Real versus Psychological Time:
Exploring the Relationship Between Temporal and Information Processing

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Ticking away the moments that make up a dull day
You fritter and waste the hours in an offhand way.
...You are young and life is long and there is time to kill today
And then one day you find ten years have got behind you.
...Every year is getting shorter; never seem to find the time...

‘Time’ from ‘The Dark Side of the Moon’: Pink Floyd

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Abstract

The primary investigation of this thesis was the relationship between information processing and the internal clock. Clicks trains have previously been found to increase internal clock rate and information processing (Jones, Allely & Wearden, 2010). Chapter 1 examines the existing literature on the internal clock and information processing. Chapter 2 reviews possible mechanisms underlying the effect of clicks and Chapter 3 outlines the research strategy and aims. Chapter 4 investigates the behavioural parallels between internal clock speed and information processing. Chapter 5 explores the parametrics of clicks using a 1, 2 and 4 choice reaction time (RT) task (Experiment 1a, b & c). Overall, RT was reduced on trials preceded by clicks compared to no-clicks and we found that this advantage of clicks can persist for up to 10s. Chapter 6 investigates whether any prestimulus event (in this case white noise) would have the same effect as clicks in tasks of verbal estimation (VE), RT and mental arithmetic (Experiment 2a, b & c). White noise was found to have no effect on either information processing or internal clock speed, which strengthens the idea that the clicks effect is mediated by its influence on the speed of the internal clock. Chapter 7 explores whether processing the clicks as opposed to passively experiencing them would change their effect on a 1, 2 and 4 choice RT and VE task (Experiment 3a & b). Both experiments included two experimental groups (Ask & Don't Ask). In the Ask group, participants had to actively process the clicks by reporting whether there had been a shift in pitch in the clicks. In the Don't Ask they were never asked this. Experiment 3a found longer RTs across all conditions in the Ask group compared to the Don't Ask group suggesting that this processing manipulation had an effect on information processing. Experiment 3b explores the same change to the stimuli in a VE task and found that the click processing manipulation had no detrimental effect on the typical effect produced clicks. Both click types increased verbal estimates of duration in both the Ask and Don't Ask groups. Greater overestimation was found with the clicks compared to the click-change condition. So the processing manipulation had an effect on information processing while leaving the internal clock spared, weakening the idea of a link between the two processes. Frequency and duration of the clicks were manipulated in Experiment 4a and b (Chapter 8) in tasks of RT and VE. Experiment 4a demonstrated no significant effect of frequency on RT. In Experiment 4b, the main findings highlighted the importance click *duration* not frequency. Experiment 5 (Chapter 9) addresses the question of whether participants have a *simultaneous* lengthening of subjective duration as well as an increase in information processing by investigating the effect of clicks on memory recall and time estimation of the same stimuli. Overall, clicks enabled participants to correctly recall more letters as well as increasing participants' verbal estimates. Experiment 6 (Chapter 10) used clicks to change the rate of memory decay using a 3, 5 and 8 s delay. Clicks increased the rate of memory decay for the 3 and 5 s delay duration only. In order to explore whether the effect of clicks is due to arousal, Chapter 11 *replaced* clicks with *arousing* visual (Experiment 7a) and auditory stimuli (Experiment 7b) in a VE task. There was no relationship between arousal and time estimation. Experiment 8 (Chapter 12) explores whether estimating the duration of emotionally arousing auditory stimuli *themselves* has an effect on the internal clock. No relationship between arousal and time estimation was evident. Experiment 9 (Chapter 13) explores electrophysiological arousal in a VE task. While there was a behavioural effect of clicks, they did not alter physiological arousal. These findings have major implications for the common notion that arousal mediates the effect of clicks.

Declaration

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Research Publications and Presentations

The research reported in this thesis has led to the following publications:

Based on Chapter 5, 6, 9 and 10.

Jones, L.A., Allely, C.S., & Wearden, J.H. (2010). Click trains and the rate of information processing: Does "speeding up" subjective time make other psychological processes run faster? *The Quarterly Journal of Experimental Psychology.*

Based on Chapter 12.

Allely, C.S., & Jones, L.A. (under review). An Electrophysiological investigation into the effect of repetitive stimulation on the perception of duration. *Quarterly Journal of Experimental Psychology.*

Allely, C. (2009). Timing dysfunctions may underlie schizophrenia, depression and mania: new perspective in the treatment of mental illness. *Psi: Magazine of the Psychology Support Group,* Issue 111, 12-15.

Allely, C. (2009). A switch in time: does our awareness of time disappear when we sleep? *Psi: Magazine of the Psychology Support Group, 11*, Issue 1, 4-8.

Presentations

Allely, C., & Jones, L.A. (2010). Exploring the role of arousal in experimental manipulations of time perception and information processing. *PsyPAG conference*, convened in Sheffield.

Allely, C., & Jones, L.A. (2010). Exploring the role of arousal in experimental manipulations of time perception and information processing. *Proceedings of the Experimental Psychology Society,* convened in Manchester.

Allely, C., & Jones, L.A. (2009). The effect of repetitive stimulation on memory recall and time estimation: Are increases in information processing speed proportional to increases in clock speed? *Proceedings of the Experimental Psychology Society,* convened in Leicester.

Allely, C. (2009). Perception of Time: An investigation into the role of clicks and arousal on both time estimation and information processing rate. *PsyPAG conference,* convened in Cardiff.

Allely, C., & Jones, L.A. (2008). Perception of time: real time versus psychological time. *PsyPAG conference,* convened in Manchester.

Chapter 1

Literature Review: The Internal Clock, Arousal and Information Processing

“We cannot think our way down to a level where time does not apply, because no parts of our experience, however small or odd, lie outside time” (Bennett, 2004, p. 172).

1.1 Internal Clock Theory: Origins

1.1.1 Internal Clock and Body Temperature

The strongest evidence that humans possess an internal clock initially came from evidence that its speed could be manipulated. Internal body temperature is one physiological variable which is thought to affect human time estimation through a speeding-up or slowing-down of metabolic processes in the brain which underlie the workings of the “internal clock” (Green & Simpson, 1977). Francois (1927) deserves historical recognition for his research on body temperature and time estimation, although the English-speaking psychology community usually award credit for publicising the idea to Hoagland (1933). Hoagland initially became interested in this area when his wife was ill with influenza and he noticed that she “was impressed by the fact that time seemed to pass very slowly” (Hoagland, 1935, p. 108). To test whether his wife’s subjective time had been changed, Hoagland asked her repeatedly to count up to 60 at an estimated rate of 1 count/second and noted how long she took when her body temperature had different values. Not only did Mrs Hoagland count faster when her temperature was elevated but the data showed evidence of a parametric effect, with rising body temperature resulting in increasingly faster count rates (Wearden, 2005a). In terms of the passage of subjective time, Mrs Hoagland’s shorter interval productions at higher temperatures are evidence that her internal timing mechanism ran faster when her temperature was higher. Body temperature increases would make the productions shorter, although they would make external events seem to last longer, accounting for the subjective effects of body temperature that Hoagland’s wife experienced. In terms of theoretical explanation, Hoagland reasoned that if some underlying chemical process provides a time estimation mechanism, then like any other chemical process it will run faster when heated and slower when cooled (Wearden, 2005a). In order to eliminate the influence of pathological factors which might have been involved in the experiment with his wife, Hoagland (1933) tested one of his students. The participant received diathermy treatment and was naïve as to the true purpose of the experiment. The participant was insulated from heat loss by wrapping and exposed to a high frequency alternating current until their temperature reached 38.8 degrees centigrade. Using a tapping procedure it was found that the participant – and subsequent participants – consistently showed an increase in the speed of tapping with an increase in body temperature (Hoagland, 1933).

Baddeley (1966) further tested Hoagland’s notion of a chemical-clock hypothesis, in terms of the effects of reduced body-temperature on time-estimation. Twenty amateur scuba divers (all men) were tested during a week of diving in cold sea water (four degrees centigrade) and findings supported Hoagland’s hypothesis of a chemical clock. There was a tendency for the participants to count more slowly when body temperature was reduced. Most participants appeared to find the diving relatively stressful and since there is evidence that anxiety may influence time-estimation, it is possible that the results may be due to pre-dive stress causing faster counting before the dive, rather than low body-temperatures producing slower counting after the dive (see Falk & Bindra, 1954). However, findings from another experiment (Baddeley, 1966) examined this possibility by requiring participants to estimate a minute before and after a warm but stressful dive. Results suggested a fairly similar level of arousal in both experiments as measured by the only available measure of arousal – mean pulse rate or count rate.

In general then, these results support Hoagland’s chemical clock hypothesis and suggest that it holds for reduced as well as for increased temperatures. Assuming Hoagland’s generalisation is justified, we are left with the problem of why Bell and Provins (1963) failed to demonstrate a similar effect. Unlike Hoagland, Bell and Provins (1963) failed to show that changes in body temperature affects ability on tasks involving verbal estimation (time intervals of 45 and 100 seconds). Perhaps this inconsistency is due to the longer durations used in the Bell et al. (1963; 1975; 1977) studies. Hinton and Rao (2004) suggested that chronometric counting (when participants use a counting strategy to estimate durations of time) may come in to effect during longer durations and added that their study supported the idea that counting does not appear to “exhibit the scalar property” (see section 1.1.3. for explanation of this). Wearden and Penton-Voak (1995) reviewed all the data from studies carried out on body temperature and time estimation and found that almost all studies where body temperature had been elevated found increased rates of passage of time and the (much rarer) (e.g., Baddeley, 1966) studies where temperature had been reduced found reduced rates of passage of time (Wearden, 2003). The fact that a physical manipulation can alter subjective time is evidence for the existence of some internal clock but early researchers had little concern for the exact mechanisms of such a clock, such as how it operates, how its readings are used as the basis for time judgments, etc. Only much later in the 1960s were any further developments made (Wearden, 2005b).

1.1.2 Treisman (1963) Proposal of an Arousal-Sensitive Pacemaker

In 1963, Treisman linked his work specifically to the “chemical clock” proposition of Hoagland (1933) and to 20th century psychophysics (e.g. Woodrow, 1930). The model he proposed suggested that the raw material for time judgments comes from an arousal-sensitive pacemaker, which sends pulses to a counter (Wearden, 2005b). The counter could be switched on and off by external stimuli so as to provide measures of the duration elapsing between such stimuli (Treisman, Cook, Naish & McCrone, 1994). The pulses are assumed to be periodic. As well as the pacemaker and counter, the model also involves a store of “reference” durations and comparator mechanisms. Comparison of values in the counter and the store determine behavioural output (Wearden, 2005b). Later, Treisman and collaborators (Treisman, Faulkner & Naish, 1992) modeled a temporal pacemaker in which pacemaker frequency is adjusted by a calibration unit (Burle & Casini, 2001). The second assumption of Treisman’s later model (Treisman et al., 1992), which is more relevant for the present study, is that the pacemaker may vary in the degree of arousal or activation specific to it (Treisman et al., 1994). When arousal level increases, the pacemaker output frequency should increase, thereby leading participants to overestimate time (See Chapter 4, Section 4.1.1., for figure of model).

1.1.3 Animal Psychology and the Development of Scalar Expectancy Theory (SET)

At the end of the 1970s and the beginning of the 1980s, Gibbon (along with colleagues Russell Church & Warren Meck), developed scalar expectancy theory (SET). SET bears many similarities to Treisman’s model, in that both models share (a) a pacemaker-counter/accumulator mechanism (b) a “store” or “reference memory” and (c) a comparison process on the results of which behavioural output is based. However, SET was based on large studies carried out on rats and pigeons, whereas Treisman used much smaller data sets using humans which may explain why Treisman received less attention (Wearden, 2005b).

Based on observations from animal timing experiments, Gibbon (1991) found the evidence for proportional timing to be by far the most interesting aspect. Proportional timing is where measures of behaviour seem to adjust to the proportions of time intervals, rather than their absolute values for example, Dews (1970). Dews trained pigeons on fixed interval (FI schedule) values of 30, 300 and 3,000 seconds and recorded response rate during successive fifths of the FI value. In a fixed interval schedule a reward is given after the first response after a specified amount of time has passed, in this case 30, 300 or 3,000 seconds. When the response rate was plotted as a fraction of the rate at the end of the interval, the resulting functions looked the same. So, for example, halfway through an FI value, the response rate was the same fraction of what it was at the end, regardless of the absolute duration timed. Such proportion timing provided the basis which gave rise to the term “scalar” in SET. According to scalar expectancy theory, the growth of subjective time as real time passes is a simple linear function, one in which subjective time reflects real time with almost perfect accuracy on average (Wearden, 2002). Advocates of the scalar expectancy theory argue that a Poisson-variable “pacemaker” begins emitting pulses a short time after onset of a time marker and these are accumulated until a short time after reinforcement, at which point the value of the accumulator is stored in a reference memory and the accumulator is reset to zero. It is important to mention that the Poisson-variable emits the pulses at a constant average rate in the given interval of time. Gibbon and Church (1984) recognises that Poisson variance is inconsistent with the scalar property of timing: ‘‘In the Poisson system, variance increases directly with the mean, so that the system is more efficient, i.e., the ratio of standard deviation to mean is lower at long times than at short times’’ (Gibbon & Church, 1984, p. 475); and go on to say that,‘‘These results, we feel, rule out Poisson variance acting alone’’ (Gibbon & Church, 1984, p. 477). Parameters in the simple theory are the start and stop delays and the rate of the pacemaker (which determines the variability of time estimates). To generate behaviour, the stored accumulator total is compared with the current total and when the difference falls below a threshold (which may also vary), responding at a steady rate is initiated. This was found in studies carried out on rats and pigeons (Brunner, Fairhurst, Stolovitsky & Gibbon, 1997). In sum, the poisson system argues that the longer the duration, the lower the variability which conflicts with the idea of scalar timing theory which argues that people are more variable at estimating longer durations as explained by Wearden (1991).

The associated information-processing model of SET (Gibbon, 1977) operates as the following. The clock stage involves a pacemaker which receives the raw material for time representation (see Figure 1). The pacemaker emits pulses and a switch controls how many pulses enter into the accumulator. The accumulator stores the amount of pulses during the event to be timed. Therefore, the longer the stimulus duration, the more pulses are accumulated. The more pulses that are accumulated the greater the judgment of the duration. The information processing models also state that temporal judgments rely on memory and decision stages. The "current duration measured by the accumulator is compared, using comparison rules, with a sample drawn from a distribution of duration values stored in reference memory to determine whether to respond" (Droit-Volet & Meck, 2007).

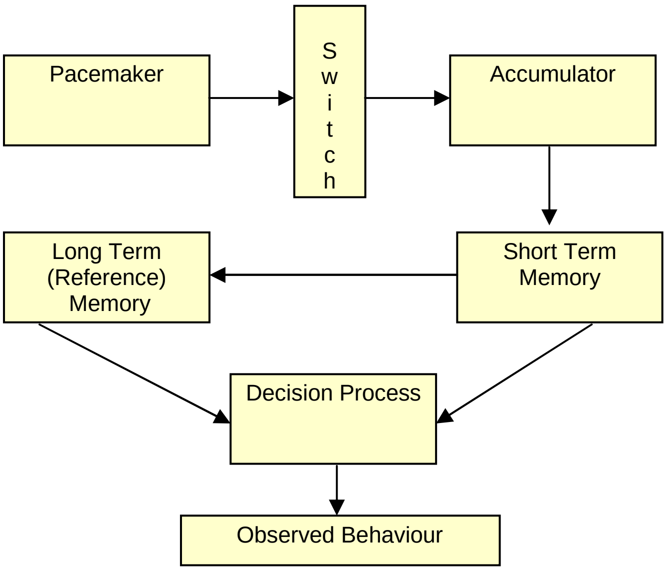

Figure 1: Information processing model (SET) (Gibbon, Malapani, Dale & Gallistel, 1997, p. 171).

In the majority of timing procedures, the accuracy of temporal judgments is believed to depend on the functioning of these different devices, with each component being viewed as a source of variance. Gibbon and Church (1984) have tried to determine which factors affect temporal processing.

As we have seen, the pacemaker concept in the SET model is problematic since it is fundamentally at odds with real timing properties (Staddon & Higa, 1999). However this inconsistency can be resolved by the proposition that people are worse at estimating longer durations due to variability in one or more other parts of the internal clock, for example, the switch (Staddon & Higa, 1999). If there is no error in the accumulator (or if the error is independent of accumulator value) and if there is pulse-by-pulse variability in the pacemaker rate, then by the law of large numbers, relative error (standard deviation divided by mean, termed the coefficient of variation (CV)) must be less at longer time intervals. This relative improvement with absolute duration is independent of the location of variability in the pacemaker. Therefore, the coefficient of variation, at longer durations, has a tendency to decrease (rather than increase) with the duration of the timed interval (Gibbon, Malapani, Dale & Gallistel, 1997). This property of timing is known as Weber's law.

Given all these constraints on the pacemaker, why not simply assume a linear time code (no counts) with a slope that varies normally from trial to trial instead? Indeed, Staddon and Higa (1999) propose that there may be no "internal clock" as such at all. Instead, interval timing discrimination is just like any other discrimination. In time discrimination, Staddon et al. (1999) argue that animals can assess (i.e., respond selectively to) the rate of occurrence of an event like food reinforcement without being directly sensitive to the time at which food occurs. Moreover, the accumulator assumption is itself problematic, because it implies a biological process that can increase without limit. SET assigns no upper bound to the duration of intervals that can be timed, so if the time code is linear, there is no limit on the accumulator total (Staddon & Higa, 1999). The fundamental contradiction between the pacemaker-accumulator idea and the Weber law property of timing should be detrimental for any pacemaker-accumulator theory, so why has it remained the leading theory? The most obvious reason is that it seems an intuitive explanation since older timing devices such as the hourglass accumulate (albeit, sand rather than pulses).

Many drug effects find a natural interpretation within SET (e.g., Meck, 1996), but they can also be explained by other competing theories, so this evidence is also not conclusive (Staddon & Higa, 1999). Another major challenge is to try to understand the physiological processes underlying timing. Mattel and Meck (2000) have criticised the idea of a pacemaker-accumulator clock on physiological grounds. As discussed earlier, timing behaviour often conforms well to the mathematical predictions of a pacemaker-accumulator clock. However, physiological models proposed as alternatives to the idea of a pacemaker-accumulator idea (i.e., Church & Broadbent, 1990; Mattel & Meck, 2000) still fail to account for the behavioural findings. Essentially, there are significant theoretical problems with using different brain states themselves to enable time judgments (A full discussion of which falls outside the scope of this thesis).

1.2 Manipulations of Internal Clock Speed In Humans

Many studies have demonstrated that the speed of the internal clock can be manipulated. The following sections will discuss the major studies which have demonstrated either a “speeding up” or a “slowing down” of the pacemaker. For instance, Hoagland (1933) was one of the first to show that the internal clock can be speeded up by increases in body temperature. The following sections explore studies which have manipulated the internal clock in other ways.

1.2.1 The Effects of Repetitive Stimulation (Clicks/Flashes) on Internal Clock Speed

Treisman, Faulkner, Naish and Brogan (1990) reported that if a visual or auditory stimulus was presented simultaneously with a train of repetitive stimulation (periodic clicks or flashes) people behaved as if the duration of the stimulus had increased, compared with the control condition. In effect, repetitive stimulation was used to “speed up” the pacemaker of the internal clock in humans. The effect of periodic stimulation was supposed to produce an increase in “arousal” and such an increase, consistent with Treisman’s model, would lead to a higher pacemaker rate (Wearden & Penton-Voak, 1995; Wearden, 2005b; Treisman et al., 1992, 1994).

