked congruent trial in prime-target strength 2.5-2.5 and 125 mask-target SOA that crosses the threshold after 821cycles (from the top, ML, CL, AA, RL-prime, but RL-target and IL are not shown).

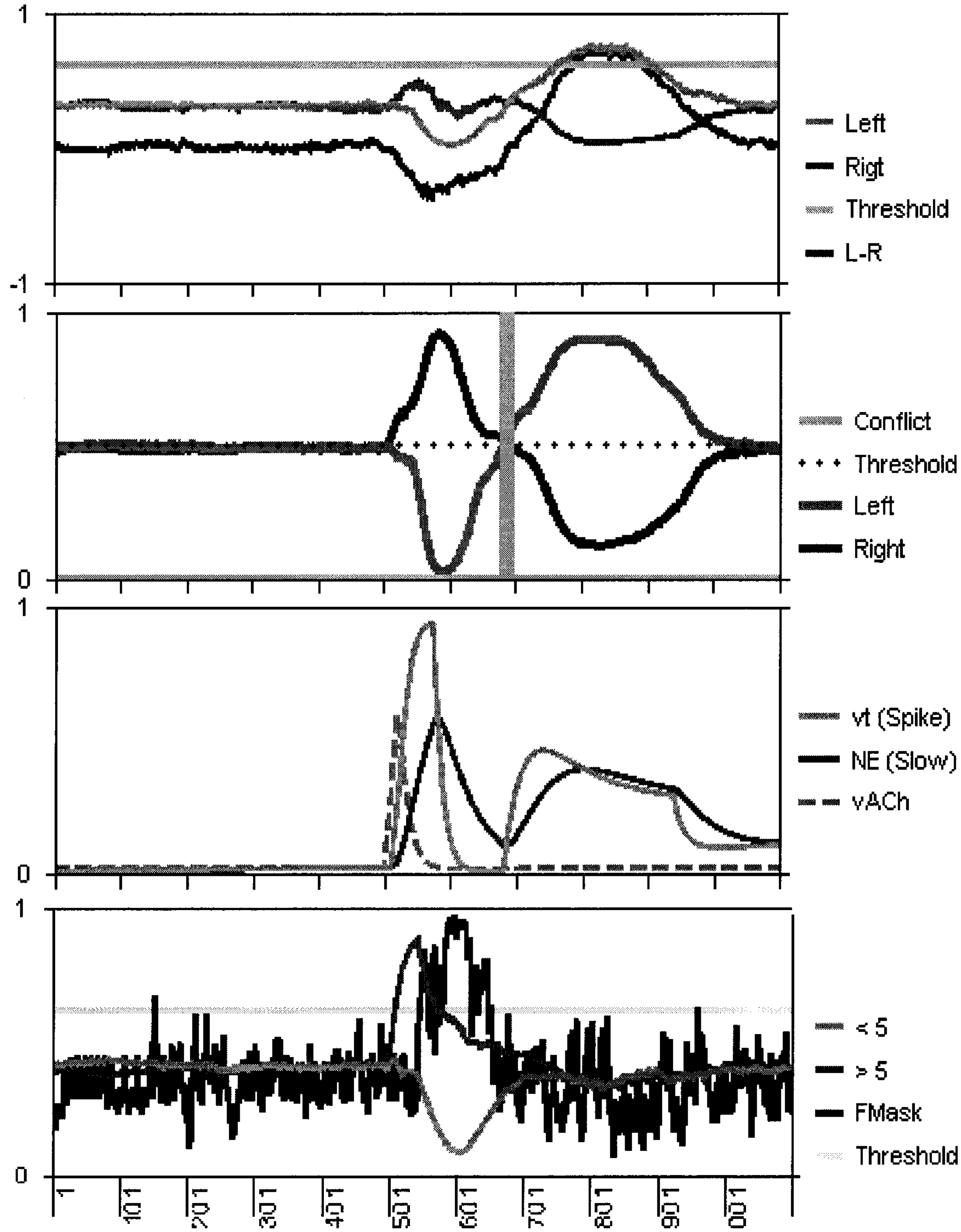

Figure 24. The effect of attention to the prime on a masked incongruent trial in prime-target strength 2.5-2.5 and 125 mask-target SOA that crosses the threshold after 762cycles (from the top, ML, CL, AA, RL-prime, but RL-target and IL are not shown).

Appendix E. The fMRI study (Experiment 1).

Co-ordinates (MNI) and *p* values of contrasts Unmasked – Masked and Illusory – Non-illusory and their opposites.

Unmasked – Masked:

cluster-level			voxel-level					x,y,z {mm}		
$p_{corrected}$	k_E	$p_{uncorrected}$	$p_{FWE-corr}$	$p_{FDR-corr}$	T	$(Z_\equiv)$	$p_{uncorrected}$			
0.833	12	0.017	0.391	0.177	10.10	4.26	0.000	12	-15	65
0.000	260	0.000	0.531	0.177	9.64	4.20	0.000	-15	-96	10
			0.805	0.177	9.04	4.10	0.000	3	-75	25
			1.000	0.177	7.65	3.84	0.000	-9	-78	20
0.030	34	0.000	1.000	0.177	8.14	3.94	0.000	24	-87	20
0.001	60	0.000	1.000	0.177	7.91	3.90	0.000	-21	-72	-5
			1.000	0.216	5.42	3.29	0.000	-36	-63	0
			1.000	0.218	4.88	3.12	0.001	-48	-51	0
0.001	58	0.000	1.000	0.177	7.84	3.88	0.000	-57	21	10
			1.000	0.213	6.70	3.64	0.000	-36	24	0
			1.000	0.260	3.80	2.71	0.003	-42	30	0
0.895	11	0.021	1.000	0.177	7.76	3.87	0.000	36	3	50
			1.000	0.237	4.50	2.99	0.001	42	-3	55
0.996	7	0.058	1.000	0.177	7.48	3.81	0.000	33	-3	-10
0.943	10	0.027	1.000	0.177	7.40	3.79	0.000	-15	-12	20
1.000	6	0.077	1.000	0.204	7.07	3.72	0.000	42	21	30
0.974	9	0.034	1.000	0.213	6.82	3.66	0.000	36	-39	-20
0.833	12	0.017	1.000	0.213	6.32	3.54	0.000	-12	-9	70
0.006	44	0.000	1.000	0.213	5.90	3.43	0.000	21	-45	10
			1.000	0.216	5.43	3.30	0.000	27	-45	0
			1.000	0.218	5.20	3.23	0.001	21	-24	5
0.895	11	0.021	1.000	0.213	5.75	3.39	0.000	36	-9	65
0.530	16	0.007	1.000	0.218	5.09	3.19	0.001	24	12	-15
			1.000	0.218	5.05	3.18	0.001	36	24	-10
			1.000	0.238	4.40	2.95	0.002	30	15	-10
0.943	10	0.027	1.000	0.218	5.02	3.17	0.001	-6	60	30
1.000	5	0.103	1.000	0.218	4.87	3.12	0.001	21	-69	-15
1.000	4	0.141	1.000	0.218	4.83	3.11	0.001	-9	24	40
1.000	4	0.141	1.000	0.231	4.69	3.06	0.001	-21	-3	55
0.035	33	0.000	1.000	0.238	4.33	2.93	0.002	3	51	35
			1.000	0.238	4.29	2.91	0.002	-9	45	35
			1.000	0.238	4.28	2.91	0.002	-9	36	40
1.000	4	0.141	1.000	0.238	4.24	2.89	0.002	45	-39	55
0.943	10	0.027	1.000	0.238	4.24	2.89	0.002	12	39	5
1.000	5	0.103	1.000	0.238	4.20	2.88	0.002	6	42	-25
1.000	6	0.077	1.000	0.245	4.12	2.85	0.002	-12	27	55
1.000	4	0.141	1.000	0.252	3.96	2.78	0.003	54	-21	-25

Masked – Unmasked:

cluster-level			voxel-level					x,y,z {mm}		
$p_{corrected}$	k_E	$p_{uncorrected}$	$p_{FWE-corr}$	$p_{FDR-corr}$	T	$(Z_\equiv)$	$p_{uncorrected}$			
0.991	8	0.044	1.000	1.000	4.44	2.97	0.002	-3	-93	-15

Illusory – Non-Illusory:

cluster-level			voxel-level					x,y,z {mm}		
$p_{corrected}$	k_E	$p_{uncorrected}$	$p_{FWE-corr}$	$p_{FDR-corr}$	T	$(Z_{\equiv})$	$p_{uncorrected}$			
0.999	7	0.080	0.430	0.430	9.95	4.24	0.000	-54	-27	55
0.910	12	0.027	1.000	0.666	8.07	3.93	0.000	-45	-48	30
0.072	33	0.001	1.000	0.666	7.55	3.82	0.000	-18	-9	5
			1.000	0.666	5.93	3.44	0.000	-24	-3	5
1.000	4	0.176	1.000	0.666	6.96	3.70	0.000	-54	21	0
0.997	8	0.064	1.000	0.666	6.11	3.49	0.000	-9	45	-5
0.910	12	0.027	1.000	0.666	6.04	3.47	0.000	-51	-30	0
0.048	36	0.001	1.000	0.666	6.04	3.47	0.000	-24	0	70
			1.000	0.666	4.99	3.16	0.001	-30	-9	55
			1.000	0.666	4.55	3.01	0.001	-33	-3	65
0.862	13	0.022	1.000	0.666	5.74	3.39	0.000	-42	-24	30
			1.000	0.666	5.70	3.38	0.000	-36	-21	45
0.144	28	0.002	1.000	0.666	5.73	3.39	0.000	42	24	-5
			1.000	0.666	5.30	3.26	0.001	54	24	0
			1.000	0.666	4.60	3.03	0.001	57	24	10
1.000	4	0.176	1.000	0.666	5.01	3.17	0.001	-36	-69	5
0.741	15	0.015	1.000	0.666	4.92	3.13	0.001	48	6	10
			1.000	0.666	4.68	3.05	0.001	60	3	5
0.989	9	0.051	1.000	0.666	4.63	3.04	0.001	-30	27	0
1.000	6	0.103	1.000	0.666	4.59	3.02	0.001	-33	-30	-5
1.000	5	0.134	1.000	0.666	4.39	2.95	0.002	6	12	60
1.000	6	0.103	1.000	0.666	4.38	2.94	0.002	-51	6	25
1.000	4	0.176	1.000	0.666	4.28	2.91	0.002	18	30	-20
1.000	6	0.103	1.000	0.666	4.02	2.80	0.003	33	12	35

Non-Illusory – Illusory:

cluster-level			voxel-level					x,y,z {mm}		
$p_{corrected}$	k_E	$p_{uncorrected}$	$p_{FWE-corr}$	$p_{FDR-corr}$	T	$(Z_{\equiv})$	$p_{uncorrected}$			
1.000	4	0.176	1.000	1.000	5.19	3.22	0.001	0	0	-10
1.000	5	0.134	1.000	1.000	4.95	3.15	0.001	-3	-27	-30
0.999	7	0.080	1.000	1.000	4.37	2.94	0.002	-42	21	-15

Appendix F. Miscellaneous

Part 1: Dynamics and non-linearity[2]

Below is a simple classic equation in dynamic systems (see for example Barton, 1994): $Y' = Y + rY(1 - Y)$, which can be programmed in Visual Basic as follows.