More recently, Penton-Voak, Edwards, Percival and Wearden (1996) showed that *preceding* an auditory or visual stimulus by 5 seconds of periodic clicks also made the stimulus seem to last longer (see also Wearden et al., 1998 and Wearden et al., 1999a, for replications) whereas when people were required to produce time intervals of specific durations, preceding the production with clicks made the productions shorter. The key characteristic of “speeding up” experiments that suggest that an internal clock has indeed been sped up is the ‘slope effect’. For example, in a verbal estimation task, when participants’ verbal estimates are plotted against actual stimulus duration, the function for the judgments of stimuli preceded by click trains differs in slope with that for judgments preceded by silence. In other words, the longer the duration of the stimuli to be judged, the larger the estimation differs. Burle and Bonnet (1999) and Burle and Casini (2001) replicated these findings, also showing a shortening of intervals produced when preceded by click trains. The different effects on the subjective estimate of stimulus durations and on intervals produced by a "speeding up the clock" manipulation are consistent with the internal clock theory. If time judgments are made based on the amount of "ticks" of the internal clock, then more ticks will accumulate per unit of time when a stimulus is presented if the clock is speeded up as opposed to the amount of ticks accumulated in a "normal" control condition. Therefore, it would appear longer in duration. On the other hand, if production tasks are performed by emitting responses when a certain number of ticks have been accumulated (see Wearden, 2003, for a reproduction model of this sort), then these ticks will be accumulated in a shorter real time with the "speeded up" clock, thus shortening the time produced (Wearden, 2005b). Droit-Volet and Wearden (2002) instead of using clicks, used repetitive flicker to apparently speed up the internal clock of children as young as 3 years of age. Consistent with a change in pacemaker speed, a multiplicative effect of flicker was found (Wearden, 2003; also replicated in a later study by Droit-Volet, 2003). The multiplicative effect is a term for the phenomenon of the effect of clicks/flicker being greater with increasing stimulus duration consistent with the notion of an increase in pacemaker rate. As Droit-Volet and Wearden (2002) note, obtaining such an effect in young children implies that the effect is a very "primitive" one, operating on some fundamental, perhaps even biological level, rather than affecting complex response strategies (Wearden, 2003).

Further evidence consistent with a speeding up of the internal clock, comes from a study carried out by Wearden, Philpott and Win (1999) which found that click trains can affect subjective time judgments. In experiment 1, Wearden et al. (1999) used a pair comparison procedure, where two tones of the same duration are presented on each trial. The duration of each trial pair was randomly selected from between 300 and 900ms and therefore the duration of the pair differed between trials. Clicks could precede either stimulus within the pair, both or neither, which produced four conditions: 1) both are preceded by clicks (C/C), 2), neither are preceded by clicks (N/N) or with either the first or the second tone preceded by clicks (C/N) or (N/C). After being presented with the pair of tones, participants were asked whether the second tone was shorter or longer than the first. First the authors compared the number of *'longer'* responses on the two trial types where only one of the tones was preceded by clicks. The C/N versus the N/C comparison revealed that there was significantly more '*longer*' responses given in the N/C condition than in the C/N condition. This suggests that the clicks could affect judgements of durations which were of the same duration. Comparison of the N/C and N/N conditions showed that there were more '*longer*' responses when the second stimulus was preceded by clicks, suggesting that clicks had increased the subjective duration (by speeding up the internal clock) of durations they preceded, relative to a no-click condition. On the other hand, comparison of the C/C and C/N conditions revealed that more '*longer*' responses were made in the former condition. This suggests that with the removal of clicks the internal clock speed was relatively reduced. Interestingly, the C/N condition produced less 'longer' responses than N/N, again, demonstrating a slowing down effect of the internal clock.

However, an alternative explanation to the idea of click-trains 'speeding up the clock' hypothesis is that of 'assimilation'. This is the idea that click-trains are assimilated into the total length of the stimulus that they precede, so effectively lengthening it. Consistent with this idea of assimilation, Penton-Voak et al. (1996) found that preceding responses *produced* by the participant by click-trains decreased their duration. However, inconsistent with the notion of an internal clock, assimilation would lead to an intercept not a slope effect (where the the effect of clicks becomes greater with increased duration compared to no-clicks).

Although there is evidence that repetitive stimulation in the form of clicks and flicker increase internal clock speed, is there any evidence that the effects are mediated by "arousal"? A train of clicks is obviously not very arousing in the everyday sense of the word - but it may induce "specific arousal" of the internal clock. The term "specific arousal" of the pacemaker is used by Treisman (1963) to distinguish it from the "general arousal" of the organism. The "specific arousal" of the pacemaker can be increased by external inputs which subsequently alters our subjective duration of time. Treisman (1963) carried out a task requiring participants to produce and reproduce intervals of pre-specified duration. Treisman (1963) found that they became consistently shorter the greater the intensity of the tone to be judged and interpreted this effect as due to the increased arousal of the participants occasioned by the louder tones (Wearden, 2005b). Hockey (1970) also suggested that noise acts as a kind of general stimulant which raises the level of arousal. In addition, Glicksohn (1992) found that the more varied the sensory environment (i.e., perceptual overload versus perceptual deprivation), the longer the subjective time that is verbally estimated (the opposite being the case for the reproduction method), which is consistent with the notion that the internal clock will speed up or slow down as arousal levels altered, irrespective (to a degree) of particular attention demands imposed by concurrent information processing. This is in line with Treisman's (1963) model of the effect of arousal on duration perception (Glicksohn, 1992). The notion of the click effect being mediated by arousal is an issue that will be investigated empirically in this thesis (see Chapter 11 and 13).

In summary, preceding tones or visual stimuli by trains of clicks or flickers (compared to no-click trials) increased their subjective length, with larger effects being obtained with 3 or 5 seconds of clicks than with 1 second (Penton-Voak et al., 1996). Moreover, the presence of a slope effect is evidence that the internal clock has been speeded up as opposed to the effect being a simple bias or assimilation.

1.2.2 Modality Effects on Internal Clock Speed

Internal clock models consistent with the pacemaker-accumulator model of SET have also been used (Wearden, Edwards, Fakhri & Percival, 1998) to account for the well-known modality effect in timing, that "tones are judged longer than lights". Treisman et al. (1990) also found that an auditory stimulus appears to have a greater subjective length than a visual stimulus, despite both being the same duration and argued that the pacemaker of an internal clock runs faster during auditory than visual stimuli (Wearden et al., 1998). Similarly, Droit-Volet, Tourret and Wearden (2004) found that auditory stimuli were judged to be longer than visual stimuli in both 5-year-olds and 8-year-olds. The auditory and visual stimuli produce a slope effect consistent with the pacemaker of the internal clock running faster for the auditory than for the visual stimuli. Additionally, Jones, Poliakoff and Wells (2009) using a staircase threshold procedure, verbal estimation and a temporal generalisation task showed that timing in the vibrotactile modality conforms to scalar timing theory (SET) and that the internal clock speed for vibrotactile stimuli is significantly slower than that for auditory stimuli. Experiment 1, demonstrated that duration discrimination is superior with auditory stimuli, least sensitive with visual stimuli and that vibrotactile thresholds are significantly worse than auditory and "lie statistically closer to that of visual thresholds". In experiment 2, the speed of the internal clock appears to be faster for auditory stimuli than either visual or vibrotactile stimuli, shown by higher estimates for auditory, with increasing differences at longer durations. Conversely, there appears to be no difference between estimates for visual and vibrotactile stimuli and so clock speed could be considered to be approximately the same for these two modalities. Experiment 3 showed that the timing of vibrotactile stimuli exhibits similar scalar characteristics to that of auditory or visual stimuli, consistent with the findings from Experiments 1 and 2.

1.3 Role of Emotion on Pacemaker Speed and Time Estimation

The present section will explore whether arousal plays a role in the clock speed effect seen in Section 1.2 through the use of various arousing stimuli and by inducing various different states of arousal/stress in the individual.

1.3.1 Emotional Expression and Arousal

What exactly is happening to our internal clock in emotional situations? In other words, why are we so inaccurate in making timing judgments during emotional experiences despite having a complex internal clock mechanism (Droit-Volet & Gil, 2009)? Research suggests that the interaction between increased arousal and accompanying psychological mood has a combined effect on behaviour, i.e., judgments of durations (Ward & Cox, 2004; Krug, 1999). Angrilli, Cherubini, Pavese and Manfredini (1997) argued that induced emotional states systematically influence error in time estimation; i.e., the perceived duration of an event is affected by manipulations of the two emotional dimensions of affective valence and arousal. Using a time production and a verbal estimation task, Angrilli et al. (1997) explored the effect of various scenes that were at opposite extremes in terms of their valence and intensity. For emotional valence there were two levels. Low-valence which depicts negative emotion and high-valence which depicts positive emotion. For arousal, there were also two levels, low and high arousal. Participants were shown scenes that were high intensity-pleasant (e.g., kissing couple), high intensity-unpleasant (e.g., baby with eye tumour), low intensity-pleasant (e.g., smiling baby) and low intensity-unpleasant (e.g., large spider). Participants in the low-intensity scenes, tended to underestimate the duration of unpleasant scenes more than the pleasant ones. Interestingly, for the high-intensity scenes, there was an overestimation of the duration of unpleasant scenes compared to pleasant scenes. Angrilli et al. (1997) argue then that both attention and arousal mechanisms are involved in estimating the duration of emotional stimuli. A criticism of their study, however, is that they failed to compare these conditions with neutral pictures, instead using neutral conditions merely as fillers (Noulhiane, Mella, Samson, Ragot & Pouthas, 2007). (See Chapter 12, section 12.1 for more details on this). Additionally, a potential problem with the study by Angrilli et al. (1997) is that they did not use a sufficient range of durations to test for slope effects. However, despite this, they still produce results in the direction that would be expected.

Thayer and Schiff (1975) specifically examined the effect of eye contact and facial expression on the experience of time. If arousal increases with the duration of the experience, as the period of eye-contact increases one would expect to find still greater overestimation (Thayer & Schiff, 1975). They found that for reproduction of time periods, during which eye contact was maintained, time was experienced as passing more slowly (greater overestimation relative to clock time) when combined with a negative-unpleasant (scowling-angry) rather than a positive-pleasant (smiling-friendly) facial expression. Using a temporal bisection task, Droit-Volet et al. (2004) found that the duration of emotional faces (anger, happiness and sadness) was systematically overestimated compared to neutral ones consistent with the arousal model.

Despite the consistency of these findings with the arousal based model, it still fails to explain the exact reason the internal clock produces such effects. There are two ways put forth by pacemaker-accummulator internal clock theories to explain how arousal might impact on the internal clock (Gibbon, 1977). First, arousal causes an increase in the speed of the pacemaker. The alternative explanation could be due to changes in the functioning of the switch of the internal clock, the link between the pacemaker and the accumulator (Church, 1984). So, emotional stimuli may cause the switch to close faster or open later than usual. Individually and combined, both these theories can plausibly explain how the amount of pulses accumulated during the event to be judged can be increased as a result of arousal. It has been shown that the speed of the pacemaker is multiplicative with real time, however it is not clear whether this is the case in the study by Droit-Volet et al. (2004). Therefore, the effect would have more of an impact at longer durations compared to shorter ones under conditions when the speed of the pacemaker is increased as a result of arousal (Meck, 1983). Since the switch is independent of the durations to be judged, it appears that the switch is not a feasible explanation for these effects (Droit-Volet et al., 2004).

Gil, Niedenthal and Droit-Volet (2007) then went on to determine whether there is such an effect of anger on time perception in children. They argued that, if the perception of angry faces results in increased levels of arousal (and if this has adaptive effects on temporal perception), then the tendency to overestimate the duration of angry faces compared to happy or neutral would be expected to occur in very young children and demonstrate little or no change over the course of development. Using the temporal bisection task, Gil et al. (2007) examined children aged 3, 5 and 8. Four emotional facial expressions (sad, happy, neutral and anger) and two duration ranges (400 – 1,600ms and 600 – 2,400ms) were used. For each age group children were randomly assigned one of the two duration ranges. The comparison durations were 600, 900, 1,200, 1,500, 1,800, 2,100 and 2,400ms. Participants were presented with the comparison durations as represented by facial expressions and asked to judge whether the duration they are presented for is the same as the short standard duration or the long one. They found that even though their sensitivity to time improves with age, the 3-year-old children were able to estimate time consistent with the notion that the internal clock operates in very young children (Droit-Volet & Wearden, 2002). What was of most interest was the finding that the perceived duration of angry (compared to neutral) faces was overestimated in all age groups, replicating findings in adults (Effron et al. 2006; Droit-Volet et al., 2004). In addition, there was no evidence of variability in the level of overestimation in the three age groups used here (Gil et al., 2007). The findings by Gil et al. (2007) are consistent with scalar expectancy theory as the effect was proportional to the duration of the standards. Findings showed that overestimation of angry faces compared with neutral faces was greater for the long stimulus durations than for the short stimulus durations. This supports the arousal effect hypothesis and the effect demonstrated with the short and long durations used shows that it is not a simple response bias effect and that the internal clock has been sped up.

Based on these previous findings, one might naturally go on to suspect that there is a link between individual differences in negative emotionality and overestimation due to negative facial expressions. Tipples (2007) investigated whether temporal bias due to angry and fearful expressions is greater in individuals who consistently report high levels of negative emotional arousal. Determining whether the same effect can be found using fearful expressions is important because previous studies (for instance, Droit-Volet et al., 2004: Effron et al., 2006) did not compare angry facial expressions with other negative, highly arousing expressions. Ratings for pleasantness and arousal are equal for fearful and angry facial expressions. So if an arousal-sensitive mechanism is responsible for the effects of emotional facial expressions on temporal estimations, similar degrees of overestimation for both angry and fearful expressions would be expected. To examine these issues, Tipples (2007) adopted the temporal bisection task described by Droit-Volet et al. (2004). Supporting the expectations, there was evidence of a link between individual differences in negative emotionality and increased levels of overestimation due to both angry and fearful expressions but not happy expressions. Previous studies have demonstrated the relationship between anxiety (Fox, Russo & Dutton, 2002; Yiend & Mathews, 2001), fearfulness (Tipples, 2006) and attention bias in response to negative stimuli. For example, Fox, Russo, Bowles and Dutton (2001) results showed that when participants are anxious, they usually spend longer looking at angry and fearful expressions relative to neutral and happy expressions. Fox et al. (2001) argue that this is due to the “delayed disengagement of attention” in individuals with anxiety (Fox et al., 2001; 2002). Tipples (2008) attempted to reconcile these findings with those from his study which argued for an arousal based explanation opposed to Fox et al. (2001) attentional-based one, by arguing that perhaps both studies are mediated by the same general arousal-based process associated with the release of the neurotransmitter noradrenaline. Indeed, Tanaka, Yoshida, Emoto and Ishii (2000) found that an increased release of noradrenaline is associated with the stimulation of negative emotions such as anxiety and/or fear. Noradrenaline affects the operation of both attentional and time processes (Penney, Holder & Meck, 1996; Droit-Volet et al., 2007). However, others have argued that noradrenergic activity does not have a major involvement in the timing of brief durations in the range of milliseconds (Rammsayer, Hennig, Haag & Lange, 2001). Surprisingly, Tipples (2008) found that there was a greater overestimation of time with angry facial expressions compared to fearful and happy expressions. Specifically, there was a higher proportion of longer responses (overestimation of the duration) of the angry facial expressions in the 1200ms duration compared to the shorter 400ms duration. However, fearful faces tend to be judged as being more arousing than angry facial expressions. Fearful and angry facial expressions should have led to relatively the same level of overestimation if the effect of facial expressions on time perception change as a direct result of the aroused facial expression of the sender (Tipples, 2008). Tipples (2008) used more than one duration and was therefore able to demonstrate a slope effect supporting the idea of the internal clock being sped up.

It is a common experience that time seems to fly when we are enjoying a favourite meal at a restaurant. Experiences of this nature prompted Gil, Droit-Volet and Rousset (2009) to investigate the relationship between time perception and food-elicited emotion. In a temporal bisection task, healthy adult participants were required to judge whether the presentation duration of pictures (neutral, liked and disliked foods) were more similar in duration to a short (400ms) or a long (1,600ms) standard duration. The five intermediate duration values that the participants had to judge as being similar to either the short and long standards durations were 600, 800, 1,000, 1,200 and 1,400ms. Based on pretest findings, three liked food pictures were chosen: cream cake, dark chocolate and French bread. Pre-tests findings also enabled the appropriate selection of three disliked food pictures: blood sausage, beef sausage with vegetables and dried beef sausage. The neutral stimulus comprised of a picture of a white oval with similar perceptual characteristics to the plate used in the food stimuli pictures. Findings showed that the presentation duration of food pictures was underestimated compared with the presentation duration of the neutral picture and that this underestimation was more marked for the disliked than for the liked food pictures. Gil et al. (2009) argue that these findings suggest that time underestimation in this instance, is due to an attentional-bias mechanism (i.e., Zakay & Block, 1996). Such a mechanism serves to distract attention away from the processing of time in emotional situations, in this case the liked and particularly the disliked food pictures. If we recall how the information processing model of timing operates, pulses are switch or gated to an accumulator. It is the amount of pulses that determines the perception of duration. Therefore, if there are lost pulses because of distraction then the duration will be underestimated. If we consider it from an evolutionary perspective, it is not surprising that the disliked food pictures captured more attentional resources (as evidenced by greater underestimation) than the liked food pictures. Potentially, disliked food represents an increased danger and significance to health and therefore, are given more attention.

At first inspection these findings by Gil et al. (2009) may seem fundamentally at odds with those of Angrilli et al. (1997) who found overestimation (not underestimation) of emotional visual stimuli (e.g., mutilated bodies). Gil et al. (2009) suggest a convincing hypothesis which is consistent with both these seemingly contrary findings. If we take the emotion of disgust used in both the study by Angrilli et al. (1997) and Gil et al. (2009), participants were found to judge them differently in terms of arousal level between both these studies which may explain the differences. Specifically, in the study by Gil et al.

(2009) participants using the Self-Assessment Manikin scale, rated the disgust stimuli as being low in arousal. Whereas, the participants in the study by Angrilli et al. (1997) judged the same stimuli to be highly arousing using the same measure. Different mechanisms become involved in both types of arousal level. Attentional processes are primarily involved in non-emergency situations such as with low arousing stimuli/events. However, high arousing stimuli would serve to increase autonomic arousal, preparing the organism to act according as fast as possible. Droit-Volet and Meck (2007) argue that such an increase in arousal is suggested to speed up the internal clock which explains why the participants in the study by Angrilli et al. (1997) overestimated the same stimulus type (disgust) as that used by Gil et al. (2009).

Taking this notion of a relationship between emotion and time perception a step further, Gil and Droit-Volet (2009) investigated the impact of depressive symptoms on human timing. In a task of temporal bisection, Gil and Droit-Volet (2009) found that the greater the score of depression, the greater the underestimation of duration (indicative of the fact that the depressed group underestimated the duration of the standard durations). Additionally, the Brief Mood Inventory Scale (BMIS) also revealed that the depression scores were positively correlated with the sadness scores and negatively correlated with the happiness scores. These findings are consistent with the notion that the depressive participants have a slower internal clock. However, a potential problem with the findings of the study carried out by Gil and Droit-Volet (2009) is that they did not employ a state change design. Unless you have a state change you cannot state with confidence that you have actually manipulated the speed of the internal clock. Other studies have used this state change design within temporal generalisation to ‘prove’ that they have actually speeded up the internal clock (i.e., Penton-Voak et al., 1996).

1.3.2 Inhibiting Imitation Eliminates the Effects of Emotions on the Perception of Duration: Role of Embodiment

Our ability to synchronise ourselves with other individual’s rhythms and time in our lives is crucial in maintaining successful social interaction. A good example of this is the ability of babies to synchronise their vocalisations to that of their mother. Pouthas, Droit and Jacquet (1993) also showed that as well as this, mothers also modulate their speech according to their child’s information processing speed. Gourlay (2010) has also emphasised the fact that fast food seems to stir us into a hurry. Zhong and DeVoe (2010) in one experiment revealed that even an unconscious exposure to fast-food symbols can automatically increase participants' reading speed, despite being under no time pressure. This suggests that we even 'embody' non-human things like fast food. Fast food symbols represent a culture of getting food fast and eating it quickly in order to go on to the next thing.

The role of embodiment in the perception of the duration of emotional stimuli was explored by Effron, Niedenthal, Gil and Droit-Volet (2006) using a temporal bisection task. They wanted to investigate whether embodiment plays a role when individuals overestimate the duration of emotional, compared with neutral, faces (Droit-Volet et al., 2004). They asked their participants to estimate the duration of angry, happy and neutral faces by comparing them to two durations learned in the training phase. In order to inhibit the imitation of the faces, individuals in the experimental group were told to hold a pen in their mouth, thus limiting movement. Control participants, on the other hand, were not restricted in their ability to imitate faces. So in the condition where participants are inhibited from imitating the faces, Effron et al. (2006) are removing the possible effect of embodiment on the estimation of durations in their participants. Effron et al. (2006) found that when participants were allowed to imitate faces, they tended to overestimate the duration of angry faces (and to a smaller degree, happy faces) compared to neutral faces. They also found that when imitation was inhibited (by inserting the pen in the mouth), participants estimates of the angry, happy and neutral faces were equal. There was no evidence of overestimation of emotional faces as was seen when they were free to imitate the faces (Effron et al., 2006).