Create a form (Form1) and a button (Command1) then add the following codes:

```
Private Sub Command1_Click()
Dim r, x, y As Double
y = 0.5
Dim i As Integer
 For r = 3# To 1.5 Step -0.001
  For i = 1 To 200
    y = y + r * y * (1# - y)
    Form1.PSet (r * 3000, y * 4000), vbRed
    Next i
  Next r
  End Sub
```

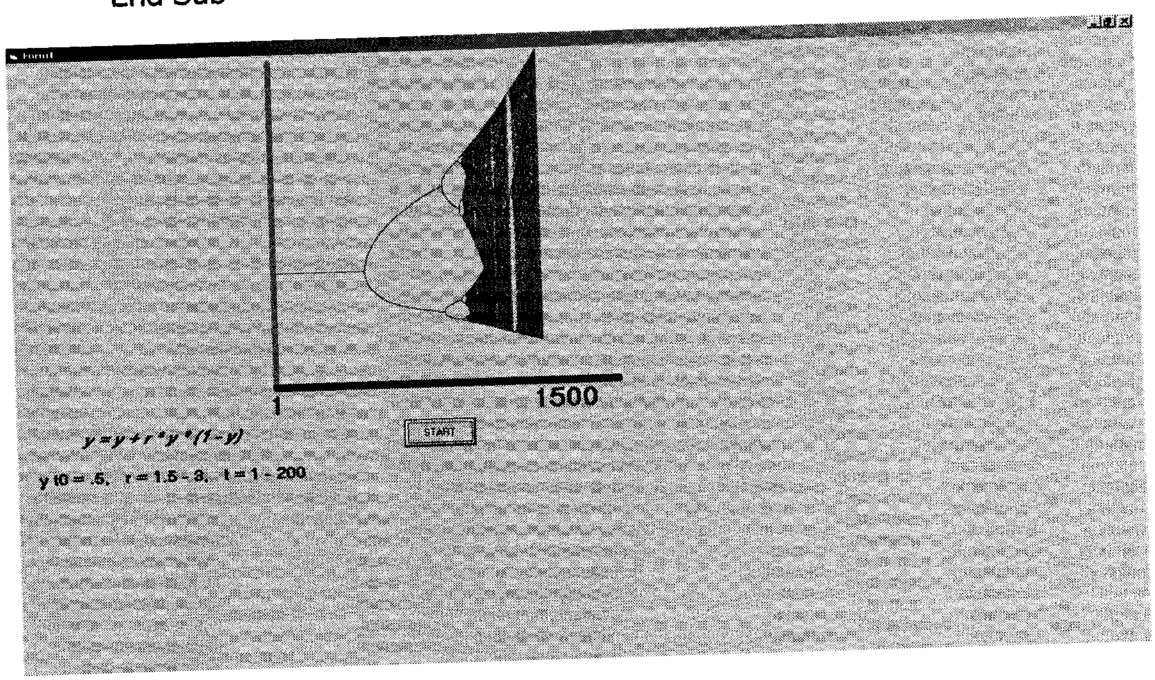

Figure 1. The result of dynamic equation $Y' = Y + rY(1 - Y)$. The graph shows bifurcation, oscillation, and chaos by introducing small changes in *r*.

[2] This part is from a previous unpublished work.

Part 2: Adjusting weights using error back-propagation algorithm[3]

In a classic connectionist model (Cohen et al., 1990) the Stoop task was simulated by adding an attentional modulation module (see Chapter 4) to a two-path feed-forward network, one for colour naming and one for colour word naming. Below a version of this model is introduced to show the possibility of weight adjustment by learning algorithms (instead of adjusting weights manually as in Chapter 4). The word naming is supposed to be a stronger (or faster) process than colour naming, therefore, here the epoch numbers to train the word naming was twice as that of colour naming. Congruent trials are processed faster than incongruent trials, especially in word naming. The congruency effect is higher in colour naming than word naming.

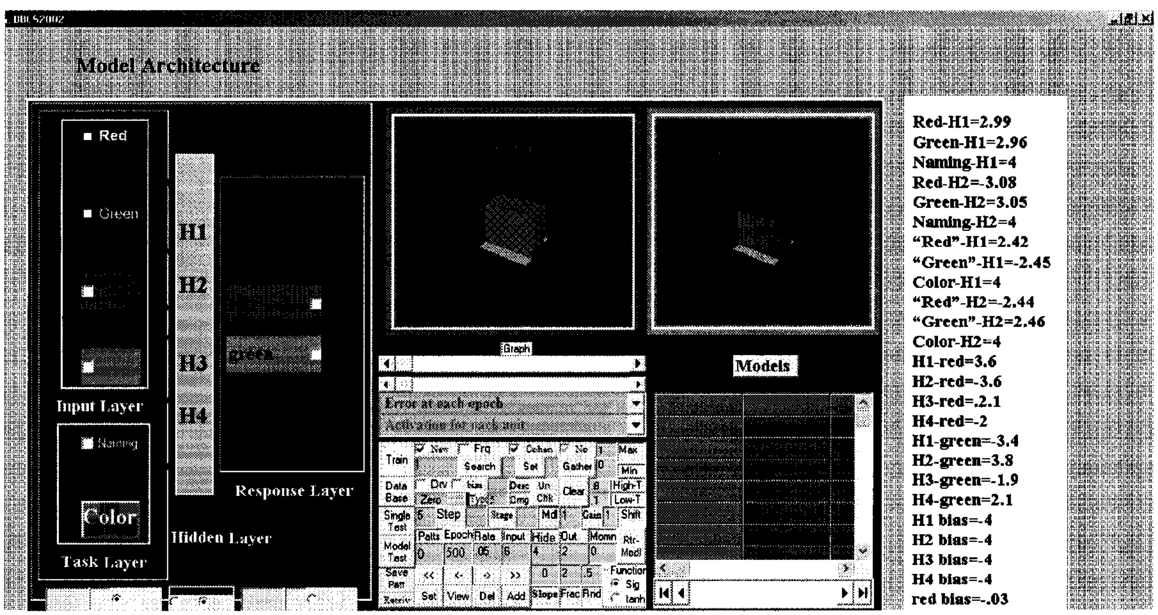

Figure 2. A model of the Stroop task (Sohrabi, 2002), which is based on Cohen et al.'s model. The weights and biases are shown at the right side (after a 500-epoch training). The connections are denoted by a – sign between units. The colour naming units are denoted by the name between quotation marks, e.g., "Red". The Response units are denotes by the word colour name with small letters. H1-H2 are hidden units in the word naming path and H3-H4 are units in the colour naming path. Task (attention) units can be manipulated to simulate normal and abnormal cognitive control.

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[3] This part is based on: Sohrabi, A. (2002). Cognitive deficits in schizophrenia: A connectionist approach. Poster presented at Twelfth Annual Meeting of Canadian Society for Brain, Behavior and Cognitive Science, Vancouver, BC, Canada.