Using a temporal estimation task, Mondillon, Niedenthal, Gil and Droit-Volet (2007) explored the automatic imitation of facial expressions of anger by in-group and out-group members. Mondillon et al. (2007) found that Caucasian participants overestimated the duration of the angry faces compared to the neutral Caucasian faces. No such effect was found when the Caucasian participants were shown the Chinese angry facial expressions. However, Chinese participants did show an overestimation of the duration of angry faces from both the Chinese and Caucasian facial expressions because they imitated both Chinese and Caucasian facial expressions. Mondillon et al. (2007) again used short and long durations and found a slope effect only with the Caucasian facial expressions.

These results give rise to the issue of how exactly the perception of emotional expressions, such as fear or anger, result in the speeding up of the internal pacemaker in the observer? Moreover, the emotional expression that an observer is exposed to might in fact give rise to a different emotion in the observer (Droit-Volet & Meck, 2007). An example of this would be an expression of anger which would usually produce fear rather than anger in the observer (Atkinson & Adolphs, 2005). This complicates the issue of what it is that results in the acceleration of the internal clock, as it may not be the perception of anger per se, but the fear produced that causes the speeding up effects. However, a possible explanation might be easier to derive than initially thought as there are numerous studies which demonstrate a clear relationship between the neural substrates of emotion perception and emotional experience. When someone observes an emotion, their neural system activates in the same way as if they were producing the emotion themselves (Niedenthal, 2007; Atkinson & Adolphs, 2005). The possible role for this emotional-imitation may be in providing the basis for empathy for others, as we are essentially emulating to some degree, another individual’s state (Niedenthal, 2007).

1.3.3 Stress and Arousal

In order to investigate the possible effects of varying moods, in particular stressful moods, on ones ability to estimate durations of time, Gupta and Khosla (2006) used a prospective timing task. Participants were therefore aware that they would be asked to make judgments based on time. Participants were shown two short stressful film excerpts and a neutral one. One of the stressful films was an aggressive and violent fighting scene and the other was a tragic scene which invoked strong feelings of sadness. Gupta and Khosla (2006) then recorded variability in mood and prospective estimates of duration and found that the duration of stressful scenes was underestimated while neutral scenes tended to be overestimated. These results are inconsistent with those of previous studies which have looked at the effect of emotional stimuli on temporal estimations of duration and found overestimation of the duration of particular arousing stimuli (Noulhiane et al. 2007; Droit-Volet et al., 2004; Gil et al., 2007). However, a possible criticism of this study is that the the overestimation of neutral scenes may have been due to the fact that they were boring to participants rather than any internal clock speed manipulation. Since only one duration was being used in this retrospective task, it is uncertain whether any internal clock speed changes took place in this study. Previous studies, for example Droit-Volet (2004), presented participants with short and long standard durations and then asked them to compare durations to these standard durations. This clearly involves the internal clock as evidenced by slope effects which demonstrate a “speeding up” of the internal clock. However, Gupta and Khosla (2006) failed to demonstrate a slope effect as they only used a fixed duration of 130 seconds. Therefore, the notion then that the effects here are due to a bias cannot be ruled out.

Loftus, Schooler, Boone and Kline (1987) examined the effect of film-induced stress on retrospective time estimation task. In a retrospective timing task, participants are asked after the stimulus or event to complete a timing task. They are unaware they will be asked to make a timing judgment until after the stimulus. Loftus et al. (1987) showed participants a short videotape of a bank robbery. They then completed some filler tasks and were asked to return to the laboratory 48 hours later under the disguise of an unrelated task. After 48 hours, participants significantly overestimated the duration of the tape and the degree of overestimation was independent of the amount of detail recalled. However, a criticism of this experiment is that they failed to use a control. In another experiment, they found that females overestimated duration to a greater degree than males, even though they did not store more information in memory about the event. To shed further light on the gender difference, they conducted a further study designed to determine if level of stress or arousal played a role in mediating the gender differences in the duration estimation task (Loftus et al., 1987). However, the study by Loftus et al. (1987) failed to use more than one duration. The video was shown to everyone at a set duration of 30 seconds. Therefore, as a result, this study cannot demonstrate a slope effect which would support a “speeding up” effect. Deffenbacher (1986) found anxiety to be an important variable: high-test-anxious participants’ time estimates have been shown to be significantly greater than the estimates of low-test-anxious participants. Moreover, high and low-test-anxious participants differed on physiological arousal, with high anxious participants having a higher pulse rate, indicative of a higher level of arousal. However, Deffenbacher (1986) did not find a significant gender effect. Like the study by Loftus et al. (1987), Deffenbacher (1986) only had participants estimate a single 15 second duration, thus not able to show any slope effect. Inconsistent with Deffenbacher (1986), who did not find gender differences, Loftus et al. (1987) found that the same degree of film-induced stress produces more internal arousal for females than males. They also concluded that it may also be the case that internal arousal is differentially related to reported arousal. Both hypotheses are plausible. The same degree of induced stress could produce more arousal for females because females are less likely to engage in aggressive play in childhood for example (Goldstein, 1994). Participants who watched a more stressful version of the event produced longer time estimates than those who watched a less stressful version (Loftus et al., 1987).

Schedlowski and Tewes (1992) proposed that psychological fear and psychological arousal are distinct concepts. Understandably, there are few examples of experiments that systematically evaluate the distortion of time under stress or danger. Many look at natural occurrences of situations whereby time distortions could take place. For example, Ursano, Fullerton, Epstein, Crowley, Vance, Kao and Baum (1999) found that the most common peritraumatic symptom was a sense of time change during the event (Ursano et al., 1999). Using a retrospective task, Watts and Sharrock (1984) found that 35 individuals with arachnophobia showed significant changes in the appreciation of a specific time interval of exposure to a spider. Participants with arachnophobia overestimated the duration of the short interval with the spider compared to the 18 participants without arachnophobia; therefore lending further support to the idea that fear speeds up the internal clock, increasing time-estimates. The phobics' estimates were also more variable (Watts & Sharrock, 1984). Using a production task, Fox, Bradbury, Hampton and Legg (1967) induced cold stress by having participants remain in a room at 0 degrees centigrade in light clothing. This cold stress actually speeded-up the internal clock and increased the rate of subjective time. Using a retrospective measure, Auerbach (1974) found evidence which suggest that time estimation may be insensitive to immediate environmental fluctuations (i.e., anxiety). This is inconsistent with findings which show that states of arousal have an effect on timing task. Campbell and Bryant (2007) examined the relation between stress and judgments of the duration of time in novice skydivers and found that increased levels of fear prior to and during the skydive - in first time divers - was associated with the perception of time passing slowly. On the other hand, increased excitement was associated with the perception of time passing quickly. Auerbach (1974) also used a retrospective task, so these differences in findings are inconsistent. Besides the results from the study carried out by Auerbach (1974), all the other studies lend much support to Angrilli et al.’s (1997) approach/avoidance model of time perception.

Werner and Wapner (1955) developed a method of obtaining changes in psychological distance with physical distance held constant to explore the effect of perceived danger on time estimation of specifically, five seconds. Werner and Wapner (1955) asked participants not to use any counting strategies during the task. They found that psychological distance changed under conditions of danger; e.g. when the *blindfolded* participants were wheeled via a motorised contraption towards and stopped short of a precipitous edge, he/she overestimated the distance he/she traveled, in other words, the edge appeared closer. Langer et al. (1961) found that distance traversed was overestimated under conditions of danger and the time elapsed was overestimated under danger.

1.3.4 Summary of Emotion, Arousal and Clock Speed Effects

In sum, numerous studies support the idea that moods, in particular stress moods, have an effect on humans' estimates of duration. Highly arousing stimuli such as angry faces results in overestimation of duration (i.e., Gil et al., 2007) as it increases the speed of the internal clock. Since clicks are also found to produce overestimation of duration, could it be because they are also arousing? This prompted one of the research questions of this thesis (see Chapter 3), which is to explore what are the underlying mechanisms of clicks. In other words, what mediates their effect on internal clock speed? It has been argued that the effect of clicks *is* because they are arousing. For instance, Treisman et al. (1992) argues that when arousal level increases, the pacemaker output frequency increases, leading to overestimate duration.

1.4 Evidence of a Link between Internal Clock Speed and Information Processing

The previous sections discussed how emotionally arousing stimuli and various states of arousal and stress can affect one's ability on timing estimation tasks, plus other manipulations of clock speed. This suggests then that arousal may play a role in the clock speed effect. The next sections explore the real-life distortions of time and how these experiences suggest that there is a link between the internal clock and information processing speed.

1.4.1 Real-Life Experiences of Time Distortion

Laboratory experiments have shown that we can slow down people's perception of time (i.e., speed up the internal clock) and in other experiments, increase information processing rate (Jones et al., 2010). However, what about everyday situations in which people experience a distortion of time? People speak of "time flying" when they are enjoying themselves, or slowing right down in perilous situations such as a car crash (Gillings, 2006). Also, individuals who suffer from lack of sleep typically overestimate the duration of nighttime (Meerlo, 1981). The question is whether in a situation where time appears to slow down, is information processing rate increased? The next few sections explore everyday situations in which time distortion is experienced with a possible simultaneous experience of an increase in information processing.

1.4.2 Situations of High Adrenaline and Subjective Time

Noyes and Kletti (1977) investigated depersonalisation in response to life-threatening danger using personal interviews. One of their participants recalled an accident which happened a few years previously. The accident happened when he had been driving at 60 mph in an old car when the steering became ineffective. He states:

“…My mind speeded up. Time seemed drawn out. It seemed like five minutes before the car came to a stop when, in reality, it was only a matter of a few seconds”. (p. 376).

The notion of time distortions under conditions of extreme and life-threatening stress is well known. Such time distortions can often be critical in situations where the wrong decisions can be fatal, so every single second can mean the difference between life and death. One such example from a real-world event is during combat, involving emergency ejection from high-performance aircraft (Hancock & Weaver, 2005). Investigating time distortion in such a situation, Fair (1984) interviewed 28 pilots who had ejected from jet aircraft about their experience. Fair (1984) asked five questions about the temporal experience of their ejection experience. Fair (1984) found that 75% of the pilots reported distortions in time (7% were not sure and 18% experienced no temporal distortion). 64% of pilots who said yes to the first question experienced a slowing down of time, whereas 18% experienced the opposite effect. In question three about previous experiences, 36% said that they had already had a temporal distortion experience. On the other hand, 46% reported no such previous temporal distortions (18% were unsure). Of the 46% who had previous experience of such an effect of time, 90% said their temporal distortion was experienced as slowed down. Lastly, when asked how well they recalled the event, 17 recalled in high detail, 10 simply remembered a sketchy outline of the event and one reported barely any memory at all. In sum then, it appears that there is an experience of temporal distortion in such a life-threatening situation and it seems that such a distortion appears to make clock time slow down (Hancock & Weaver, 2005).

As we have seen, in dangerous or extreme situations, people frequently report temporal distortions, in that the external world seems to slow down - giving them more time to react. Indeed, Chapman, Cox and Kirwan (2005) highlighted the example of a car crash in which the "moments seem to stretch out towards the inevitable collision" (p.164). In their study, Chapman, Cox and Kirwan (2005) found that drivers remembered dangerous situations as if time had slowed down. Additonally, Ursano, Fullerton, Epstein, Crowley, Vance, Kao and Baum (1999) found that the most common peritraumatic dissociative symptom was temporal distortion (time slowing down or speeding up). In their sample of individuals suffering from peritraumatic dissociative disorder, 56.6% had experience temporal distortion. Such commonly reported experiences have inspired 'bullet time' in films (e.g. The Matrix) and, more recently, in computer games. The idea here is that the player, as in a real life experience, will have more time to make decisions and react quicker. "Bullet time" is a visual effect which "combines slow motion with dynamic camera movement" (Smed, Niinisalo & Hakonen, 2005).

In sum, these studies show that during the experience of dangerous situations in which the external world appears to slow down, people exist seemingly outside of time and outside of themselves. In other words, they lose track of passing time. Ornstein (1977) maintained that a successful experience is better organised in the memory than a failure. Essentially, the memories of good experiences take up less cortical space and are subsequently experienced as having taken less time.

1.4.3 The 'Zone'

The Dalai Lama (at the Society for Neuroscience, 2007) gave a talk on how time seems to slow down during meditation, as you focus away from the internal clock. Yet when you surface from meditation, you think more time has passed than actually has. This is a similar experience to the feeling of being in the zone (Williams, 2006). This is also known as flow. Flow or the zone, is a state of mind in which you become fully immersed and focused in what you are doing, where action and awareness become integrated. When you are in the zone, your normal way of experiencing things is dramatically altered. Nideffer

(2007) identified and examined common alterations of perception that occur when an athlete has a “peak experience”, or enters the “zone” or “flow” state (Mathes, 1982). Flow is an optimal state (Csikszentmihalyi, 1990) “involving total absorption in a task and creating a state of consciousness where optimal levels of functioning often occur”. There is a feeling of complete control, total confidence. The athlete knows with certainty what is going to happen before it actually occurs. An example of this would occur in fast racquet sports such as tennis where the player feels as if they have all the time in the world to return service. Here time is slowed down. Objects seem larger and/or more vivid than usual. There is considerable evidence supporting the theory that alterations in an individual’s focus of concentration and/or changes in physiological arousal are what precipitate an altered state of consciousness (Nideffer, 2007). It is also regarded as a universal phenomenon (Young & Pain, 1999; Young, 1999a).

Athletes under very extreme pressures in sport situations often have associated changes in physiology which means that they are more likely to pay attention to task relevant cues during competition (Nideffer, 2007). They will also be more likely to pick up on a greater amount of task relevant cues. Since all of these cues exist outside of their body, they will need to spend a majority of their time with an external focus of attention. This leads them one step closer to immersion in an external focus, in other words, the zone (Krug, 1999). Jackson (1995) investigated the factors which may influence the occurrence of flow in elite athletes. Using twenty-eight elite athletes, Jackson (1995) found 361 themes which helped understand the factors which underlie the occurrence of flow in this group. The factors or themes which best resulted in the state of flow were both physical and mental preparation; confidence; focus; how the performance felt and progressed; optimal motivation and arousal level. The majority of the athletes in this study perceived the flow state to be controllable or potentially controllable.

1.4.4 Effect of Manipulations on Information Processing Speed: Is Clock Speed the Same as Brain Speed?

So far we have discussed real life situations in which people feel time has flown by and in situations of danger where time seems to slow down. During the experience of time slowing, the question is whether the experience gains added vividness only afterward rather than during the subjective experience of distorted time perception (Gillings, 2006).

When an individual experiences a situation where time appears to slow down, does such an experience actually provide people with more information processing time? (Burdick, 2006). Stetson, Fiesta and Eagleman (2007) attempted to address the question of whether there is a real distortion of time during the event in question by setting up an arousing situation which would slow down subjective time. They made use of the fact that in some instances, stimuli that are presented sequentially in time and meet the temporal combinatory properties (two or more stimuli occurring in a time frame of about 80ms) can become perceptually integrated (Di Lollo, 1977). A well known example of this effect is the child’s toy known as a thaumatrope. On one side of the disc, for example, is a picture of a bird and on the other is a picture of a tree branch. The disc is wound up and, when released, spins so fast that both sides are seen in rapid alternation and as a result, the visual system cannot distinguish them temporally and they appear as though simultaneously present; in this example, a bird resting on a branch (Stetson et al., 2007). Eagleman (2006) adopting the same principle in his experiment to explore whether an arousing situation does indeed slow time, set up an experiment in which the participant (Jesse) was required to perform a backwards free-fall of 33 meters. In order to establish whether the experienced slowing down of time increased information processing speed, Eagleman (2006) used a device called a "perceptual chronometer". This was a wristwatch-like device which flicked extremely fast between two LED screens. Under normal conditions, the two screens flick so fast that the participant is unable to see a two digit number on one of the screens. Results suggested that when subjective duration of time is lengthened in time of arousal, the participant was more able to identify the two different screens and read a random number on one of them. Repeat falls by the same participants, received similar results. However, the findings are not entirely convincing. The participant reported that he had seen the number "98" when the actual number was “96”. Due to the similarities between these two numbers, it suggests that the participant was processing information at a much higher rate than normal. So while time on the clock may be constant, the time in ones brain is flexible and subject to our personal feelings and experience. “Time is not simply a fourth dimension in which we exist. It's something we, at least partly, create in our minds” (Gillings, 2006).

However, Stetson et al. (2007) in a later study using the same methodology but this time testing more than one participant (20 participants), found conflicting results. This time using a 31 meter free fall set up they found that participants, despite reporting an overestimation of the duration of the free fall, failed to demonstrate a “speeding up” of the brain and ultimately information processing. Eagleman then went on to argue that “It can seem as though an event has taken an unusually long time, but it doesn't mean your immediate experience of time actually expands. It simply means that when you look back on it you believe it to have taken longer." (Eagleman, 2007). However, it could be argued that there was an increase in information processing capability but it was ineffectual in the task of deciphering the individual images in the watch.

However, there is a major problem with Eagleman’s experiments involving the “perceptual chronometer” in the free-fall experiment, namely, the problem of ‘persistence of vision’. Eagleman (2006) and Stetson et al. (2007) in their experiments using the "perceptual chronometer", controlled for temporal separation not for spatial separation. The "perceptual chronometer" works by flashing a number, say, 96. Then, the inverse of this number is presented. These two resultant images are alternately flashed and as you increase the speed of alternation it becomes more difficult to discern the number until it is so fast that it becomes impossible. Eagleman (2006) argues that during an emotional situation such as a free fall, participants may be able to process the information from the perceptual chronometer (that they could not otherwise see on the ground) due to their perception of time slowing down. The problem with this is that the effect is induced not by a distortion of the perception of time, rather it is due to the phenomenon known as ‘persistence of vision’ (see Efron & Lee, 1971). Persistence of vision refers to the phenomenon whereby the retina retains an image for a brief split-second after it was seen. For instance, imagine you had a device on a piece of string which flashed alternatively between blue, green and red. Then, adjust it so it flashes so fast between the colours that you cannot discern the colours. If you spin the device round very fast on the piece of string you can make out the three colours in their after image. This is exactly what is happening in the study by Eagleman (2006). Because the participant is moving around as they fall, the image they see is shaken and they are more able to see the numbers. Therefore, this well known phenomenon would suggest that the findings by Eagleman (2006) have nothing to do with temporal distortion.

Eagleman (2004) was interested in exploring whether our brains do anything to keep timing judgments calibrated so that distortions are the exception rather than the rule. Indeed, Wohlshlager, Engbert and Haggard (2003) found that duration judgments are distorted during slow-motion video sequences of natural biological motion. In their experiment they found that a flash presented during a slow-motion sequence of a movie is erroneously perceived as having a shorter duration than an identical flash presented during the same sequence at normal speed. Therefore, it appears that the apparent speed of time can be modified by sensory feedback. In other words, predictions about future positions of a moving object are compared against sensory feedback and the difference can modulate the nervous system to speed or slow perceived time to match the physics of the sensory feedback (Wohlshlage et al., 2003; Eagleman, 2004). Thus, the brain may ease its task of consistent timekeeping by constantly calibrating its time estimation against physical laws in the outside world (Eagleman, 2004). Stetson et al. (2007), argue that the perception of time slowing is due to the ‘function of recollection’ not perception. Despite finding that estimates of duration were greater during a frightening situations (such as free-fall), they failed to find a concomitant improvement in perceptual perception (information processing rate). They suggest that duration estimates are not directly related to temporal resolution. Instead, they postulate that the role of the amygdala during emotional memory serves to increase estimates of duration retrospectively because they recode the memory, making them more detailed. This addition of greater detail results in a greater estimate of duration (Hamann, Ely, Graton & Kilts, 1999).

The studies so far, raise various questions. For instance, when an individual experiences a situation where time appears to slow down (such as a car crash), whether such an experience provides people with more information processing time? The small amount of studies so far have found results which are conflicting and in some cases (Stetson et al., 2007) have used measures which are fraught with limitations. Can people act quicker in some situations? Is internal clock speed really the same as brain speed? In other words, is information processing speed determined by internal clock speed? The experiments in this thesis will investigate these questions.

The previous sections left us with the question of whether internal clock speed really is the same as brain speed (information processing speed). Evidence that the two are linked is discussed in the following two sections. The first evidence of a link comes from a case study involving a neurological patient who experienced external objects as moving at an incredible rate while also demonstrating distortions in internal clock speed as demonstrated by a time production task. Then, the effect of age on time estimation is discussed. Before moving onto to these issues, it is important to define what we mean by information processing. Information processing refers to cognitive functioning or cognition and is interpreted with the aid of various concepts drawn from computer science. Information processing includes all of the processes studied within cognitive psychology, namely, attention; perception; learning; memory; thinking; problem solving; executive function; decision making and language (Colman, 2001). The measuring of information processes (the mental process of cognition) has generally depended on time and accuracy measures. Interpretations about speed and/or difficulty of mental processes can be derived from any differences in reaction time (RT), which ultimately led to inferences about cognitive processes and events (Ashcraft, 2002). Cognitive psychology’s use of reaction time seems natural when we consider that mental events take time. Consequently, one way of “peering into the head” is to investigate the time it takes for a specific set of mental processes to be completed. As Donders (1868/1969) a Dutch physiologist and numerous others have found, careful comparisons of individual’s reaction times to different stimuli can often give a strong indication of the mental processes operating internally. Another way in which we can explore the underlying mental processes is by looking at the accuracy of performance (whether by measuring correct recall of a list or accurate paraphrasing of text) (Ashcraft, 2002).

1.4.5 Unnatural Accelerated Time Experience in Neurological Patients: A Case Study

Documented cases of time distortions in neurological patients are very rare. However, Binkofski and Block (1996) investigated a patient (BW) who permanently experienced accelerated time. Due to a glioblastoma, BW suffered damage in the left hemisphere prefrontal cortex. One day, BW noticed while driving that external objects seemed to come towards him at terrific speed and he could not react fast enough to them. BW found that time seemed to pass very quickly and this distorted experience of duration was found in his duration judgment performance. When asked to produce a sixty second duration, his mean production was 286 seconds. Scalar-timing theory would best explain this by suggesting that the pacemaker component of BW’s internal clock was now producing pulses at a considerably decreased rate (Binkofski & Block, 1996). What the investigations of BW suggest is a link between information processing rate and clock speed. In this case, the speed of the pacemaker was slowed down combined with the subjective perception that everything externally was going very fast.

1.4.6 Effect of Age on Time Estimation

There have been many studies demonstrating the decline of information processing in older individuals (e.g., Philips & Sternthal, 1977; Hertzog & Bleckley, 2001; Bryan, Luszcz & Crawford, 1997). So, the evidence suggests deficits in information processing in older age. If there is a link between clock speed and brain speed then one would expect to see a difference in older people's ability on timing tasks compared to their younger counterparts. According to Vanneste, Pouthas and Wearden (2001) no previous study has explored internal tempo in different age groups. Vanneste et al. (2001) decided to investigate this comparing young (20-30-year-old) and aged (60-76-year-old) participants' performance on a free motor-tapping task as a measure of internal tempo. Participants took part in one session per day for five days. Participants were instructed to tap with their right hand as regularly as possible at the rate they preferred. At the first beep they began to tap until they heard the second beep. Findings showed a significant effect of age on internal tempo. Across all five sessions, the older group spontaneously tapped at a much slower rate compared to the younger group. Such findings lend support to the idea of a slowed down pacemaker in older people (Vanneste et al., 2001).

Furthermore, Espinosa-Fernandez, Miro, Cano and Buela-Casal (2003) investigated the interaction between age and gender in a time estimation task. 140 participants (70 males, 70 females), were divided into seven age groups: 8-10, 11-20, 21-30, 31-40, 41-50, 51-60, 61-70 and each was individually set the following task: they were asked to produce three time durations – 10 seconds, 1 minute and 5 minutes – and to stop a chronometer when they felt that the specific time interval stated by the examiner had elapsed. The results claimed to show an increase in underproduction of intervals with advancing in age. This increase in underproduction with advancing age is difficult to explain in terms of the internal clock. One of the effects or consequences of increasing age is precisely a decrease or slowing down of the internal and/or physiological processes within which is situated the speed of what is known as the internal clock. This deceleration of the internal clock in proportion to increase in age should have produced an overproduction instead of the underproduction that was observed. However, the experiment is open to question because of the number of tests for each time period estimation. The participants made 25 estimates of the 10 second interval, 3 estimates of the 1 minute interval and only one estimate of the 5 minute interval. There was no significant result in the 10 second estimation, some limited effect in the 1 minute estimation and an apparent significance in the 5 minute estimation. The only ‘significant’ result is based on a sample of one test per participant which is scientifically unsound.

In summary then, these two studies have demonstrated timing deficits in old age. Since it is well known that old aged individuals have deficits in information processing (Vanneste et al., 2001), the fact that they also display timing deficits does support the idea that information processing is linked to the internal clock. In other words, brain speed does appear to be linked to clock speed. Chapter 4 of this thesis explores the behavioural parallels between interval timing (internal clock speed) and information processing (reaction time) in a meta-review. It investigates various factors such as attention, arousal, age and stimulus modality to see whether they have an effect on either internal clock speed and/or information processing. Evidence for each factor regarding both internal clock speed and information processing is scrutinized to see whether (for instance) something which produces overestimation of durations is also found to increase information processing. Such evidence would strengthen the idea that there exists a link between brain speed (information processing) and the internal clock.

1.4.7 Potential Theoretical Models to Explain the Link between Information Processing Rate, Arousal and the Internal Clock

So there are studies which have attempted to address the issue of whether arousing stimuli can induce a speeding up of the internal clock resulting in faster information processing and time distortions. The most relevant study carried out to understand the link between information processing rate and internal clock speed comes from Jones et al. (2010). In a series of experiments they demonstrated that a 5 second train of clicks can have an effect on information processing rate. This was a novel and interesting exploration because previous studies using click trains (e.g., Penton-Voak et al., 1996; Wearden et al., 1998) only demonstrated the clicks ability to increase the subjective duration of tones they precede, (in a manner consistent with “speeding up” timing processes). Jones et al. (2010) performed experiments which explored simple and choice reaction time (Experiment 1), or mental arithmetic (Experiment 2). In general, preceding trials by clicks made response times significantly shorter compared with trials without clicks, but white noise had no effects on response times (Experiment 2b of this thesis). Jones et al. (2010) also investigated whether the click trains can enable more encoding of information in some objective time period *t* when the internal clock is running faster and hence the subjective time elapsed is increased. In the famous study conducted by Sperling (1960), he presented briefly (5-500ms) matrices of letters in rows of three and then subsequently tested on their recall. In one of the conditions, Sperling requested that participants recall as many letters as they could and they would typically report 4.5 letters which Sperling (1960) called the 'immediate memory span'. In Experiment 3 using the same task, Jones et al. (2010) investigated whether the reported subjective lengthening of duration caused by the click trains would enable the participants to extract more letters from the matrix since they should feel exposed to it for longer than compared to the silence conditions. Indeed, Jones et al. (2010) did find that on those trials preceded by clicks, participants recalled more letters from the matrix than on those trials without clicks. Experiment 4 used an adaptation of Loftus, Johnson and Shimamura’s (1985) iconic masking task. The findings of this Experiment was consistent with the findings from Experiment 3, participants were able to recall or recognise significantly more information from stimuli preceded by clicks than those preceded by silence. These findings suggest that psychological processes take place in subjective as opposed to real time, if you consider the effect of clicks is to speed up the internal clock.

Taken together, the findings by Jones et al. (2010) suggest an effect of the click train manipulation, shown to increase the rate of subjective time in a number of previous studies (e.g. Penton-Voak et al., 1996; Wearden et al., 1998, 2007), on the rate or efficiency of information processing during tasks which do not themselves require time judgements. In Experiments 1 and 2, click trains reduced the time needed to make responses in tasks involving reaction time or mental arithmetic, even though the response time for the latter task was three to five times longer than that for the former one. The results of Experiment 1 and 2 suggest that responses really can be “speeded up” by the clicks: that is, people can perform faster than without clicks, even though they are instructed to respond as fast as possible in all conditions. However, results of Experiments 3 and 4 show that the effect of clicks is not merely to speed response times, but apparently to increase the quantity of information that can be extracted from a visual display. It should be noted that the performance measures in Experiments 3 and 4 involve the number of items correctly recalled or recognised, rather than response time, so increases in memory performance in these cases are not due to speeding of responses.

A small number of previous articles have reported effects of repetitive stimulation on tasks other than those requiring duration judgements. Two of these (Burle & Bonnet, 1999; Treisman, Faulkner & Naish, 1992) used click trains, although the focus of interest of both studies was on the idea that specific frequencies of stimulation had different effects on performance, rather than on click/no click comparisons as in the studies by Jones et al. (2010). Both studies investigated the effect of different click frequencies on the time taken to make motor responses. Treisman et al.'s (1992) Experiment 1 and Burle and Bonnet's (1999) study were similar in that both used click trains to examine choice responses. In Treisman et al.'s case people had to press one key if a stimulus was on the right of a computer screen and another key if it was on the left. Burle and Bonnet used a task similar to that employed by Simon and Small (1969). Here, responses to a green or red stimulus had to be made with different hands and trials were either "congruent" (when the stimulus appeared on the same side as the correct hand) or "incongruent" (where the stimulus was on the opposite side). Both studies presented click trains during the stimulus presentation and in Burle and Bonnet's case the click trains started around 0.5s before the stimulus. Treisman et al. (1992) used click frequencies ranging from 2.5 to 27.5Hz in different conditions and Burle and Bonnet used values from 19.5 to 22Hz. In both cases frequencies increased in 0.5Hz steps. A problem with both of these studies is that they both failed to include a control. Treisman et al. (1992) did not use a "no click" condition and, likewise, although pre-training included a condition without click trains was used in their study, Burle and Bonnet (1999) only reported data from conditions with click trains.

The main focus of the analysis of both studies was on the response time residuals remaining when mean response time was regressed against click frequency and both studies found that different click frequencies appeared to have different effects. For example, in Burle and Bonnet's study a 20.5Hz frequency increased response times, but frequencies of 21 and 21.5Hz decreased them, relative to the value predicted from the regression line (see Figure 2). This pattern is exactly that expected if the clicks were driving an internal pacemaker with an underlying frequency of around 21Hz, or some multiple of 21Hz.

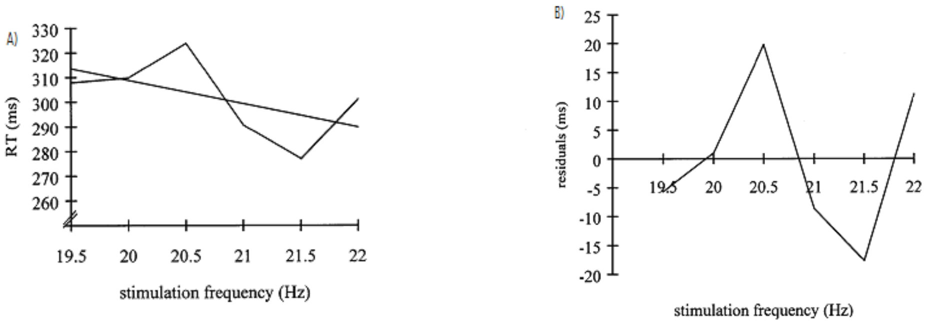

Figure 2: A) Raw mean RT as a function of stimulation frequency and regression slope computed on these data (here on correct activities of ICS trials for one subject). Figure B) Residual RT after detrending for the same data.

Treisman et al.’s (1992) work produced a complex pattern of results but in general there was evidence for both increases and decreases in response times (relative to the regression predictions) with different frequencies. Neither study produced data which are simply comparable with those of Jones et al. (2010), although in Burle and Bonnet’s work, higher click frequencies, even within the narrow range they used, made average response times shorter, which suggests that higher frequencies have more “powerful” effects, in contrast to the results Jones et al. (2010) in Experiment 2. In Experiment 2, Jones et al. (2010) found a clear reduction in reaction time (RT) in the click trials relative to the no-clicks trials for the 5Hz conditions, but no such effect for the 25Hz conditions.

In addition, effects of a different type of repetitive stimulation may have been prefigured in a slightly different literature. Wilkinson, Scholey and Wesnes (2002) investigated the effects of chewing gum on performance on a battery of cognitive tests. They found that chewing gum improved spatial and numeric working memory and also immediate and delayed recall, compared with a no-chewing condition. Particularly interesting were results from a “sham chewing” condition, where participants mimicked chewing movements, thereby generating their own repetitive stimulation. This manipulation decreased RTs in a numerical working memory task (compared with no chewing), but increased simple RTs. This work has given rise to a small literature, which is nevertheless large enough to contain contradictory results (e.g. contrast Stephens & Tunney, 2004, with Kohler, Pavy & Van Den Heuvel, 2006) and different interpretations (see Scholey, 2004, for example), so the reliability and mechanism of action of gum-chewing remains unresolved, but nevertheless the results may show some effect of repetitive stimulation on cognitive performance.[1]

If we consider that subjective time and information-processing are perhaps linked, there are at least four subtly-different theoretical possibilities[2]. First, that the clicks directly increase information processing rate. See Figure 3 for a diagram of this model.

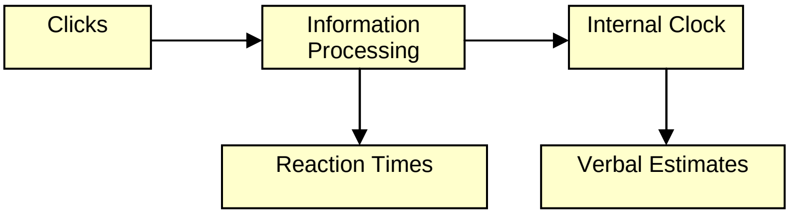

Figure 3: Clicks directly increase information processing rate, which in turn affects internal clock speed.

So even if there were changes in the participants' perception of subjective time, such an effect would be independent of information processing rate. In other words, clicks speed up information processing rates despite it operating in real time. The study by Jones et al. (2010) where participants recalled more letters from a Sperling (1960) type matrix after clicks still falls short of explaining whether, as well as an increase in information processing (as evidenced by participants being able to recall more letters), there was also a simultaneous increase in the speed of the internal clock (as evidenced by overestimate of duration). Previous studies have also shown that clicks can produce overestimation of duration (increased internal clock speed) but not also shown whether there is a *simultaneous* increase in information processing rate (i.e., Jones et al., 2010). This question is explored in this thesis (see Experiment 6).

So, exactly how are changes in subjective time produced in studies which clearly show this effect? (Jones et al., 2010; Penton-Voak et al., 1996). One explanation is that the role of

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[1] Parts of this discussion were composed in callaboration with Jones and Wearden in the course of putting together our paper (Jones et al., 2010).

[2] It is important to point out here that these four potential *parsimonious* theoretical models are examples of the cause and effect relationship underlying the effects of clicks. Obviously there could always be a more complicated model.

clicks is two-fold. They increase the speed of the internal clock which results in an increase in the rate of subjective time as well as independently increasing the rate of information processing. Therefore two independent processes are modulated by the effects of clicks. See Figure 4 for a diagram of this model.

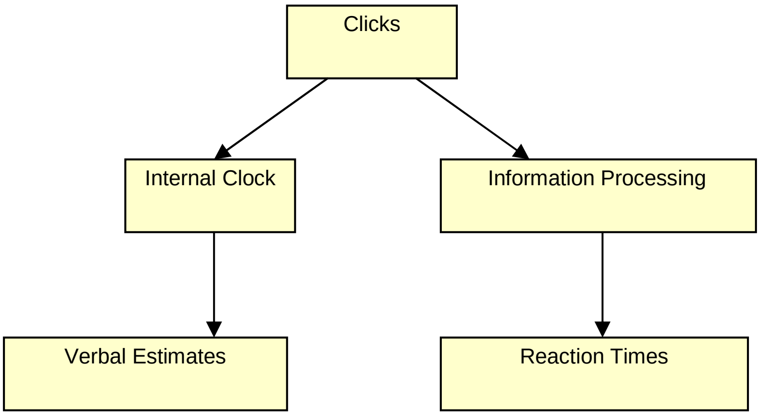

Figure 4: The role of clicks is two-fold. They increase the speed of the internal clock which results in an increase in the rate of subjective time as well as independently increasing the rate of information processing.

Another possible explanation is that changes in both the rate of information processing and subjective time are linked, not because an increase in pacemaker speed increases rate of information processing, rather temporal estimations themselves are derived from information processing rate. See Figure 5 for a diagram of this model.

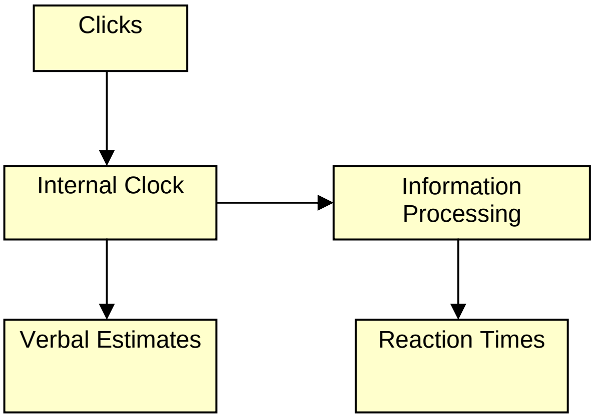

Figure 5: Changes in both the rate of information processing and subjective time are linked, not because an increase in pacemaker speed increases rate of information processing, rather temporal estimations themselves are derived from information-processing rate.

Lastly, it could be that the internal clock is mediated by a third factor (possibly arousal or attention, for example). See Figure 6 for a diagram of this model.

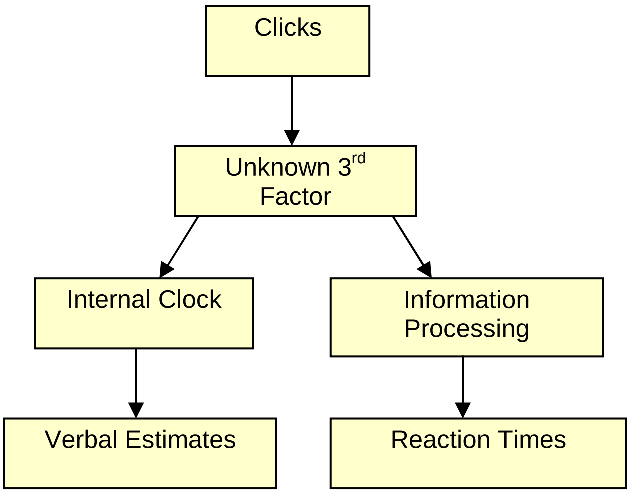

Figure 6: The internal clock is mediated by some unknown factor (possibly arousal or attention).

The findings by Jones et al. (2010) do not allow these four theories to be conclusively distinguished at present. However, the the rest of this section will explore some potential mechanisms for the click trains effect.

How does any sort of repetitive stimulation have an effect on cognitive performance? Potential answers remain highly speculative, but links between oscillatory activity of the brain, or certain brain rhythms and cognitive performance have been discussed for many years. Burle, Macar and Bonnet (2003) provide a review of many of the main ideas. The notion that the alpha rhythm (8-12Hz) plays some role in information processing has a long history, with work by Surwillo (e.g. 1963) being prominent and sometimes striking results are obtained. More recent work has suggested evidence of a link between alpha rhythms, information processing and RT, although often by way of a complicated interaction of factors. For instance, Klimesch, Doppelmayr, Schimke and Pachinger (1996) found that participants with high alpha frequency showed fast RTs, whereas slow subjects had low alpha frequency for similar results. Chapter 2 of this thesis explores the notion of alpha rhythms in time perception and information processing speed. This chapter discusses a variety of studies which renders the idea of the results by Jones et al. (2010) being due to synchronization of alpha activity problematic, since there is conflicting evidence as to the role of alpha in information processing and the issue of what, if any, role it plays is yet to be fully resolved.

Another idea, also present in the literature for some years, has been that information processing is discontinuous, with information transmission between different parts of cognitive systems occurring in “packets” separated in time (see Dehaene, 1993, for example). According to this view we call the specific frequency argument, operations which increase the rate at which packets could be transmitted, possibly by driving underlying oscillatory processes, would increase the rate of information processing. Burle et al. (2003) themselves present a similar potential mechanism for effects of repetitive stimulation, their dual pacing hypothesis. To simplify slightly, suppose two neurons, one downstream from the other, form a chain of information transmission. A problem is to transmit the neural firing through the chain efficiently in the presence of random background neural activity, which tends to obscure the transmitted signals. Burle et al. (2003) propose that repetitive stimulation has two effects. Firstly, it synchronises transmission in the upstream neuron, so spikes are grouped into “packets” distinct from random background activity. Secondly, it synchronises the receptivity of the downstream neuron for the packets received from the upstream one, so that when these arrive the downstream neuron is in a maximally receptive phase and passes the signal on efficiently. If any kind of repetitive stimulation, from clicks and flashes, does have the ability to synchronise neural activity, then Burle et al.’s hypothesis provides a potential mechanism for its action. Chapter 2 explores two more theories as to how clicks work namely, the non-specific sympathetic entrainment and the long term potentiation argument. The non-specific sympathetic entrainment argument suggests that synchronisation responses of brainwaves to periodic auditory stimuli can occur, irrespective of the frequency delivered by the repetitive stimulation (i.e., Will & Berg, 2007). Lastly, is the idea that the click effect is due to them enhancing the fire rate between neurons and increasing efficiency, a phenomenon known as long term potentiation.