Part 3: The order effect in learning[4]

In addition to the frequency of previous exposure, another difference between well-learned symbols (e.g., Arabic numerals) and recently learned symbols (e.g., arbitrary symbols used mentioned in Chapter 3) is the order of learning. Arabic numerals have been learned early in life (henceforth, Early) but symbols have been mapped to numbers later, right before the experiment (henceforth, Late). It has been shown that things learned earlier are processed faster than those learned later, a phenomenon known as the Age of Acquisition effect (AoA) or the Order of Learning (OoL) that has been simulated by connectionist modeling (e.g., Sohrabi, 2003). Here I describe the result of a previous study (Sohrabi, 2003) to show this effect.

McClelland, McNoughton, & O'Reilly (1995) simulated the graded improvement of children's lexicon. Using a network devised by Rumelhart and Todd (1993) that was trained to reproduce the correct semantic propositions for a small set of concepts (trees, flowers, birds and fish), McClelland et al (1995) examined the consequences of introducing a novel concept (penguin) after the network had been trained. They did this using either "focused" or "interleaved" learning. With focused learning, the new knowledge is presented to the system without interleaving it with the old knowledge. Under such conditions, information about penguins can be acquired rapidly but at a cost to pre-existing knowledge – known as catastrophic effect (Figure 5). But with interleaved learning, continuing the exposure to the old material alongside the new, the new

[4] This part is based on: Sohrabi, A. (2004). Simulation of the Order of Learning (OoL): Implication for second language learning. Paper presented at the Sixth Annual Psycholinguistic Short Seminar, University of Ottawa, Ottawa, Canada.

information can acquired without cost to the old, but the Early maintains its superiority over the Late (Figure 6).

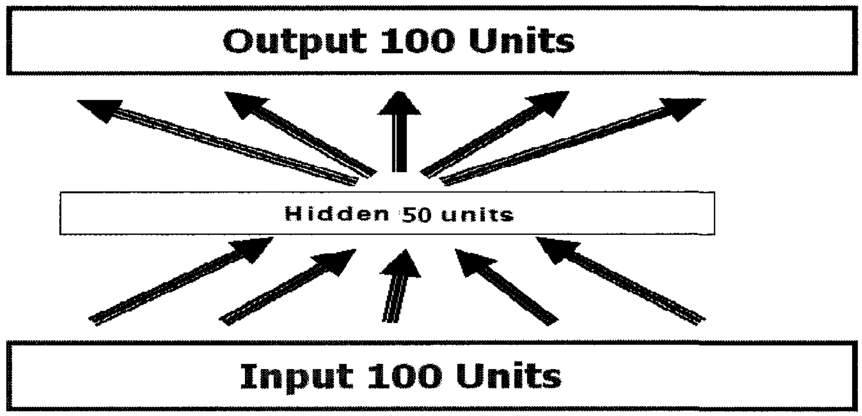

Figure 3: The architecture of the model. Input patterns were random binary codes with 20% 1s and 80% 0s. The output patterns were produced by flipping 10% of bits from 1 to 0 or vice versa. For Early, 100 patterns were used and the same numbers were used for Late. Other parameters are as follows: 100 input units, 100 output units, 50 hidden units, learning rate 0.05 without momentum.

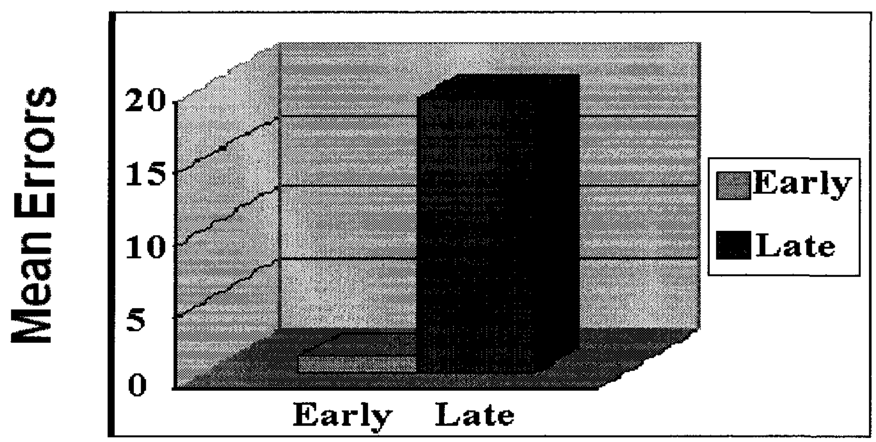

Figure 4. At the beginning of the training, connections were weighted initially by random values between +0.5 and -0.5. Then the model was trained for 300 epochs on Early only (by error back-propagation algorithm in Rumelhart, Hinton, & Williams, 1986).

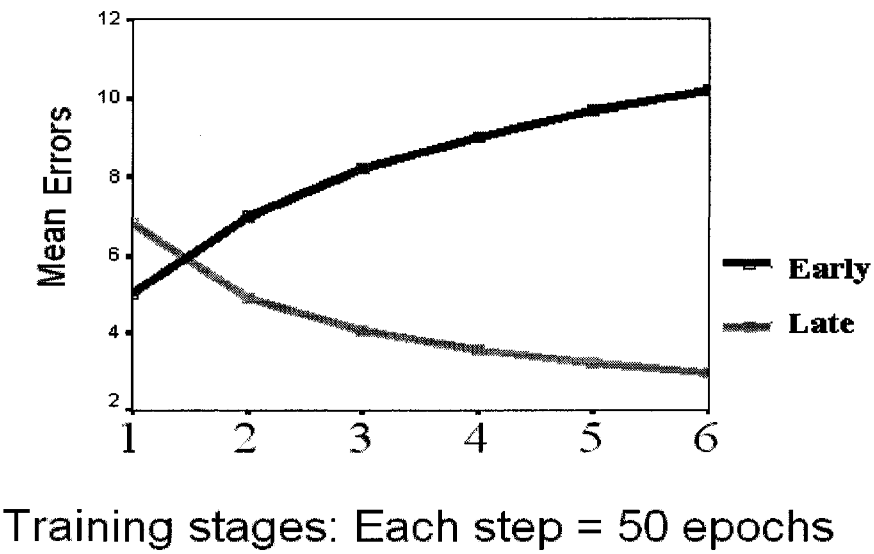

Figure 5. The trained model of shown in Figure 4 were trained on Late for another 300 epochs. As a catastrophic effect, the learning of Late destroyed the learning of Early because Early has no longer been trained alongside Late.