Chapter 2

A Review of the Possible Mechanism/Explanations of the Effect of Clicks on Information Processing and Internal Clock Speed

2.1 The Role of Alpha Rhythms

Brain oscillations reflect neural activity and arise from the correlated activity of a large number of neurons whose interactions are generally nonlinear (Steriade, McCormick & Sejnowski, 1993). Brain oscillations, in response to a sensory or cognitive event (known as evoked or event-related oscillations) are typically classified according to the ‘natural frequencies’ of the brain. These ‘natural frequencies’ or rhythms are: alpha 8-13Hz, theta 3.5-7Hz, delta 0.5-3Hz and gamma 30-70Hz (Başar, Başar-Eroglu, Karakaş & Schürmann, 2001). However, despite a range of rhythms, the alpha rhythm is undoubtedly the best known rhythmic activity that has been described in the nervous system (Anokhin & Vogel, 1996; Klimesch, Sauseng & Hanslmayr, 2007). Its source is unknown, however, there has been an increase in studies investigating the physiological mechanism underlying brain oscillations, in particular those in the alpha frequency band (i.e., Lopes da Silva, 1991). Many suggestions have been put forward, including the proposal that it is controlled by a pacemaker (i.e., Derbyshire & Bohn, 1938; Goody, 1958). The extent to which it is present in the electroencephalogram has often been used as a measure of arousal. It is common principle to order various degrees of “general arousal,” often not distinguished from the sleep-waking cycle, along a continuum and to associate them with characteristic EEG patterns. Of the states categorised in this way by Lindsley (1960), the three most likely to be seen in waking subjects are (i) “alert attentiveness,” in which fast low-amplitude waves dominate the encephalogram; (ii) “relaxed wakefulness,” in which the record becomes more synchronised and the alpha rhythm is most strongly represented; and (iii) “drowsiness,” which is characterised by a decrease in alpha activity, the record becoming flat with occasional slow waves. Thus, as general arousal decreases, the proportion of alpha in the record first rises and then falls.

There is evidence that the frequency of the alpha rhythm may also vary as a function of arousal, following the “Inverted-U” model of arousal, a theory originally proposed by Yerkes and Dodson (1908). Repetitiveness, immobilisation and sensory or perceptual deprivation reduces the frequency of alpha and is also reduced in both waking and drowsy subjects. Since Treisman’s internal clock model (1963) argues that raised arousal increases the rate of the pacemaker and reduced arousal slows it, it would seem reasonable to suggest a relationship between alpha rhythms and the internal clock (i.e., Brazier, 1960). However, as pointed out by Shaw (2003) some studies have attempted to use alpha amplitude as a measure of arousal and even tried to establish a relationship between the two (i.e., Davis & Davis, 1936). However, it is largely found that such attempts are thwarted from the start due to the significant inter-individual differences found in alpha amplitude and wave morphology. For instance, certain alpha amplitudes may represent entirely different degrees of arousal for different subjects entirely (Shaw, 2003).

A number of studies argue for a relationship between time perception and alpha frequency. Time has been reported to pass more rapidly as we grow older (Carrasco, Bernal & Redolat, 2001; Wearden, 2005b). Since average frequency of the alpha rhythm in individuals over 80 years may gradually decrease to 8Hz from 10Hz when younger, slowing down of this 'clock' could have a profound effect on timing estimations (Surwillo, 1966). Surwillo (1966) investigated whether there was a relationship between the alpha rhythm and the sense of time using one participant, a 28 year old healthy male. The participant lay on a cot with his eyes closed and held a pushbutton in his hand. The participant was asked to estimate a 10s interval by pressing and releasing the button whenever a soft, 0.3 s tone (presented randomly) was heard over a loudspeaker and then successively pressing and releasing 10 more times, once each after he decided that one second had elapsed. One-hundred and twenty estimates of 10 s were made during a 1 hour session while EEGs were simultaneously recorded. Findings showed that despite providing some evidence for the alpha rhythm as an internal clock, the correlation they found for this relationship was very small. Specifically, the variation of the alpha rhythm was only between 96-105ms, while the variation in estimations displayed significantly more variation, between 8.72 and 11.43 s. Moreover, it was found that the alpha rhythm can only account for 5.5% of the total variation displayed in the estimations of time elapsed. Therefore, factor(s) other than the alpha rhythms must account for the variations in the sense of time.

Treisman (1984) investigated three hypothesese of the relationship between time judgments (internal clock) and alpha rhythms. First, the “specific arousal” hypothesis, which suggests that there may be similarities between the effects of external influences on temporal arousal (specific arousal) and on general arousal. In other words, time judgement and alpha rhythms may be entirely independent, each reflecting the specific arousal of the mechanism determining it. The second hypothesis is the correlated arousal hypothesis which, in contrast to the first hypothesis, argues that specific arousal is simply the local action of general arousal. In other words, factors which influence the level of arousal in the subject as a whole also act on the temporal pacemaker, in a similar way, to produce corresponding states of high or low arousal in it, causing it to run correspondingly fast or slow. The alpha rhythm may be an index of a state of general arousal which also acts on the temporal pacemaker. Because of this common influence, the alpha frequency and the proportion of alpha in the electroencephalogram, may be correlated with the speed of the temporal pacemaker. Lastly, the common pacemaker hypothesis in which the alpha rhythm and the frequency of the temporal clock may be modulated by a single common pacemaker. So, the same pacemaker may be common to the internal clock and an alpha rhythm generator (This hypothesis orignates from the work of Hoagland (1936) who found that the frequency of the alpha rhythm was directly proportional to the speed of the underlying 'metabolic phenomena' – see Chapter 1, Section 1.1.1). Both the correlated arousal hypothesis and the common pacemaker hypothesis will predict an inverse relation between alpha frequency and time productions.

So, in order to test the validity of these three hypotheses, Treisman (1984) investigated whether there were any simultaneous variations in temporal judgment and in an indicator of general arousal, namely, the alpha rhythm. In the study carried out by Treisman (1984), each trial began with the onset of a 500Hz tone which the participant was asked to terminate when they estimated it to be exactly four seconds, by pressing the reaction key. The inter-stimulus interval varied randomly between 3 and 8 seconds. Participants were asked not to count and to keep their eyes closed throughout the experiment for consistency. Treisman’s (1984) findings demonstrated that the common pacemaker hypothesis cannot be sustained. Findings suggested that the stability of the alpha rhythm is greater than that of temporal productions over the duration of testing. The variability of the temporal pacemaker greatly exceeds that of the alpha rhythm, as indicated by the coefficients of variation. This is consistent with the findings of Surwillo (1966) discussed earlier. In sum then, simultaneous observations of alpha frequency, alpha prevalence and temporal productions show that there are no simple relations between these measures such as might support the general arousal or common pacemaker hypotheses. However, relations are found between the variables. For instance, since the alpha rhythm may be an indicator of the general state of arousal as well as influencing the rate of the pacemaker in the internal clock, it can be argued then that the alpha frequency and the proportion of alpha in the electroencephalogram may be correlated with the rate of the internal clock.

Despite inconsistency in the literature concerning the origin of the alpha rhythm, it is still possible to identify two facts which support the link between the alpha rhythm and the time measuring mechanism. First, there is the significance of the thalamus and thalamo-cortical connections, both for the origin of the alpha rhythm and for the sense of time (Matell & Meck, 2004; Lopes Da Silva, Vos, Mooibroek & Rotterdam, 1980; Dusser de Barenne & McCulloch, 1941). Second, this idea is further supported if we consider situations which are optimal for the occurrence of the alpha rhythms, i.e., undisturbed quiet, which is also the optimal conditions for more accurate time sense (Holubar, 1961). However, Lippold (1970) argued that, rather than originating in the brain tissue, the 8−12Hz rhythmical waveform can be recorded from the scalp of most human participants when their eyes are closed. Lippold (1970) maintains that it is generated by physiological tremor in the extra-ocular muscles modulating the field set up by the standing potential of the eye. So it appears then, that the idea of the importance of the thalamus and its connections with the cortex for the origin of the alpha rhythm is not without some criticism. However, more recent studies investigating the relationship between the thalamus and alpha rhythms have controlled for eye movements and maintain that there is indeed a “close functional relationship between thalamic activity and alpha rhythm in humans mediated by cortico-thalamic loops which are independent of sensory afferences” (Schreckenberger, Lange-Asschenfeldt, Lochmann, Mann, Siessmeier, Buchholz, Bartenstein & Gründer, 2004).

In sum, there appears to be much evidence to suggest that there is a link between internal clock speed and alpha rhythms (i.e., Treisman, 1984). Treisman (1984) argue that alpha rhythms may be an indicator of the general state of arousal. In Chapter 1, Section 1.3, we show numerous studies which have shown a link between arousal and internal clocks speed. Therefore, if alpha rhythms are an indicator of arousal level, then it is possible that this may underly the effect of clicks on information processing and internal clock speed.

2.1.1 The Relation of Alpha Rhythms to Cognition (in particular, reaction time) and the Rate of Information Processing

The electroencephalogram is produced by synchronous postsynaptic potentials from thousands to millions of neurons and is usually recorded at the scalp, although intracranial EEG is sometimes recorded. When amplified, digitized and plotted, the raw EEG signal appears as a complex oscillatory pattern. This complex signal can be filtered to isolate narrow frequency bands (Hz) that reflect specific brain sources and functions (Duffy, Iyer & Surwillo, 1989). Theta oscillations dominate in lower mammals. However, Alpha oscillations are manifestation of activity which dominate in adult humans (Knyazev & Slobodskaya, 2003). Alpha suppression, interpreted in terms of 'desynchronization', suggests that during information processing large populations of neurons no longer oscillate in synchrony. Thus, event-related desynchronization (ERD), calculated as the percentage of a band power change during the performance of some kind of task with respect to a reference or 'resting' interval (Pfurtscheller & Aranibar, 1977), may be considered a measure reflecting the extent to which synchrony is lost. Klimesch et al. (2007) argued that these and other findings (e.g., about the relationship between ERD, cognitive performance and intelligence) demonstrate that a decrease in alpha band power (particularly in the upper frequency range) is closely related functionally to active cognitive processing. They conclude that ERD reflects active information processing in the sense of excitatory brain processes. Alpha event related synchronization (ERS), on the other hand, demonstrates a functional correlate of inhibition in cognitive and motor tasks. Put simply, large amplitudes of synchronized alpha activity reflect a brain state of reduced information processing (e.g., Pfurtscheller, 2001). Pfurtscheller (1992) also demonstrated that ERD and ERS can occur simultaneously in different areas of the brain depending on the nature of the task the participants undertake.

What Klimesch et al. (2007) described here regarding ERD and ERS may appear to contradict the findings we review below regarding level of alpha frequency and information processing as measured by RT. However, it is important to stress that they are both dealing with different types of alpha rhythms or patterns (i.e, Basar, Schurmann, Basar-Eroglu & Karakas, 1997). This supports earlier findings by Walter (1957) who argued that the alpha rhythm in an individual comprises of numerous alpha rhythms. Essentially, there is no support for the notion of a 'unique alpha generator', instead there is a "diffuse and distributed alpha system" (Basar & Schurmann, 1996). The brain areas described by Klimesch et al. (2007) here are the primary and secondary visual areas, namely, the occipital lobe. The ERS and ERD effects Klimesch et al. (2007) described relate to resting states. On the other hand, the alpha behaviour we describe below is located in the frontal brain areas particularly during semantic information processing. Thus, there are four primary conditions of alpha activity: low alpha in the occipital region; high alpha in the occipital region; low alpha in the frontal brain regions and high alpha in the frontal brain regions.

The EEG reflects changes in postsynaptic (i.e., dendritic) membrane potentials (cf. Logothetis et al., 2001) primarily in cortical neurons. Thus, rhythmic changes in the EEG, typically observed during pronounced alpha activity, reflect rhythmic changes in the excitability of (primarily cortical) neurons. Rhythmic activity must have a strong influence on information processing in the brain, because the generation of action potentials is much more likely during the excitatory (extracellular negative) phase than during the less excitatory or inhibitory (extracellular positive) phase of an oscillation. It has been suggested for a long time that the cortex exhibits cyclical changes between maximal and minimal responsiveness (Bishop, 1933) that are related to the negative and positive phase of alpha.

Indeed, the notion that the alpha rhythm (8-12Hz) plays some role in information processing has a long history, with work by Surwillo (e.g., 1963) being prominent. For example, Surwillo (1961; 1962; 1964) postulated that alpha frequency is significantly correlated with the speed of information processing as measured by RTs. Subjects with high alpha frequency show fast RTs, whereas slow subjects have low alpha frequency for similar results (see also Klimesch, Doppelmayr, Schimke & Pachinger, 1996; Callaway & Yaeger, 1960; Lansin, 1957). Moreover, Woodruff (1975) used biofeedback to either increase or decrease alpha frequency compared to baseline and found that increases in frequency decreased RTs and decreases in frequency increased them, relative to baseline conditions. This raises the possibility that our click trains are having some effect on alpha (although our frequencies are usually lower than the alpha frequency). Although links between alpha rhythm and aspects of information processing are sometimes found (Callaway & Yaeger, 1960; Lansin, 1957), other studies (Boddy, 1981; Treisman, 1984) have failed to obtain relations between alpha frequencies and either information processing or timing. More recent work has again suggested evidence of a link between alpha rhythms, information processing and RT, although often by way of a complicated interaction of factors. For instance, Klimesch et al. (1996) found that participants with high alpha frequency showed faster RTs, whereas slow subjects had low alpha frequency for similar results.

These recent findings by Klimesch et al. (1996) support the findings from earlier studies, for example, those of Varela, Toro, John and Schwartz (1981). Varela et al. (1981) asked their participants to judge whether two briefly exposed visual stimuli with asynchronous onset appear as simultaneous or moving stimuli. They found that stimuli presented during negative polarity were perceived as simultaneous whereas those presented during positive polarity appeared moving. Further, Dustman and Beck (1965) found that RT to the onset of a light flash was fastest during the surface positive alpha cycle. In assuming that a visual stimulus is processed in the cortex after a delay (due to peripheral transmission time) of about 50ms, the critical time window for the prediction of behavioural effects is not the phase of alpha at stimulation but at the time of cortical processing which is 50ms post-stimulus for the present example. Thus, if a stimulus is presented during the positive cycle, alpha will be at its negative cycle 50ms later (in assuming that alpha period is about 100ms). In assuming that alpha is now in its excitatory phase, stimulus processing in the visual cortex will be enhanced and RTs will decrease. When applying the same reasoning to the findings of Varela et al. (1981), Klimesch et al. (2007) concluded that stimuli presented during the positive cycle should coincide with enhanced stimulus processing in the brain which in this case means that the two stimuli would not be perceived as one simultaneous but instead as two separate (moving) stimuli. Thus, there are reasons to assume that alpha phase controls cortical excitability.

The idea that information processing rate can be enhanced with increased alpha power was also shown by Klimesch, Sauseng and Gerloff (2003) who artificially increased alpha power by means of repetitive transcranial magnetic stimulation at individual upper alpha frequency[3] and found enhanced performance on a task of mental rotation. It is important here to explain what is meant by alpha power.

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[3] Peak alpha frequency (PAF) measures the distribution of alpha rhythm frequency which usually resembles a bell-shaped curve with an average peak of 10–11Hz in healthy adults. Primarily, the peak alpha frequency is typically greater/faster in adults (10Hz) and there is also variation across individuals (Angelakis, Lubar, Stathopoulou & Kounios, 2004).

From a physiological perspective, EEG power reflects the number of neurons that discharge synchronously. In principle, it can be argued that the measurement of EEG power reflects the performance of cortical information processing. However, measurements of power can also be influenced by a variety of other factors, for example, thickness of the skull or age. In sum, it is clear that a simple explanation of our results based on synchronization of alpha activity is problematical, since there is conflicting evidence as to the role of alpha in information processing and the issue of what, if any, role it plays is yet to be fully resolved.

In sum, the section suggests that there is a relationship between alpha rhythms and information processing rate. Klimesch et al. (1996) found that participants with high alpha frequency display faster RTs, while participants with lower alpha rhythms had increased RTs. This strongly supports the idea that alpha rhythms are linked to information processing. Since clicks are also shown to increase information processing, it is possible that the clicks mediate their effect by increasing the level of alpha activity.

2.1.2 The Relation of Alpha Rhythms to Memory

Lebedev (1990, 1994) has proposed a functional role for the human alpha rhythm in stating that cyclical oscillations in an alpha rhythm determine the capacity and speed of working memory. The higher the frequency the greater the capacity and the speed of memory (Lebedev, 1994). Klimesch (1999) demonstrated that EEG oscillations in the alpha and theta band reflect cognitive and memory performance in particular. Numerous studies by Klimesch’s laboratory demonstrate that alpha frequency of good memory performers is about 1.25Hz higher than that of age-matched samples of bad performers. The sites that were recorded from were the hemisphere (Hemi); left and right side of the scalp; localization (LOC), frontal (f), central (c), parietal (p), temporal (t) and occipital (o).

Individual alpha frequency (IAF) measures the center of gravity, as opposed to the peak, within the range of alpha frequency for each individual. Essentially, what this creates are frequency bands above and below the average peak of 10–11Hz, for example 8–10Hz (low alpha) and 10–12Hz (high alpha) (Angelakis et al. 2004). IAF is considered a potentially more sensitive measure of distribution than PAF (Klimesch, 1997).

Since it appears that good performers are faster in retrieving information from memory (Klimesch, 1993) than bad performers, it suggests that alpha frequency is linked to the speed of information processing or RT. Indeed, it was primarily found that at parietal sites, the left hemisphere of bad performers but not the left hemisphere of good performers demonstrated decreased individual alpha frequency. Therefore, providing further evidence for the link between information processing and alpha, consistent with later findings (e.g., Klimesch, 1994; Klimesch, 1996; Klimesch, 1997; Klimesch, Pfurtscheller, Mohl & Schimke, 1990; Klimesch, Schimke & Pfurtscheller, 1990; Klimesch, Schimke, Ladurner & Pfurtscheller, 1990). In addition, Osaka, Osaka, Koyama, Okusa and Kakigi (1999) investigated the effect of the working memory demands on the peak alpha frequency of the power spectrum of magnetoencephalography (MEG). (It is important to note here that the frequency of the alpha wave changes with local activity of the brain and the peak frequency of the alpha power changes with the cognitive mental loads. See earlier Notes [1]. (Klimesch, Schimke & Pfurtscheller, 1993).

A study carried out by Williams, Ramaswamy and Oulhaj (2006) actually explored the effect of a repetitive stimulation in the form of a flicker on alpha rhythms and memory performance. Williams et al. (2006) investigated whether alpha-frequency flicker enhances memory in older people. It is known that both alpha and memory decrease as we get older. Participants aged 67–92 were asked to identify short words following 1 s of flicker at either 9.0Hz, 9.5Hz, 10.0Hz, 10.2Hz, 10.5Hz, 11.0Hz, 11.5Hz or 500Hz. After a delay duration of a few minutes, they then explored participants' recognition of the words (without flicker). The findings showed that flicker frequencies close to 10Hz (9.5–11.0Hz) enhanced the identification of the test words in older participants. These particular flicker frequencies also increased recognition of the words compared to the other frequencies (9.0Hz, 11.5Hz and 500Hz), irrespective of age. Therefore, it appears that flicker can induce alpha-like activity. These findings by Williams et al. (2006) are consistent with their previous study which also showed that alpha-frequency flicker can improve memory in healthy participants. Further, the effect of flicker was highly specific in that it only improved memory when it was presented at 10Hz, not 8.7Hz or 11.7Hz.

In sum, numerous studies appear to support the idea of a relationship between alpha and memory processes. Williams et al. (2006) showed that memory in older people can be enhanced by repetitive stimulation in the form of a flicker, presented at alpha frequencies.

Again, this shows that alpha rhythms are related to information processing. This is still consistent with the idea that the clicks operate by increasing alpha, since clicks have shown to improve memory recall (Experiment 5a of this thesis; and Experiments 3 and 4 of Jones et al., 2010).

2.1.3 The Relation of Alpha Activity to Intelligence

Dongier et al. (1976) highlighted that there is great inconsistency in the findings of whether there is a relationship between alpha and intelligence with some studies finding normal adults with faster alpha frequencies score higher than people with slower alpha frequencies, some the opposite and others finding no relationship at all. Dongier et al. (1976) suggest that the lack of consensus is a result of the multi-variable nature of intelligence, the discrepancies between the differing tests used and the different methods of administering the tests.