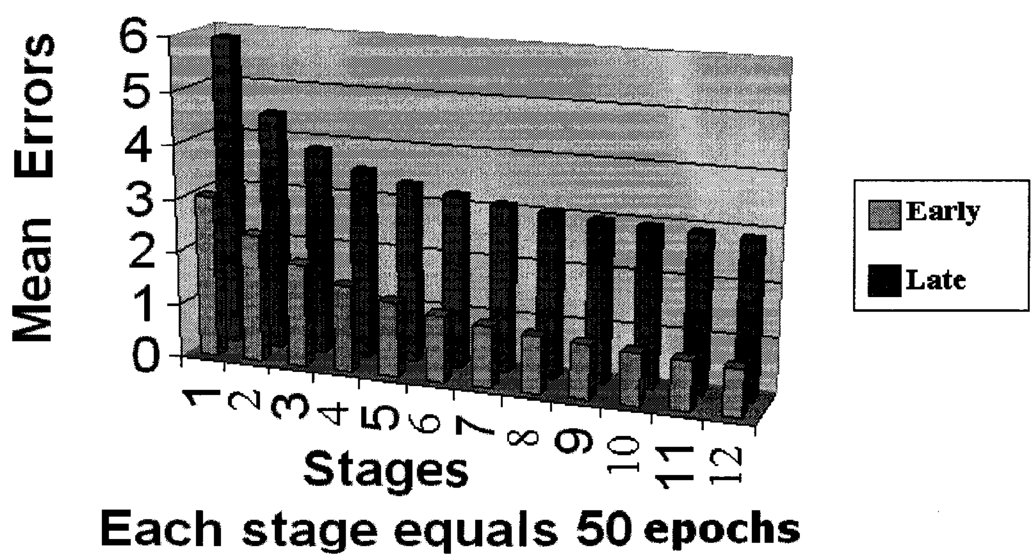

Figure 6. The trained model shown in Figure 4 was trained on both Early and Late for 600 epochs, but with Late trained more frequently, 1200 epochs on Late compared to 600 epochs on Early. As can be seen, Early keeps its superiority for a long time even with rare epochs.

Part 4: Implementing number recognition with a Hopfield network.[5]

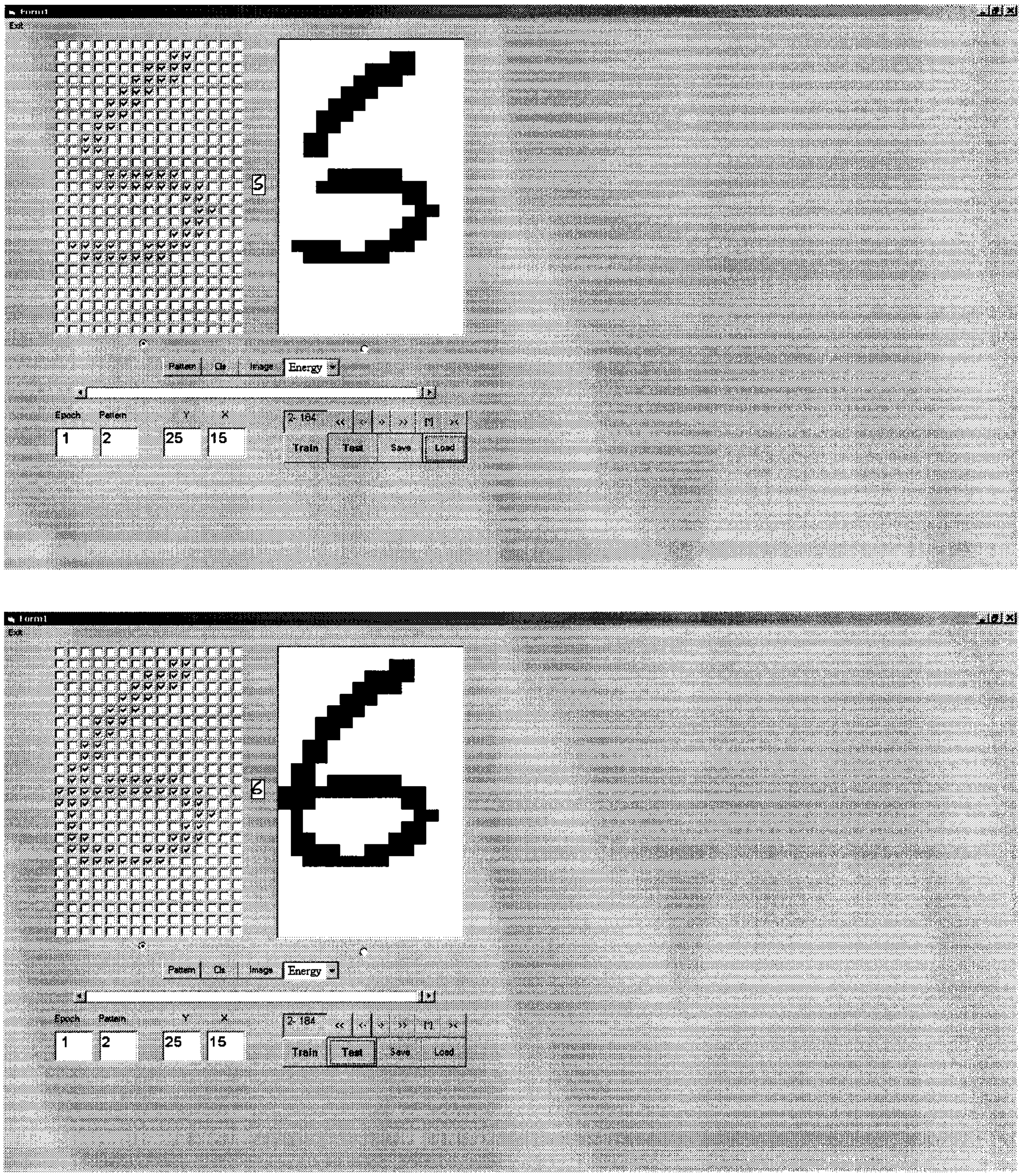

Figure 7. A Hopfield network can recognize handwritten number. Even if the numbers are damaged (top), the model can reconstruct the original stored pattern (bottom). The example is from a model with only two stored pattern, 3 (not shown) and 6 (shown).

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[5] A Hopfield network from a previous unpublished work.

Part 5. Simulation of the change in priming direction by motor inhibition[6]

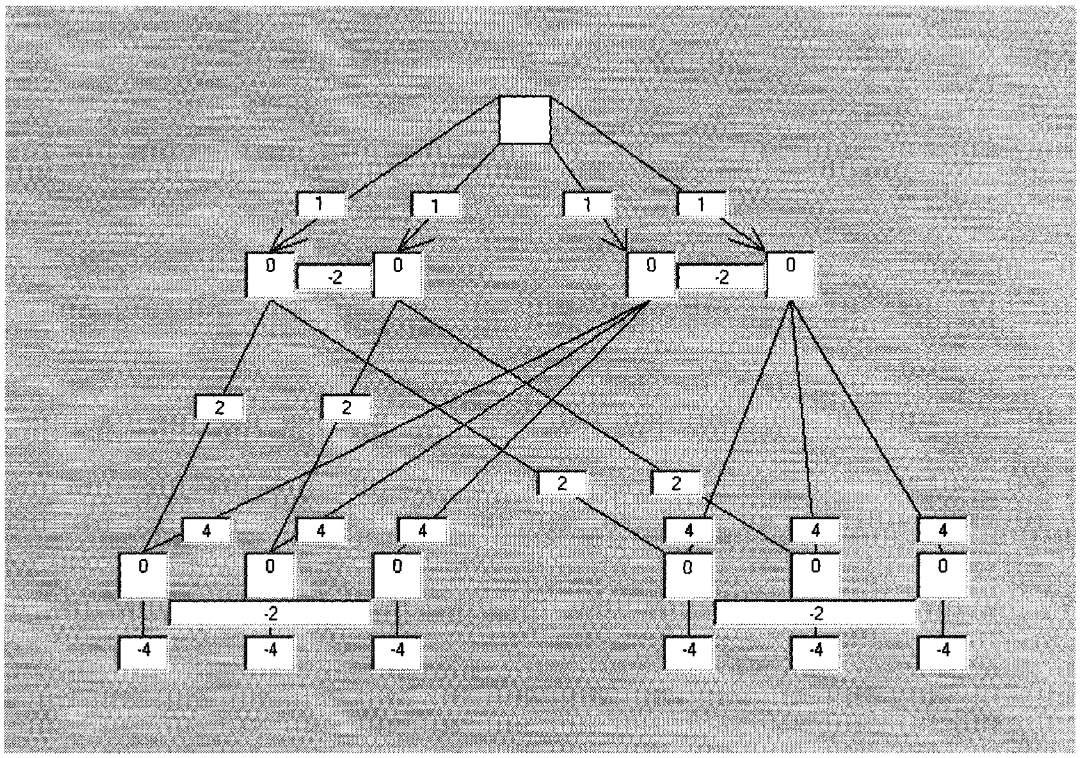

Figure 14. The architecture of a recurrent model based on motor inhibition for masked and unmasked priming in 4:2 ratio with non-illusory prime condition and in Experiment 1 (Chapter 2). Squares containing 0 are processing units. Squares containing -4 are bias units and those containing -2 are within-layer inhibitory connections. The other units are excitatory between-layer (recurrent) connections (except the top one, showing the conflict monitoring module). The simulation of conflict was implemented through the selective feedback from conflict module to inhibit or facilitate the response module in the conscious condition, and non-selective excitatory feedback to the attention module in both conscious and unconscious conditions.

[6] From Sohrabi et al. (2006, see also Sohrabi, 2005)