Because working memory is a central component of intelligence (Engle, Tuholski, Laughlin & Conway, 1999), it seems reasonable to expect that alpha peak frequency is important to intelligence. The electroencephalogram (EEG) reflects stable individual differences in brain function and therefore can be a powerful instrument for exploring the biological basis of intelligence (Anokhin & Vogel, 1996). Previous studies have attempted to demonstrate the relationship between peak frequency to intelligence, arguing that a faster oscillating brain reflects rapid information processing, which is subsequently associated with higher intelligence (i.e., Osaka et al., 1999; Anokhin & Vogel, 1996), Jausovec (1996) found that compared to average individuals, gifted individuals demonstrated higher EEG alpha power only while resting with eyes open not with eyes closed. Jausovec (1996) argues that the findings suggest that rather than working faster, the gifted individuals' brains are simply more efficient in activating more task-relevant brain regions (Jausovec, 1997; 1998). Klimesch (1997) consistently reported a relationship between high alpha peak frequency and good memory performance. Contradicting these earlier findings showing that high peak frequencies appear to be associated with higher intelligence, etc (i.e., Anokhin & Vogel, 1996), Posthuma, Neale, Boomsma and de Geus, (2001) found no evidence of a genetic correlation between alpha peak frequency and intelligence (based on the four WAIS dimensions) and concluded that "smarter brains do not seem to run faster." Rather, it is the efficiency of connectivity which is important

(Jausovec & Jausovec, 2000; Anokhin et al., 1999). Inconsistent with all the above studies, Alexander, O’Boyle and Benbow (1996) showed that the overall alpha power (8-12Hz resting potential) was significantly greater in average ability participants compared to both college-age and gifted adolescent participants during an eyes open task.

In sum, alpha rhythms appear to be linked to intelligence. Jausovec (1997) study showed that gifted individuals during problem solving tasks had higher alpha activity compared to average intelligence individuals. So far, we have seen that higher alpha levels enhance memory, information processing and intelligence which strengthens the idea that clicks are resulting in increased alpha activity.

2.1.4 Peak Alpha Frequency Training for Cognitive Enhancement in the Elderly

Although previous studies have shown the effectiveness of neurofeedback in the treatment of various neurological and psychiatric disorders such as epilepsy (Sterman, 2000), by altering EEG amplitude in the alpha, beta, or theta frequencies, there has been no exploration of the effects of training individuals to change the peak frequency of their alpha rhythm. It is important to state here that Peak alpha frequency (PAF) corresponds to the discrete frequency with the highest magnitude within the alpha range and is known to be slower in children and the elderly, although it also varies across individuals (Klimesch, 1997; Posthuma, Neale, Boomsma & de Geus, 2001). Among other correlates, PAF is inversely correlated with age after the age of 20 (Kopruner, Pfurtscheller & Auer, 1984). Noting these age differences, Angelakis, Stathopoulou, Frymiare, Green, Lubar and Kounios (2007) explored whether training elderly individuals to restore (i.e., increase) their PAF to the levels of younger people would result in improved cognitive performance. To do this, Angelakis et al. (2007) employed the process of Neurofeedback (NF, also called EEG biofeedback), which is an electroencephalographic (EEG) operant-conditioning training technique enabling subjects to manipulate their own brain activity. As a control for this experimental treatment, two other neurofeedback (NF) conditions were employed, one to train an increase in alpha amplitude and one pseudo-neurofeedback placebo condition in which the participants were led to believe that they were experiencing their own neurofeedback while in actual fact, it was a recording of another participant’s recorded beforehand. The hypothesis was that out of the three treatments, PAF NF would result in the largest improvements in cognitive performance. Using a sample of six healthy senior citizens, findings revealed that after NF training, all experimental (PAF) participants rated themselves as thinking faster, averaging a 1-point (19%) improvement, whereas controls reported slight worsening in concentration.

The specific effects of PAF NF on processing speed support the idea that PAF reflects speed of information access (Angelakis et al., 2007). However, this increased speed did not appear to improve memory functions as would be predicted by the model suggested by Klimesch (1997), so this idea must be treated with some degree of skepticism until other studies measure the specific effects of PAF changes on different types of cognitive speed. In contrast, the findings from the study carried out by Angelakais et al. (2007) unexpectedly showed that memory improvement occurred in the alpha magnitude control group that was specifically trained to not increase PAF. Some studies (e.g., Garrett & Silver, 1976) have reported decreases in test anxiety after alpha amplitude NF, which may have selectively affected memory functions in the study by Klimesch (1997).

2.1.5 Alpha Activity and Exercise

Exercise has previously been found to have a facilitative effect on choice RT tasks. For example, Brisswalter, Arcelin, Audiffren and Delignières (1997) explored the effects of physical fitness as well as energy expenditure on a simple RT task performed during exercise. While carrying out the simple RT task, participants pedalled on a cycloergometer at different relative power output corresponding to 20, 40, 60 and 80% of their own maximal aerobic power. The simple RT task was also carried out immediately after exercise has ceased. Findings showed that performance on the simple RT task was significantly better in the trained middle-distance runners compared to the group that do not regularly take part in physical training. More interestingly, this noted improvement was more pronounced when the energetic constraint was higher (80% Pmax). These findings are consistent with later findings by Davranche, Burle, Audiffren and Hasbroucq (2006). Perhaps a potential explanation for the underlying mechanisms for this facilitary effect of exercise on RT is alpha rhythms (for more studies investigating the relationship between reaction time and exercise, see Chapter 4, section 4.10).

Previous studies have demonstrated a relationship between exercise and alpha power despite widely different electrophysiological methodologies employed across studies (Hatfield & Landers, 1987). Electrophysiologic effects of physical exercise were investigated by Polich and Lardon (1997), who compared groups of individuals who engage in relatively low amounts of physical exercise (<5 h/week) to subjects who engage in relatively high amounts of aerobic exercise (>5 h/week). Event-related brain potentials (ERPs) were recorded using auditory and visual stimuli in separate oddball task conditions. The auditory oddball task involved obtaining auditory event related potentials with 1000Hz (standard) and 2000Hz (target) tones. The participants were instructed to keep their eyes open throughout the duration of the experiment and the task required them to press a button in response to the presentation of the target stimulus. The visual oddball task, on the other hand, involved presentations of either a 2.5cm wide black and white striped (standard) stimulus and a 2.5cm square black and white checked (target) pattern. Again, participants had to respond by pressing a button to the target visual stimulus. Polich and Lardon (1997) found that extended exercise helps to contribute to increased amounts of alpha-band activity and, therefore, increased P300 amplitude and decreased peak latency. These findings support and extend previous findings demonstrating increased alpha power for high-fit relative to low-fit subjects (i.e., Dustman et al., 1985, 1990).

Lastly, Dustman et al. (1990) assessed the interaction between exercise and age by comparing groups of healthy young and older men such that half of the subjects in each group were in good aerobic condition. Relative to low-fit men, high-fit subjects had better neuro-cognitive functioning and significantly greater amounts of alpha activity (8-10Hz) regardless of age. These findings imply that exercise contributes to central nervous system function and superior cognitive performance (Dustman et al. 1994; 1993) consistent with a previous study by the same group (Dustman, et al., 1985).

This section has demonstrated a relationship between alpha activity and exercise. The effect of exercise on both information processing and internal clock speed is explored in more detail in Chapter 4, Section 4.10. Exercise was shown to increase both internal clock speed and the rate of information processing. The studies explored in the current section suggest that alpha rhythms may have mediated these effects.

2.1.6 Biological Basis for the Sense of Time and Alpha Rhythms

Generally, injuries to the brain and the neurological experience bear witness to the significance of the thalamus and hypothalamus for our time sense (Goldman, Stern, Engel & Cohen, 2002; Holubar, 1961). Indeed, Spiegel, Wycis, Orchinik and Freed (1955) found transient disorders of temporal orientation and estimation of time in 23 out of 30 patients with operations on the thalamus (dorsomedial thalamotomy). For instance, one patient two months after thalamotomy, knew from repeated discussions with her family that she had lived in her home for five years. However, she expressed the feeling that she had resided in her home for only a few weeks. Cases such as this one, led Spiegel et al. (1955) to conclude that connections between the dorsomedial nuclei of the thalamus and the frontal lobes may be essential for the sense of time. Laufs, Kleinschmidt, Beyerle, Eger, Salek-Haddadi, Preibisch and Krakow (2003) argue that thalamic activity is of importance since it may lend some support to the notion of whether there are localised generators of alpha synchronization in the brain for which the thalamus appears to be the potential structure. Indeed, Schreckenberger, Lange-Asschenfeldt, Lochmann, Mann, Siessmeier, Buchholz, Bartenstein and Gründer (2004) study, using positron emission tomography (PET) scans with simultaneous EEG recording, also supported the notion of a close functional relationship between thalamic activity and alpha rhythm in humans mediated by cortico-thalamic loops which are independent of sensory afferences, a finding consistent with much earlier findings (i.e., Dempsey & Morison, 1943). Lastly, Ben-Simon, Podlipsky, Arieli, Zhdanov and Hendler (2008) findings suggested that it may be that the “thalamus subserves the mechanism of alpha generation that concords with its role as an ongoing pacemaker”.

2.2 Specific Frequency Argument

As discussed in Chapter 1 (section 1.5.3), consistent with earlier findings (Burle & Bonnet, 1997), Burle and Bonnet (1999) explored the effect of variation in click train frequency in a choice RT task. They found increases in RTs with 20.5Hz frequency clicks, while decreased RT were found for frequencies of 21 and 21.5Hz. A problematic issue regarding the design of the studies carried out by Burle and Bonnet (1997, 1999) is that they failed to provide a control for the clicks, i.e., silence replacing clicks. They simply compared differing frequencies of clicks since this was the main focus of their studies. More importantly, however, are the potential flaws in their argument. First, it assumes that there exists a common pacemaker speed in humans which seems very unlikely. Secondly, Burle and Bonnet (1997, 1999) findings cannot be explained simply by an increase in brain wave frequency rather, the repetitive stimuli would only be able to increase the amplitude of brain waves. Imagine, for instance, a pendulum. All pendulums have a fixed period of oscillation, independent of amplitude (isochonism). In order to increase the number of swings (frequency) we have to modify the length of the pendulum by shortening it. Increased frequency cannot be achieved simply by giving the pendulum a greater push[4], or in the case of the studies carried out by Burle and Bonnet (1997, 1999), by accelerating the periodic frequency of click stimuli.

2.3 Non-Specific Sympathetic Entrainment Argument: Effects of Repetitive/Rapid Visual Stimulation on Oscillatory Activity

Will and Berg (2007) explored the effect of auditory stimulation at a variety of different frequencies on the synchronisation of brain waves. As they pointed out, there has been little research carried out on the synchronisation of brain waves to auditory stimuli with repetition rates below 10Hz. Exploring the effect of repetition rates below 10Hz is particularly relevant since this would include 5Hz which is the frequency of clicks typically used in studies exploring its effect on information processing and internal clock speed (i.e., Jones et al., 2010; Penton-Voak et al., 1996). The well researched phenomenon of synchronisation of oscillatory activities in distributed neural assemblies can be understood as “a reflection of the cooperative activity of neurons within distributed assemblies” (Gruzelier, 1996, p.2). In their study, Will and Berg (2007) recorded the EEGs from 10 participants (balanced for gender; mean age 26 years) who were instructed to listen to the auditory stimuli passively. Drum sounds and clicks with repetition rates of 1-8Hz acted as the periodic acoustic stimuli. A silence condition and continuous pink noise condition served as the control and baseline. The stimulus-locked inter-trial coherence (ITC) analysed the synchronisation between periodic auditory stimuli and EEG responses. ITC is a measure of “consistency across trials of the EEG spectral phase at each frequency and latency window” (Will & Berg, 2007, p.56). ITC values were obtained for 21 EEG

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[4] This holds true for small swings where the pendulum acts as a harmonic oscillator. At much larger swings, period increases gradually with amplitude.

frequency bands (ten 1-Hz bands from 1 to 10Hz, five 2-Hz bands from 12 to 20Hz and six 4-Hz bands from 22 to 42Hz).

Interestingly, findings revealed synchronisation responses of brainwaves to periodic auditory stimuli. Stimulation with repetition rates of 1 to 8Hz resulted in increased phase synchronisation across all 21 EEG frequency bands. Even more interesting was the tonic ITC response (i.e. not reflecting the periodicity of the stimulus sequence) in the delta range (1 to 4Hz) which the authors argue reflects an ‘entrainment’ response. Specifically, the repetition rates between 1 and 5Hz resulted in ITC response peaks in the corresponding EEG frequency bands and the response showed an absolute maximum around 2Hz. This observed maximum is consistent with previous studies which have shown this to be the optimal rate or tempo seen in repetitive human sensorimotor behaviour (i.e., Large & Jones, 1999).

The hypothesis of the non-specific sympathetic entrainment to explain the click effect is related to the Burle and Bonnet idea of the dual pacing hypothesis or as we have termed it, the specific frequency argument. Instead of relying on the specific frequency enhancement of a common pacemaker frequency (and the subsequent implausibility that we all possess the same frequency), the non-specific sympathetic entrainment hypothesis would argue that the frequency of the repetitive stimuli is to a major extent irrelevant. All that matters is that the brain frequency is entrained to whatever frequency of repetitive stimulation is administered. The idea that the brain frequency can be entrained to the frequency of repetitive stimulaton delivered is consistent with the majority of findings in the timing literature and the effect on RT and information processing rate reported by Jones et al. (2010) that the frequency of the repetitive stimulation is typically inconsequencial. This non-specific sympathetic entrainment could then enhance information processing either by reducing the signal to noise ratio through the enhanced neural synchronicity or by influencing the rate of the internal clock/pacemaker.

Adrian and Matthews (1934) demonstrated that regular potential waves at frequencies other than the typical 10Hz can be induced by flicker. If a cluster of cells has a tendency to pulse spontaneously, then the idea is that they should be able to pulse at greater rate through the application of rhythmic stimulation. Indeed, Adrian & Matthews (1934) investigated this idea by recording from electrodes on the skull the potential waves in participants as they experience a flickering field. They discovered that rhythms as great as 25Hz could be obtained. In effect, the wave potentials are ‘entrained’ in that they become the same frequency as the flickering stimulus (from 10Hz to 25Hz). Adrian and Matthews (1934) also emphasise the importance of the intensity of the flicker. If it is too dull the sensation of the flicker disappears. If too bright, it can result in the experience of the field being swamped with coloured patterns resulting in irregular waves. The findings by Adrian and Matthews (1934) were supported by later findings by Nehar (1961) in the auditory domain.

Using EEG, Clapp, Muthukumaraswamy, Hamm, Teyler and Kirk (2006) explored the effects of visual repetitive stimulation on oscillatory activity. The experiment was similar to that of Teyler et al. (2005) with the visual checkerboards presented to either left or right hemisphere coupled with the oddball procedure (detecting deviant tones differing from the standard tone). Using eight healthy male participants (aged 23-38 years), after photic tetanus (checkerboard presented at a frequency of 9Hz) increased event-related desynchronisation (ERD) of the alpha rhythm lasting 1 hour was recorded over occipital electrodes. Since ERD of the alpha rhythm is believed to reflect a cortex which is active in nature, these findings by Teyler et al. (2005) suggest that rapidly presented visual stimuli can induce changes in cortical activity for a significant amount of time coupled with stronger neuronal assemblies and enhanced levels of neuronal output. Although more about motor function than entrainment as such, Thaut, McIntosh and Rice (1997) demonstrated the ability of the auditory rhythm in effectively entraining motor patterns and also influencing non-temporal parameters such as stride length.

Evidence against the idea that clicks (or repetitive stimulation) affect an underlying mechanism specific only to time (i.e., the putative pacemaker) comes from a study carried out by Droit-Volet (2010) who discovered that the click train can affect not only the perception of time, but also the perception of other quantities such as number and length. Therefore, supporting the idea of some other mechanism like the one proposed by Treisman et al. (1990) and later, Matell and Meck (2000, 2004). They argue that, rather than coming from a central pacemaker, the raw material for time representations comes from a ‘subset of cortical neurons that oscillates at different frequencies’. The frequency of these cortical oscillators would be altered by the clicks or any other rhythmic external event. This idea supports the findings by Burle and Bonnet (2000) who demonstrated that the clicks also affect RTs consistent with more recent studies (i.e., Jones et al., 2010).

Droit-Volet (2010) used the bisection procedure to investigate the effects of click trains on the bisection of time, length and number. Each of these three modalities were either presented sequentially or non-sequentially. Also some conditions included clicks and others silence. In the task, the participants were instructed to judge whether the comparison stimuli was more similar to a “short/few” (4/10) or to a “long/many” (8/20) anchor stimulus. For the timing modality, Droit-Volet (2010) used a procedure similar to that of Meck and Church (1983) in which participants had to judge the duration of the sequence of stimuli. For the number and length stimuli in the sequential condition, both were divided into “sub-lines” or “sub-numbers”, respectively. Participants therefore, had to accumulate the stimuli of each of these modalities and the final product is the comparison stimuli that they have to judge whether it is more similar to the short/few or the long/many anchor stimulus value. Findings showed that for the bisection of time, the stimulus duration was judged longer with clicks compared to silence for both the sequential and non-sequential conditions. For the bisection of number and length, the number was judged greater and the line longer with clicks, only when these two modalities were delivered sequentially. In other words, when the stimuli were required to be accumulated**.**

The role of time in processes such as memory or attention has been noted (i.e., Brown, Preece & Hulme, 2000; Lustig, Matell & Meck, 2005). In Brown et al.s’ (2000) model of working memory (Oscillator-based Associative Recall, OSCAR), the underlying mechanisms of working memory involves a series of oscillators with ‘hierarchically arranged periodicities’. Applying this model to the findings of Droit-Volet (2010), it could be argued that the click trains may be increasing the periodicity of these cortical oscillators which play a role in processing the constant flow of information and explains why they affect not only time, but other processes such as number and length. Despite studies showing the effect of click trains on the periodicity of cortical activities (Treisman, Cook, Naish & MacCrone, 1994; Treisman, 1993), the study by Droit-Volet (2010) emphasises the necessity for future studies to try to disentangle the effect of clicks on the cortical oscillators that process information that is sequential in nature, from an accumulator mechanism which manages the ‘flow of information’ in working memory (Droit-Volet, 2010).

2.4 Long-Term Potentiation Argument

There is a fourth possible explanation for how clicks work. The clicks may potentially be altering information processing rate through the process of long-term potentiation (Bliss & Lomo, 1973). Long-term potentiation (LTP) describes the process in which the efficacy of communication between brain cells is significantly and rapidly enhanced (Malenka & Nicoll, 1999). However, the actual molecular structure involved in the process remains under debate (for review of molecular processes involved, see Malenka & Nicoll, 1999). It is argued that LTP is the primary mechanism which underlies the formation of learning and memory (i.e., Bliss & Collingridge, 1993). LTP of evoked potentials has been found in isolated slices of human cortical tissue. These slices have similar properties to those found in non-human preparations (Chen, Lee, Kato, Spenser, Shepherd & Williamson, 1996).

Heynen and Bear (2001) also used an invasive technique to induce LTP in the visual cortex of rats, namely, by electrically stimulating the visual pathways. The idea that rapidly (or repetitively) presented stimuli could alter LTP was investigated by Teyler, Hamm, Clapp, Johnson, Corballis and Kirk (2005) using a non-invasive technique. Specifically, they explored whether it was possible to induce LTP by rapid presentation of visual stimuli. The visual stimuli consisted of a checkerboard stimulus presented at a frequency of 9Hz to either the left or right visual field for 120s (1080 presentations). Visually evoked potentials were collected at 2–9, 15–21, 30–37 and 45–52 min after the end of the visual stimulation. With six right-handed males (aged 23-38 years), Teyler et al. (2005) showed that a component of a visually evoked cortical response, recorded non-invasively from humans using Electroencephalography (EEG), can be potentiated after exposure to a repetitively presented visual stimulus. Further, LTP was evidenced in the hemisphere contralateral to the visual hemifield that received the visual stimulation. Teyler et al. (2005), argue that their results rule out the possibility that the findings can be explained in terms of variations in levels of attention. These results revealed in the study carried out by Teyler et al. (2005), support previous finding by Zhang, Tao and Poo (2000) who showed that repetitive visual sensory stimulation gives rise to LTP in the visual system of the developing tadpole.