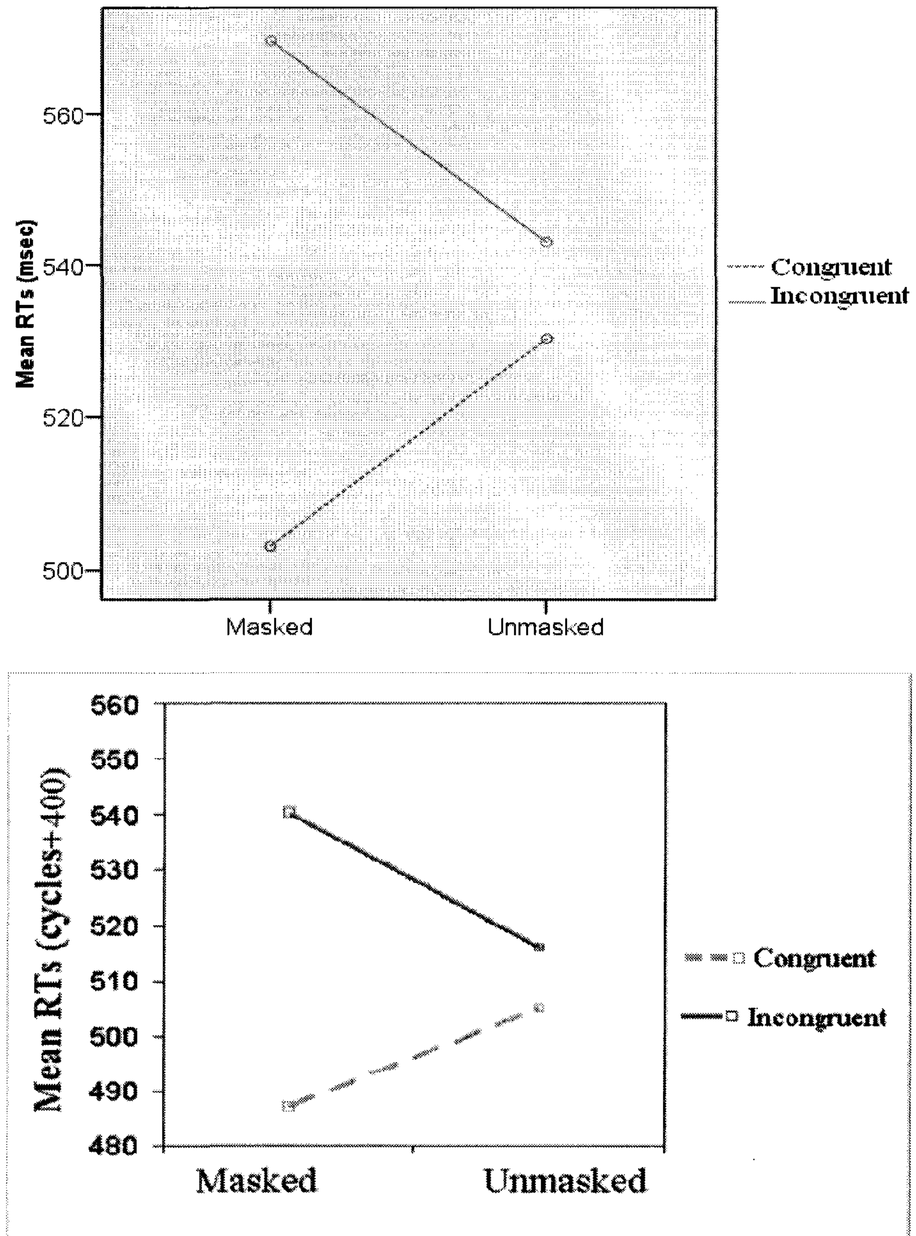

Figure 15. Human data (top) and simulation result (bottom). The number of cycles (plus 400 as extra sensory–motor processing time) was considered as RTs. The result simulated a specific condition in the behavioral data from Experiment 1 in Chapter 2.

Part 6: Simulation of the fan effect using Hopfield network and convergence zone [7]

The "fan effect" refers to the negative correlation between the number of facts (fans) memorized about one concept and the time needed to remember those facts (e.g., Anderson, 1983; Anderson, 2000). The fan effect has been shown to be important in the study of concept, categorization and memory. It has been simulated by ACT-R model (e.g., Anderson, 1983), but argued to be incompatible with the known characteristics of connectionist models such as their catastrophic effect of the competing mappings (see Part 1). Here a feed-forward model showed fan effect when trained with 1-1, 1-2, and 1-3 fan patterns but not with 2-2, 2-3, and 3-3fans.

Recently, Goetz and Walters (2000) have simulated the fan effect with an auto-associative model in which two concept are converted to a single layer through a "convergence zone" (Damasio, 1990). Their model used partial fan, that is, in each run only a subset of patterns were included. The present model simulated the fan effect by using all possible patterns with fan 1 to 3 (1-1, 1-2, 2-1, 1-3, 3-1, 2-2, 2-3, 3-2, and 3-3) in a model similar to Goetz and Walters (2000). In general, although results of this recurrent model were closer to the human data (except the fan ratio of 1-3 and 3-1 compared with 2-2 and more fans), simulation results were not consistent but changed in each run because of the dynamic behaviour of the model and the random patterns and random weight in "convergence zone".

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[7] From a poster presented at the First Summer Institute in Cognitive Sciences, Montreal, QC, Canada, 2003.

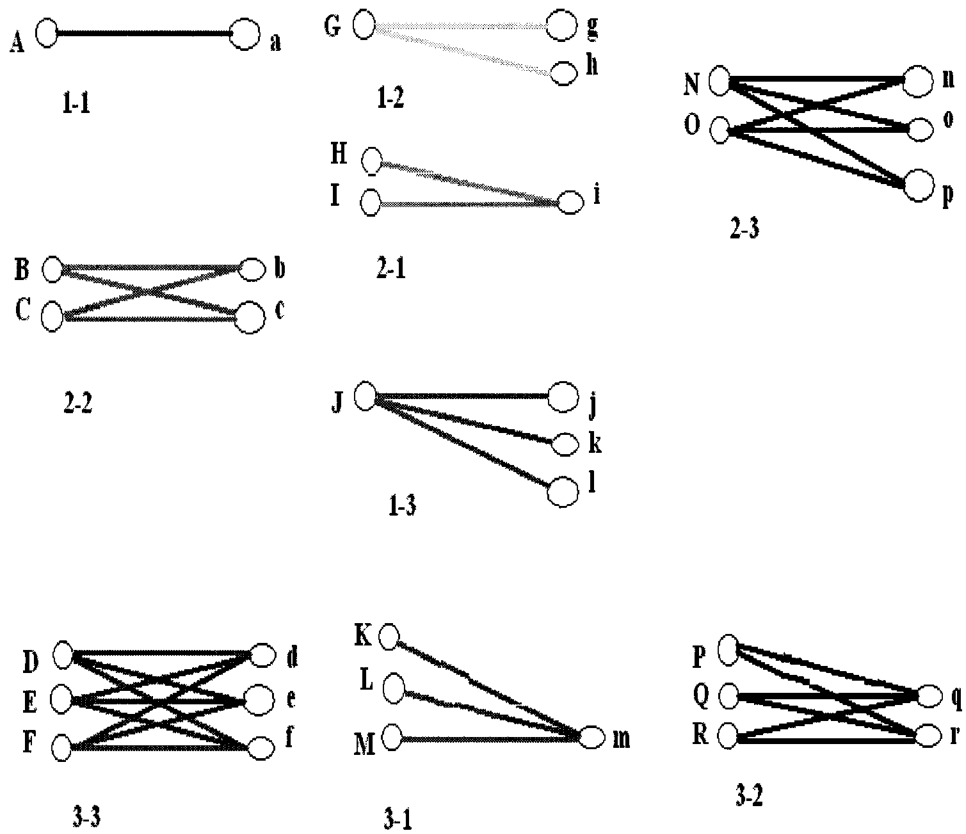

Figure 16. Mapping a group of 1 to 3 concepts (e.g., occupations) to another group of 1 to 3 concepts (e.g., locations), shown by capital and small letters, respectively.