So there appears to be a significant amount of evidence to suggest that rapid or repetitive visual stimulation increases the speed at which brain cells communicate to each other. In other words, such stimulation increases information processing speed in the brain. What evidence is there that stimulation in other modalities also has an effect? Since clicks (the repetitive stimulation used widely in the experiments in this thesis and generally in the time literature) are auditory, an effect on LTP using this modality would be even more interesting. Indeed, Clapp, Kirk, Hamm, Shepherd and Teyler (2005) showed that high-frequency, repetitive auditory stimulation can induce long-lasting plastic changes within the human auditory system as seen by a long lasting increase of the human auditory evoked potential (AEP). The stimulation adopted in this study was a train of 1000Hz tones presented at a rate of approximately 13 per second (50ms tones punctuated by 25ms gaps) for two minutes. Twenty-two males took part in the study (range 21-41 years). In a second experiment, Clapp et al. (2005) showed that over the hour after receiving the rapid auditory stimulation, there was no evidence of a significant decrease in degree of potentiation. In other words there were no findings to suggest a deterioration in the efficacy of synaptic transmission, even over an hour after the delivery of rapid auditory stimulation, as measured by the auditory evoked potentials (AEP) recorded using electroencephalogram scalp electrodes.

However, despite LTP being considered as a potential candidate for the effect of clicks seen in the experiments of this thesis, there is a major limitation to this explanation. It is important to point out that in the click experiments, the effect of clicks ‘resets’ or is ‘killed’ by the end of the trial (with each trial, in some instances, lasting no longer than a few seconds). This is inconsistent with the study by, for example, Clapp et al. (2005), who found an effect even up to an hour after auditory stimulation. However, it must be noted that their stimulation was delivered for two minutes – so LTP could occur. The stimulation duration used in the experiments in this thesis and in previous studies (e.g., Jones et al., 2010) was typically 5 seconds, so this would not result in LTP.

2.5 Conclusion

Some studies support the idea that the alpha-rhythm of the electroencephalogram (EEG) is the ultimate 'clock' in the organism's sense of time (i.e., Goody, 1958), others disagree (i.e., Treisman, 1984). Despite much evidence that alpha oscillations are linked with processes of RT, attention and memory, their functional significance remains uncertain (Knyazev, Savostyanov & Levin, 2006). The implications of these findings suggest that it is still impossible to rule out alpha rhythms as being a potential explanation for the effect of click trains (or repetitive stimulation) seen on human estimates of duration (i.e., Jones, et al., 2010; Treisman et al., 1990).

The second hypothesis for the effect of clicks, namely, the specific frequency argument suggests that clicks modulate the internal pacemaker with an underlying frequency of about 21Hz or multiples of 21Hz (i.e., Burle & Bonnet, 1999). However, the idea that there exists a common pacemaker speed in humans seems improbable. In addition the specific frequency argument is weakened further if we imagine how a pendulum works. We discussed earlier how an increased frequency of pendulum swings cannot be achieved simply by giving the pendulum a greater push, or in the case of the studies carried out by Burle and Bonnet (1997; 1999), by accelerating the periodic frequency of click stimuli. The effect of clicks then can potentially only serve to make signals stronger or reinforce them, not make the brain operate faster according to this pendulum argument. Therefore, the specific frequency argument as advocated by Burle and Bonnet (1997; 1999) is unclear and fraught with limitations.

The third possible hypothesis about how clicks work argues that brain frequency can be entrained to a non-specific frequency of repetitive stimulation delivered and there is evidence from various studies which support this. However, explaining how the synchronicity affects internal clock speed is more problematic to envisage, although it could be a consequence of the intimate causal link between information processing and the internal clock. Untangling this causal relationship is a problematic ongoing endeavour to which the experiments reported in this thesis contribute.

Lastly, the study by Clapp et al. (2005) which explored LTP (a possible explanation for the effect of clicks) and others mentioned in this chapter, still fail to bring us nearer to understanding the possible mechanisms underlying the effects that the repetitive stimuli used in this thesis – click trains – have on the brain.

Chapter 3

Research Strategy and Aims

3.1 Summary of Literature Review and Research Strategy

Scalar expectancy theory (SET: Gibbon, 1977) and its associated information processing model (Church, 1984; 1989; Gibbon & Church, 1984; Church & Meck, 1984) have maintained their popularity as the leading model for timing due to their convincing explanations for the observed timing behaviour seen in both animals and humans (Allan, 1998). As discussed in Chapter 1, section 1.1.3, the information processing model is made up of three layers, the first layer being the internal clock which contains three components (the pacemaker, the switch and the accumulator). The pacemaker receives the raw material for time representation. The pacemaker emits pulses and a switch controls how many pulses enter into the accumulator. The accumulator stores the amount of pulses during the event to be timed and the number of pulses accumulated determines the length of the perceived duration. The information-processing models also state that temporal judgments rely on memory and decision stages (Droit-Volet & Meck, 2007).

Evidence of a link between internal clock speed and information processing was shown through numerous studies in Chapter 1. I will now summarise the main findings from Chapter 1 and 2. Firstly, studies have demonstrated a link between body temperature and internal clock speed (i.e., Hoagland, 1933). Hoagland (1933) found that with increased body temperature, estimates of duration were increased, indicating that increases in temperature sped up the internal clock. Next, there was a review of studies which have manipulated clock speed effects in humans. The method most used to induce changes in clock speed was repetitive stimulation in the form of either clicks or flashes. For instance, Treisman et al. (1990) showed that repetitive visual stimulation can speed up the internal clock resulting in overestimation of duration. Further, Penton-Voak et al. (1996) showed that five seconds of periodic clicks (auditory stimuli) made participants overestimate stimulus duration. Studies have also shown that stimulus modality is also important. Treisman et al. (1990) found that auditory stimulus appears to have a greater subjective length than visual stimuli of the same duration. Droit-Volet et al. (2004) argue that this is due to the internal clock running faster for the auditory stimuli compared to the visual stimuli.

Studies looking at the effect of emotion on the internal clock were also covered in Chapter 1 and evidence suggests a strong relationship between the two. Angrilli et al. (1997) argue that emotional states induced by stimulus material systematically influence distortions in time estimation in humans. Consistent with this, Droit-Volet et al. (2004) found that the duration of emotional faces (anger, happiness and sadness) were systematically overestimated compared to neutral ones. Gil et al. (2007) also found that perceived duration of angry faces (compared to neutral faces) was overestimated even in young children (age groups 3, 5 and 8), replicating the findings from adult studies. On a similar note, the link between stress and the speed of the internal clock was found and the study which best shows this is the one by Watts and Sharrock (1984). They found that 35 individuals with arachnophobia displayed overestimation of the duration of the short interval with the spider compared to 18 participants without arachnophobia. This suggests that fear speeds up the internal clock. Therefore, arousal may be what mediates the effect of clicks, an idea explored in some of the experiments in this thesis (Chapter 11 and 13).

Real life experiences of time distortions were discussed. For example, the common feeling that when we are enjoying something time seems to fly by (Gillings, 2006). Also, the common experience amongst athletes that participating in fast racket sports such as tennis induces a particular feeling known as ‘the zone’ (Jackson, 1995). ‘The zone’ is experienced as a slowing down of time and where you feel you feel you can do things faster almost with conscious thought (Jackson, 1995). Experiences of time distortion are also found in situations of high adrenaline (Fair, 1984), such as a car crash. All these studies suggest that arousal speeds up the internal clock making subjective experience of duration appear longer.

So the question then poised was whether clock speed is the same as brain speed? Stetson et al. (2007) failed to demonstrate a “speeding up” of the brain and ultimately information processing. However, in a more systematic study, Jones et al. (2010) did show that repetitive stimulation in the form of clicks can speed up information processing as shown by faster RTs in a 1, 2 and 4 choice RT task. In another experiment, clicks were also shown to speed up the internal clock as evidenced by an overestimation of the duration of the tones when preceded by clicks compared to no-clicks (Jones et al., 2010). However, the next step is to see whether clicks can results in an increase in information processing as well as *simultaneously* speeding up the internal clock (Experiment 5 of this thesis investigates this). A neurological case study by Binkofski et al. (1996), suggested that clock speed may be the same as brain speed. Patient BW suddenly began to experience an unnatural acceleration of time experience. Things seemed to come towards him at terrific speed and he could not react to them fast enough. A production task also revealed that his internal clock was emitting pulses at a decreased rate as his production of 60 seconds was greatly overestimated at 286 seconds (mean score). This suggests that information processing and the internal clock are linked. Chapter 1 also looked at the effect of age on time. Vanneste et al. (2001) carried out a convincing study which lends support to the idea of a slowed down pacemaker in older people. Specifically, the older group spontaneously tapped at a much slower rate compared to the young group.

In Chapter 1, four theoretical models were discussed to explain the link between information processing rate, arousal and the internal clock speed. First, that clicks directly increase information processing rate, which in turn effects internal clock speed. Second, that the role of clicks is two-fold. They increase the speed of the internal clock which results in an increase in the rate of subjective time as well as independently increasing the rate of information processing. Third, that changes in both the rate of information processing and subjective time are linked, not because an increase in pacemaker speed increases the rate of information processing, rather temporal estimations themselves are derived from information processing rate. Last, that the internal clock is mediated by arousal/attention through some unknown factor.

The various theories which may explain how the clicks operate were also explored in Chapter 2. First, the role of alpha rhythms in relation to cognition (memory and intelligence), exercise and information processing was reviewed. All the studies were consistent with the idea that increased alpha activity leads to enhanced cognitive abilities and an increased rate of information processing. This suggests that the clicks may mediate their effect by increasing the level of alpha activity and as Treisman (1984) suggests, this may be due to arousal since alpha is a biological indicator for general arousal. This is consistent with the common explanation for the effect of clicks which states that they are arousing in some way. Thus, the alpha explanation supports the findings from the studies we looked at in Chapter 1, which explored the role of emotion on pacemaker speed and time estimation. Second, the specific frequency argument was explored. Burle and Bonnet (1997; 1999) investigated the effect of variation in the click frequencies and found that certain frequency were conducive to increased RT and others decreased RT. Third, the non-specific sympathetic entrainment argument is discussed. The main proponents of this theory are Will and Berg (2007) who revealed that periodic acoustic stimuli produces synchronisation of oscillatory activities in the brain. So in effect, the brain frequency is entrained to the frequency of repetitive stimulation delivered to the participant. Last, the long-term potentiation argument is suggested. Here, it is suggested that the clicks operate by altering the rate of information processing though long-term potentiation. In other words clicks may be increasing the efficacy of the firing rate between neurons (Malenka & Nicoll, 1999) which in turn leads to the faster RTs observed, for instance (Jones et al., 2010).

The aim of the rest of this thesis is a unique investigation into the connection (if any) between the internal clock and information processing. It will begin with an experimental review chapter investigating the common characteristics or behavioural parallels shared by information processing and time perception. Evidence of shared effects across various factors (i.e. arousal, exercise, drugs) would strengthen the idea of a link between information processing and the internal clock. The most common explanation for how clicks operate is that they are arousing in some way and this in turn speeds up the internal clock (Treisman et al., 1963). Numerous studies have explored the effect of emotional stimuli on human timing (i.e., Droit-Volet et al., 2004). Clicks have also been shown to speed up information processing (i.e. Jones et al., 2010). This thesis also investigates this notion that clicks are arousing in a variety of experiments designed to identify whether arousal mediates both the internal clock and information processing.

3.2 Summary of Research Aims

This section outlines the main research questions and areas that are addressed by the experiments and meta-review in this thesis.

3.2.1 What are the Parameters of the Facilitatory Effect of Repetitive Auditory Stimulation on Information Processing Speed?

In Chapter 1 we reviewed the literature which has shown that clicks have an effect on internal clock speed. For instance, Penton-Voak et al. (1996) demonstrated that preceding an auditory or visual stimulus by five seconds of clicks (a repetitive stimulation) produced larger estimates of the stimulus duration in their participants. This is consistent with other studies (i.e., Burle & Bonnet, 1999; Burle & Casini, 2001). Clicks have also been found to have an effect on information processing. Jones et al. (2010) using a 1, 2 and 4 choice RT task, showed that RT responses are faster on trials preceded by clicks compared to silence. Since this effect on both these processes has now been established, the next logical step is to explore how long this effect lasts for. The parametrics of clicks has never before been investigated and so Experiment 1a, b and c of this thesis addressed this using a 1, 2 and 4 choice RT task.

3.2.2 Is the Facilitatory Effect on Information Processing and on Internal Clock Speed Specific Only to Repetitive Auditory Stimulation?

The next question is whether the facilitatory effect on information processing and the internal clock (Jones et al., 2010; Penton-Voak et al., 1996) is specific only to repetitive auditory stimulation (in the form of clicks/flashes). In other words, would the effect found with clicks on the internal clock and information processing be found with any pre-stimulus event? The primary aim of this thesis is to try and establish the relationship (if any) between information processing and the internal clock. By replacing the clicks with another pre-stimulus event, we can see whether this also has an effect on the internal clock and information processing separately. However, if it is only found to have an effect on information processing, then it would indicate that the effect seen with clicks on information processing (Jones et al., 2010) is independent from the internal clock.

In order to explore whether any pre-stimulus can have an effect on the internal clock, Experiment 2a adopted a task of verbal estimation and each trial was preceded either by white noise or silence. While Experiment 2a explored the effect of white noise (if any) on internal clock speed, Experiment 2b explored the effect of white noise on information processing. Using a more complex task, Experiment 2c explored the effect of white noise in a RT task requiring the participants to determine as quickly as they can whether ‘easy’ and ‘difficult’ sums presented are correct or not. From the findings of these experiments we will be able to determine whether the effect of clicks on both information processing and internal clock speed is merely a coincidence. If white noise is shown to have an effect on information processing (Experiment 2b and c) while demonstrating no effect on internal clock speed (Experiment 2a), then it would suggest that the effect of clicks on information processing is not mediated by the internal clock.

3.2.3 What Effect does the Processing of Clicks have on Reaction Time and the Speed of the Internal Clock?

The previous section investigates the link between information processing and the internal clock by replacing the clicks with white noise to see if this also has an effect on *both* the internal clock and information processing. Another way we could explore this relationship is by modifying the clicks which have previously shown a robust effect on both information processing and the internal clock (Jones et al., 2010). What happens if we instruct participants to process the clicks differently? By introducing a different mode of processing we can see whether this has any differential impact on the internal clock and information processing. If it has an effect on one process leaving the other intact, then it would weaken the idea of a relationship between the two. In order to further address this question, Experiments 3a and b investigate whether having to process the clicks has any differential effect when compared to passively experiencing the clicks in a task of RT *and* verbal estimation, respectively.

3.2.4 What is the Effect of the Frequency and Duration of the Repetitive Auditory Stimuli on the Internal Clock Speed and Information Processing?

Previous studies have suggested the importance of the click frequency (i.e., Burle & Bonnet, 1999). Specifically, Burle and Bonnet (1999) found that the higher the click frequency the shorter the RT, which suggests the higher frequencies have more “powerful” effects. This is consistent with earlier findings by Treisman (1963) using a task which required participants to produce and reproduce intervals of a certain duration. Treisman (1963) found that the produced and reproduced intervals participants made became consistently shorter with increasing intensity of the tone to be judged. Later, Treisman et al. (1992) found increases and decreases in response times (relative to the regression predictions) with different frequencies. However, not all studies have found this effect of frequency variation on reaction times. Jones et al. (2010) used a 1, 2 and 4 choice RT task with some trials preceded by clicks and other by silence. They found a clear reduction in reaction time (RT) in the click trials relative to the no-clicks trials for the 5Hz conditions and 25Hz conditions. There was no difference in reaction time depending on level of frequency. This brings into question whether higher frequencies can reduce reaction time. However, a potential problem with the frequency of 25Hz selected by Jones et al. (2010) is that it is a multiple of 5Hz. Therefore, it may be driving the same effect on the synchronization of oscillatory brain waves. In other words, the 5Hz and multiples of may be crucial to this effect.

Due to the inconsistency in the findings, Experiments 4a and b *systematically* manipulated the frequency and duration of the clicks in tasks of RT and verbal estimation, respectively. If an effect of these manipulations are found only on the verbal estimation task but not on the RT task (or vice versa), then it would weaken the notion of a relationship between the internal clock and information processing.

3.2.5 Do Clicks Affect Information Processing Rate and Internal Clock Speed Simultaneously?

Jones et al. (2010) have already demonstrated that there appears to be a link between information processing and internal clock speed but what is the causal relationship between the two? Jones et al. (2010) used a variant of the classic Loftus, Johnson and Shimamura's (1985) iconic masking task. In their variant of this classic task, Jones et al. (2010) were interested in whether the click trains would reduce or eliminate the decrease in recognition rate produced as a result of the visual masks (no-mask, delayed mask, immediate mask). Jones et al. (2010) found that participants correctly recognised more pictures that had been preceded by click trains compared to those preceded by no-clicks across all masks types which suggests that the subjective duration of the presented display was increased when preceded by clicks. This increase in subjective duration meant that the picture was more deeply encoded or processed giving rise to subsequent greater recognition rates. Even more relevant to the present study, Jones et al. (2010) used an adaptation of the Sperling task to see whether clicks would increase the amount of letters that participants were able to recall from the briefly presented matrix of 12 letters indicative of an increase in the speed of information processing. However, they did not also determine whether there was a *simulataneous* lengthening of subjective duration in this task. To this aim, Experiment 5 explored this using the exact same paradigm as Jones et al. (2010) only with an added condition in which participants had to estimate the duration of the matrix. This essentially created a dual-task paradigm. If participants' demonstate an increase in the amount of letters recalled *simultaneously* with a lengthening of subjective duration, then it would present as further evidence that a strong relationship between the internal clock and information processing exists.

Chapter 4 is an *experimental* review chapter exploring the effect of various factors (such as arousal, attention, modality, drugs, etc) on both information processing and the internal clock. Factors which effect both would indicate a relationship between the two and the nature of the effect is then examined to see whether there is indeed a relationship. For instance, if a factor which is shown to reduce reaction time is also shown to increase time estimation this would indicate a stronger relationship between the internal clock and information processing.

3.2.6 Do Clicks Effect the Rate of Memory Decay?

In the previous section, we discussed previous experiments which used clicks to increase subjective duration which presumably allowed participants more time in which to process/encode information to be recalled later as indicated by improved recognition performance on trials preceded by clicks. In these tasks, clicks were used to improve performance in a recognition/recall task. The next question is whether clicks could be used to *reduce* performance in a memory task by subjectively increasing retention duration. In order to further explore the effect of clicks on memory and recognition rate, Experiment 6 looked at whether clicks would increase the rate of memory decay since they are shown to increase subjective duration and presumably would allow more time for memory decay to take place.

3.2.7 What are the Effects of Emotionally Arousing Visual and Auditory Stimuli on Verbal Estimation of Tones?

We have seen the behavioural effect that clicks have on verbal estimation and reaction time (i.e., Jones et al., 2010; Penton-Voak et al., 1996). But what is it that mediates these effects? As discussed in Chapter 1, a common explanation is that the clicks are mediated by arousal (Treisman et al., 1992). According to Treisman et al. (1994), when arousal level increases, the pacemaker output frequency should increase, thereby leading participants to overestimate time. Experiment 7a explored the effect of five seconds of clicks/no-clicks or five seconds of emotionally high and low arousing visual stimuli on the verbal estimation of tones. In order to rule out any modality differences, Experiment 7b used emotionally arousing *auditory* stimuli (presented for five seconds) to see the effect on verbal estimation of tones.

3.2.8 Can Emotionally Arousing Auditory Stimuli have an Effect on Human Timing Abilities?

Experiment 8 replicates a previous study by Noulhiane, Mella, Samson, Ragot and Pouthas (2007) which was fraught with methological limitations. For instance, they had sounds in categories that were not appropriate, including durations that could be argued to be easily guessed. Rather than the emotional stimulus being presented for five seconds followed by the tone, in this Experiment, the participants were instructed to estimate the duration of the emotional auditory stimuli *themselves*. Therefore, Experiment 8 specifically explored whether arousal changes our subjective duration of time, using an improved version of the experiment previously carried out by Noulhiane et al. (2007).

3.2.9 What is the Involvement of Autonomic Arousal in the Operation of Repetitive Stimulation: An Electrophysiological Investigation?

Previous studies have suggested that emotional stimuli can influence our perception of time in a variety of timing tasks (i.e., Droit-Volet & Meck, 2007; Droit-Volet et al., 2004; Ward & Cox, 2004; Angrilli et al., 1997). Overall, the main findings suggest that emotional stimuli are systematically overestimated compared to neutral stimuli. Since it is clear that the emotional stimuli used in these studies are arousing, the question is whether clicks (repetitive stimulation) are also perceived as arousing and it is this factor which is giving rise to these effects of clicks on timing abilities. Surprising, this has not yet been investigated and is crucial to furthering our understanding of time processing (Allely & Jones, under review). As well as speeding up the internal clock, it has recently been shown that click trains can also speed up information processing rate, in both reaction time tasks and in memory encoding (Jones et al., 2010). This has made the investigation of how click trains cause their effect imperative. In order to assess the role that arousal plays in this effect of repetitive stimulation the present experiment investigated electrophysiological (as well as behavioural) measures in a task of verbal estimation of tones when preceded with either clicks or silence (Allely & Jones, under review).