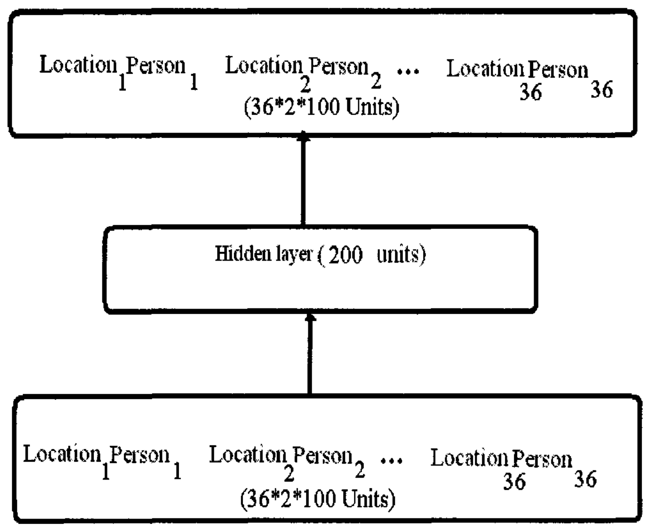

Figure 17. A feed-forward model of the fan effect.

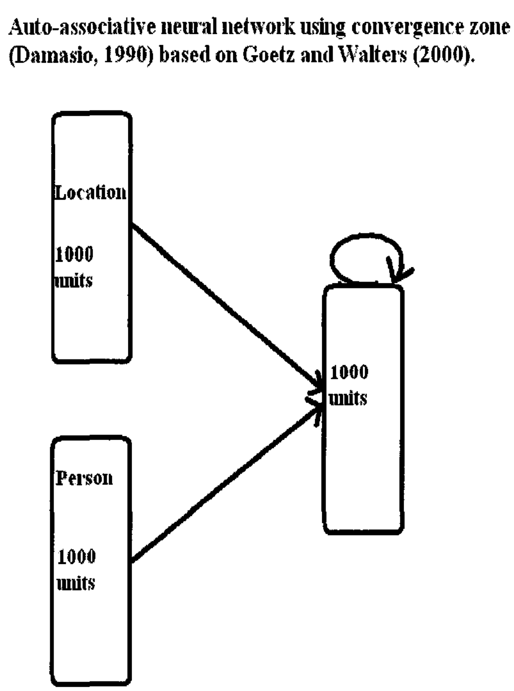

Figure 18. An auto-associative (recurrent) network for the fan effect. The two input layers are connected to a "convergence zone".

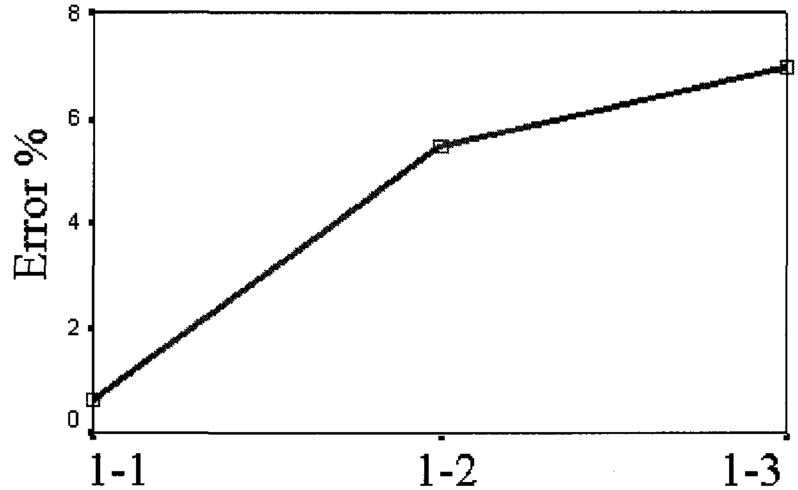

Figure 19. Simulation of the fan effect with a feed-forward model (only learned patterns are shown).

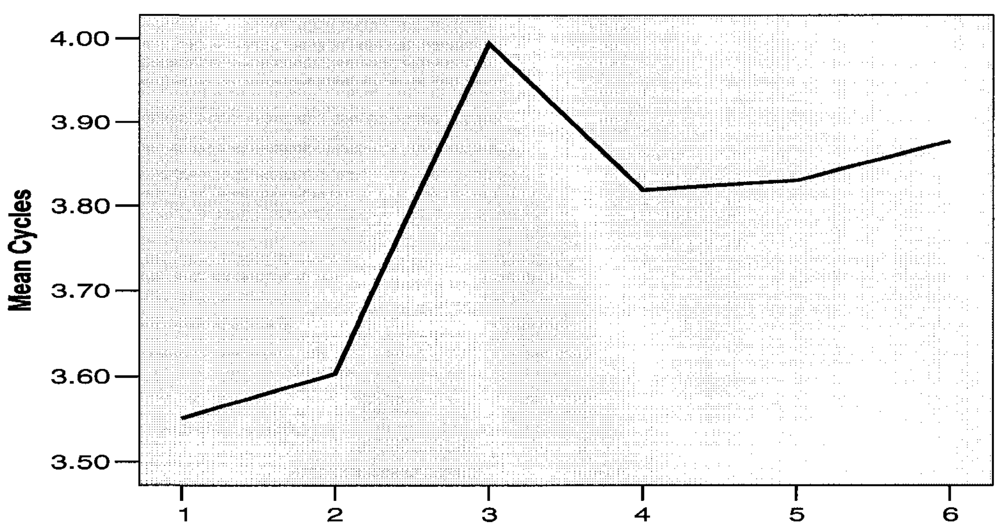

Figure 20. Simulation of the fan effect with a recurrent (auto-associative) network with "convergence zone". The pattern 3-1 (here shown by 3) was not simulated successfully due to the model limitation, presumably because of high number of patterns (36). 1= 1-1, 2=1-2 & 2-1, 3=1-3 & 3-1, 4=2-2, 5=2-3 & 3-2, and 6=3-3.