Experiment 9 measured whether there were any changes in autonomic arousal occasioned by the clicks at the same time as recording a significant behavioural effect of internal clock speed (evidenced by verbal estimation of tones). The physiological effect of clicks has never previously been investigated. If there is no effect of arousing stimuli found or evidence of autonomic arousal, then this would force us to reconsider the the mechanism by which repetitive stimulation produces its effects on timing functions and information processing.

Chapter 4

Meta-Review: An Investigation into the Behavioural Parallels between Interval Timing and Information Processing Speed

This meta-review is a unique and novel investigation of the literature to explore the similarities and differences in factors which affect internal clock speed and information processing speed. Such a review into the relationship between internal clock speed and information processing speed and will allow us to determine whether they are causally linked.

4.1 Behavioural Parallels between Interval Timing and Information Processing Speed

Reaction time procedures are a prominent tool for the study of information processing by humans and animals. The interpretation of how reaction time (RT) changes after manipulating certain experimental variables has enhanced our understanding of a variety of cognitive constructs, including attention and memory. It has been observed that during both human and animal RT experiments, RT to a signal often speeds-up as more time is allotted to prepare for the signal's onset—which is known as the preparatory interval (PI) effect (MacDonald & Meck, 2004). In the literature on human RT, the PI effect has been used as evidence for time estimation having an essential role in expressions of RT. MacDonald and Meck (2004) have drawn attention to the "behavioural parallels between RT and interval-timing experiments" arguing that "interval timing and RT processes are in fact two sides of the same coin". Similarly, Grosjean, Rosenbaum and Elsinger (2001) argue that since RT tasks are generally repetitive and temporally regular, timing strategies that affect response speed and accuracy occur. MacDonald and Meck (2004), also argue that both interval timing and RT share common neural substrates. For instance, neuropathologies such as Parkinson's disease in humans as well as dopamine-depleting brain lesions in experimental animals both impact on the PI effect in RT studies. Moreover, RT often decreases monotonically as a function of PI. During variable PI experiments, RTs are faster at longer PIs because the certainty of the imperative stimulus presentation increases with time (Niemi & Na¨a¨ta¨nen, 1981; Bertelson & Boons, 1960). This prompted a model of simple RT that implicates time estimation as a significant contributor to RT, referred to as the Deadline model (see Ollman & Billington, 1972). Further, Schubotz, Friederici and von Cramon (2000), using fMRI, found results which suggest common cortical and subcortical structures underlying both time perception and motor timing. Since RT is to a large extent motor timing, this emphasises the need to further explore the effects of various manipulations on both time perception and RT.

This chapter explores various manipulations that have been found to have an effect on time perception and explores what effect, if any, these manipulations have on RT. Jones et al. (2010) have already shown that there appears to be a link between information processing and internal clock speed. In other words, the causal relationship between RT and time perception. However, the causal relationship between the two has yet to be investigated. For instance, do factors which speed up the internal clock also affect information processing as evidenced by RT speed? Various manipulations, for instance clicks, have been found to increase the rate of the internal clock resulting in overestimation of durations as well as shorter productions of duration (Treisman, 1963). Since it has been found that clicks also speed up RT it can be assumed that if there are manipulations which affect both time perception *and* RT, this is indicative of some common underlying mechanism and suggests some deep link between the two.

4.1.1 Time Perception and Information Processing Speed – Are they Subserved by the same Mechanism?

The idea that interval timing and RT processes are subserved by the same mechanism should come as relatively little surprise, since the notion that similar underlying functions are used in both timing processes and the control of the pace of motor action seems intuitive. If this were not so, it would be difficult to coordinate the rate of motor action with the perceived pace of external events. Treisman, Faulkner and Naish (1992) posed the question that, if action is timed, does the coordination of movement employ one clock or many? Treisman et al. (1992) suggested that if there were a single master clock that relayed the same timing pulses to all the mechanisms that control movement, this would ensure a high degree of temporal coordination, but such a system would be vulnerable to damage to the master clock. Special lines would be needed to distribute the timing pulses continually from their unique sources to all parts of the nervous system. If the single clock was damaged, a gross loss of coordination would occur, coupled with an inability to appreciate the passage of time. The single central system would need to process temporal feedback arising in parallel from all sources. It would be difficult for a single clock to allow different effectors to operate in parallel at different and unrelated rates or at rates that change relative to one another. Although this may sometimes be difficult, it is not impossible. One may walk fast or slowly while talking at a constant rate. Alternatively, the nervous system might contain duplicated distributed pacemakers running at similar rates. This would make complex performances possible. Provided the pacemakers run at constant similar rates, this would allow performance to be coordinated overall. However, a system based on a constant rate would also encounter difficulties. For example, a problem would arise if performance must be differently timed with different effectors, as when a pianist plays in 3/4 time with one hand and in 4/4 time with the other (Treisman et al., 1992). A potential explanation for these findings focuses on the idea of a temporal pacemaker which includes the oscillator and calibration unit. Below is a diagram (Figure 7) of the temporal pacemaker model proposed by Treisman et al. (1992).

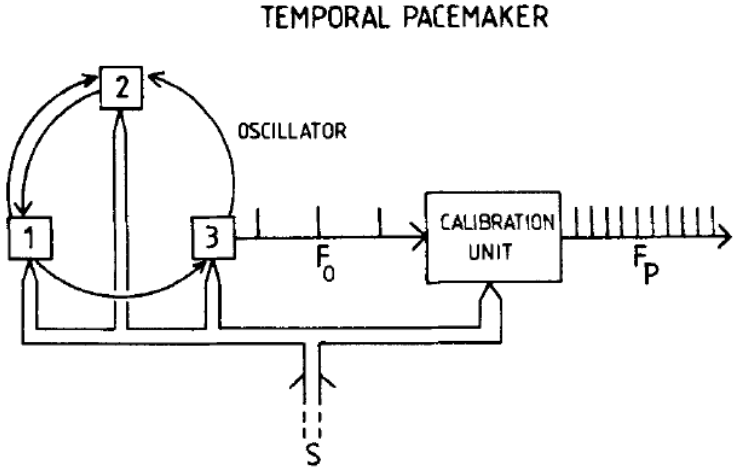


Figure 7: A model for the temporal pacemaker as proposed by Treisman et al. (1992, p 241). 1, 2 and 3 are elementary units linked by connections. These connections modulate the “specific arousal”. They are not individually defined by Treisman et al. (1992). Fo is the oscillator frequency. Fp are the pulses emitted by the pacemaker. Lastly, S represents the external inputs to the pacemaker, for instance, the effects of sensory stimuli.

The pacemaker is comprised of two components, namely the temporal oscillator (TO) and a calibration unit (CU). The TO incorporates basic units which are all linked by feedback loops which modify the arousal of each unit. This ‘self-exciting system’ emits pulses at a ‘characteristic oscillator frequency’ which are transferred to the calibration unit. The calibration unit then emits the pacemaker output pulses at a related higher frequency, Fp.

The Fp is what enables us to derive our perception of duration. Neural cross-talk may take place, expressed as a burst of noise impulses, if a strong stimulus is present. This burst of noise impulses are transferred to the neurons which make up the TO and affects their state by increasing their specific arousal and speeding up the temporal oscillator. On the other hand, a degree of the arousal frequency just less than the TO characteristic frequency would result in a slowing down of the TO. In other words, the temporal oscillator would emit fewer pulses in a fixed interval. (Thus in a time estimation experiment, that interval would be estimated as being shorter; or if the pulses were used to pace phases of a movement, that movement would be slower). The suggestions made by this model are consistent with Woodruff (1975), who found relationship between the frequency of the EEG alpha rhythm and RT using the biofeedback technique which manipulates brain wave frequency. However, conclusion about whether the alpha rhythms are a “master timing mechanism for behaviour” remains uncertain (see Chapter 2, Section 2.1).

4.2 Attention

4.2.1 Time Perception

As discussed earlier (Chapter 1, section 1.3.1) when we are enjoying ourselves, for instance, having a favourite meal at a restaurant, time seems to fly by. The reverse is true for situations in which we are bored. It has been suggested that this effect is driven by an attentional-bias mechanism (i.e., Zakay & Block, 1996). This attentional-bias mechanism results in attentional resources being shared between temporal processing and the processing of the stimuli/event. If more attention is given to the stimuli, then less is given to the processing of time resulting in underestimation of the duration. This is supported by findings by Treisman (1963) which showed that time judgments are more accurate when more attention is given to the temporal information. Hawkins and Tedford (1976) investigated this effect of attention in a prospective judgment task. They found that when participants were given interesting stories, they judged them as shorter than less interesting stories which were presented for the same duration. Zakay (1992) investigated the role of attention in 7 to 9-year-old children's time estimation using the reproduction method. Eighty children were exposed to two types of light bulb, one was a large, high intensity and the other a small, low intensity bulb. The light bulbs were illuminated for different intervals ranging from 3 to 10 s. The participants were required to estimate the lighting duration of the bulbs. Zakay (1992) found that participants gave shorter time estimates when their attention was attracted away from the time estimation task compared to when their attention was more focused on the timing task. Again supporting the attentional-bias mechanism (Zakay & Block, 1996).

4.2.2 Information Processing Speed

Nicotine is known to improve cognitive processes including attention (Warburton, 1992). Knowing this effect of nicotine on attention, Hahn, Shoaib and Stolerman (2002) tested the effects of nicotine on RT. In the study, rats were trained in a modified version of the five-choice serial RT task to detect l second light stimuli with greater than 70% accuracy and with less than 20% omission errors. Findings revealed that nicotine (0.05-0.2 mg/kg, s.c.) consistently increased accuracy and more importantly decreased RTs.

Evidence for a link between information processing speed and attention comes from studies with individuals with acquired brain injury. Stuss, Stethem, Hugenholtz, Picton, Pivik and Richard (1989), using simple RT and complex choice RT tasks, found that traumatic brain injury causes slower information processing, deficits in divided attention, an impairment of focused attention and inconsistency of performance. Additionally, Bloxham, Dick and Moore (1987) explored RT in patients with Parkinson’s disease to further explore the nature of attention in this group. They examined ten patients with Parkinson's disease and they were required to take part in a simple RT task in which, on hearing a tone, they pressed a button with their left thumb. In the experiment, tones sometimes occurred unannounced and at other times were preceded (by between 0 and 3200ms) by a warning signal. At the same time, participants were also required to perform a simple continuous task with their right hand. Bloxham et al. (1987) found that patients demonstrated slower RTs compared to controls. More importantly, the advantage of a warning signal for RT disappeared after long intervals (greater than 200ms) when a second task was being performed. Patients with Parkinson’s disease lost this advantage even when they were not performing a second task. Bloxham et al. (1987) argue that these results suggest that Parkinson's disease patients perform as if they were taking part in another task at the same time. This divided attention may explain why patients with Parkinson's disease are usually impaired at simple reaction-time (Goodrich, Henderson & Kennard, 1989). Indeed, Goodrich et al. (1989) advocate that the Parkinsonian deficit in simple RT task is the results of a deficit of the attention-demanding process which facilitates RT ability when the required response is already known.

The advantage of attention is also found in studies looking at the effect of valid and invalid cueing. For example, Posner, Snyder and Davidson (1980) found that detection latencies are reduced when participants receive a cue that indicates where in the visual field the signal will occur. Prinzmetal, McCool and Park (2005) also found RT is faster following valid cues compared to invalid cues.

4.2.3 Conclusion: The Effect of Attention on both Time Perception and Information Processing

Zakay and Block (1996) argue that when more attention is given to a stimulus/event, less attention is then given to the processing of time which results in an underestimation of duration. Thus, attention is important in enabling us to make more accurate timing estimates. An advantage of attention is also found in RT studies (i.e., Stuss et al., 1989).

4.3 Intensity

4.3.1 Time Perception

Kraemer, Brown and Randall (1995) trained rats on a short (2-second) versus long (10-second) duration discrimination. The duration of an overhead light signaled which of two lever-press responses, left or right, would produce food reinforcement. When the rats were able to correctly discriminate, probe tests were presented in which the light varied in intensity (bright or dim) and duration (values between 2 and 10 seconds). Kraemer et al. (1995) found that rats judged a bright light to be longer than a dim light of the same duration. Kraemer et al. (1995) have clearly shown that higher intensities in the visual modality result in longer judgments of duration. Human studies are consistent with this. For instance, Eisler and Eisler (1992) looked at the effects of sex and sound intensity in the auditory modality on scales of subjective duration. They compared findings between six females and six males on a task requiring the reproduction of 10 time intervals between 1.3 and 20 seconds. The durations to be reproduced were presented using white noise at varying intensities, namely, 10, 25, 40 and 55 dB SL. Eisler and Eisler (1992) discovered that with increasing sound intensity, there was shorter reproductions of duration. Also, the male group displayed reproductions which were shorter than those by female.

Lastly, Treisman (1963) carried out a task requiring participants to produce and reproduce intervals of a pre-specified duration. Treisman (1963) found that they became consistently shorter with increasing intensity of the tone to be judged, a finding also supported by others (i.e., Goldstone & Goldfarb, 1964; Hirsh, Bilger & Deatherage, 1956). Treisman (1963) interpreted this effect as due to the increased arousal of the participants occasioned by the louder tones (Wearden, 2005b).

4.3.2 Information Processing Speed

Cattell (1886) showed that increasing stimulus intensity (i.e., electric shock and light) brings about a shorter RT. Today, several formal models of simple RT are addressed to response signal (RS) intensity effects (Green & Luce, 1974). Unfortunately, the empirical evidence concerning the effects of warning signal (WS) intensity presents a picture that is far from clear. One line of research shows that an increased auditory WS intensity speeds up the response (Behar & Adams, 1966; Loveless & Sanford, 1975). Other studies, however, clearly indicate a speed decrement with increasing intensity of both the visual and auditory WS (Kohfeld, 1969a, 1969b). Pfingst, Hienz, Kimm and Miller (1975) have attempted to explain these conflicting findings. Auditory stimulation has an automatic alerting property (Posner et al, 1976) and the louder a sound, the more alerted a participant will be, up to some limit of sound intensity. There is interesting physiological evidence to support these suggestions. An auditory stimulus is followed by a frontal slow negative shift at a latency of 400-500ms (Loveless, 1973; Rohrbaugh, Syndulko & Lindsley, 1976). When this stimulus functions as the WS, the amplitude of the frontal slow shift becomes considerably larger (Rohrbaugh, Syndulko & Lindsley 1978). Increasing the intensity of an auditory WS further increases the amplitude of the frontal shift (Loveless & Sanford, 1975). Interestingly, neither a visual stimulus (Rohrbaugh et al., 1978) nor a visual WS (Gaillard, 1976, 1978; Gaillard & Naatanen, 1976) is followed by such a negative shift. On the other hand, in studies showing response speed decrement (Kohfeld, 1969a, 1969b) the WS was succeeded by a silent period of several seconds (FP). Kohfeld's studies are of particular interest because the intensity of the auditory WS (30, 60 and 90 dB) was identical to that of the RS and the intensity of visual WS was matched cross modally.

Kohfeld (1969a) found that mean RT in a simple RT task to three auditory response-signals was found to systematically increase with a corresponding increase in the intensity of either auditory or visual RS. The presence of central mechanisms is also implied here by the fact that both visual and auditory WSs operated in the same manner. This explanation strongly suggests an interaction between WS and RS intensity, however, which Kohfeld did not find. An alternative explanation is that since the intensity and modality of the WS did not change during the session, the participant was adapted to a certain stimulus intensity, which caused an additive delay relative to WS intensity in responding to the RS (Pfingst, Hienz, Kimm & Miller, 1975).

Wagner, Florentine, Buus and McCormack (2004) evaluated the relation between loudness and simple RT and found that RT is closely related to loudness, but not to sensation level. Additionally, Ulrich, Rinkenauer and Miller (1998) demonstrated that response force increases with stimulus intensity in simple RT tasks. Also, more forceful but slower responses were found for longer durations of the warning signal (WS). In addition, increasing the duration of a stimulus also increased the duration of force output. Moreover, Ulrich and Mattes (1996) investigated the notion that these findings are due to immediate arousal enhancing response force in speeded reaction-time tasks. They used a visual warning signal that was either rather weak or moderately bright in intensity. Again, more forceful and slightly faster responses were found for the brighter warning signal. This seems at variance with the pure arousal account which holds that moderately intense visual signals do create an arousal effect.

Sanford (1971) also investigated the link between SRT and stimulus intensity. It has long been established that RT become shorter as stimulus intensity increases (e.g., Roufs, 1963, Sanford, 1970) and concern here is with the possible explanation of the effect, which cannot be explained simply by changes in the time it takes the subject to hear the stimulus. Interest in the problem here began with the observation that participants know they react more slowly to quiet signals than loud ones, a result formally demonstrated in an experiment where participants had to rate their own reaction speeds on a trial-by-trial basis (Sanford, 1970). This suggests that in the auditory modality, detection time is not affected by intensity as much as RT which was supported by experimental findings (Sanford, 1971).

Farber and Spence (1956) examined the effect of stress as well as stimulus intensity on simple and choice RTs. In the simple RT experiment participants were asked to press a button as soon as the light stimulus (either dim or bright) was presented. The choice RT experiment, on the other hand, was the same except participants were requested to only respond to either the dim light or bright light stimulus, depending on group. The stress groups were threatened with an electric shock throughout the experiment. Results showed that reactions to the brighter light were faster than those to the dimmer light in the simple RT task. The choice RT greatly exceeded simple RT and within both choice and simple RT trials, speed of movement increased with practice. No main effect was found for manifest anxiety or for experimentally-induced stress. However, the effects here may be due to the fact that the participants were only threatened with shock. The second experiment actually administered electric shock. It was found that responses to the more intense stimuli (shock) were much faster than those to the weaker stimuli and speed of movement varied with practice. Level of anxiety did not affect the results in any way. Grice (1955) argued that the present negative results in respect to anxiety were due to the absence of intellectual differences between anxious and nonanxious college students.

There is a lack of consistent findings as to whether stimulus intensity affects the speed of motor processes involved in response activation and execution (Miller, Ulrich & Rinkenauer, 1999). Two experiments examined the effects of stimulus intensity on the lateralized readiness potential (LRP), a measure of hand-specific response activation. In Experiment 1, visual stimulus intensity influenced the time from stimulus onset to LRP onset but not the time from LRP onset to the keypress response. In Experiment 2, auditory stimulus intensity did not influence either of these time intervals, although it did influence the time from stimulus onset to the N100 and P300 components of the evoked potential. The results indicate that stimulus intensity does not influence the duration of motor processes in choice RT tasks (Miller et al., 1999). This suggests then that it is a change in the rate of the internal clock which is causing reduced RT, with more intense stimuli causing the clock to go faster.

Pascal and Swensen (1952), using a complex discrimination RT task, introduced very loud white noise at the onset of the preparatory interval (PI) that continued until the participant made the correct response. Under this condition patients with schizophrenia gradually responded faster, so that not only was their overall improvement from baseline greater but also their absolute RT was no longer significantly greater than that of the normal controls. Karras (1962) also found improved psychomotor performance, in individuals with chronic schizophrenia, with intense aversive stimulus – white noise. They argue, similarly to Pascal and Swensen (1952), that this improvement is due to motivation rather than simply just an increase in level of arousal. This is inconsistent with previous studies in the timing literature which argue that intense stimulus is arousing and it is this factor which causes the internal clock rate to change. Moreover, Lang and Buss (1965) argue also that the facilitating effect of aversive stimuli is not motivational.

4.3.3 Conclusion: The Effect of Intensity on Both Time Perception and Information Processing

Despite some conflict, generally studies have shown that RT decreases with greater stimulus intensities (i.e., Ulrich & Mattes, 1996). One of the earlier studies by Faber and Spence (1956) found reactions to the brighter light were faster than those to the dimmer light in a simple RT task. The fact that the effect of intensity on timing suggests that greater intensities cause overestimation of duration or a slowing down of subjective experience of time (i.e., Kraemer, 1995) explains why some studies have found that RT decreases with greater intensities. If participants experience a lengthening of subjective duration with higher intensities then they would have more time, supposedly, in which to react.

4.4 Arousal

4.4.1 Time Perception

Several studies have demonstrated that the speed of the internal clock can be manipulated (i.e., Treismen et al., 1990). For instance, studies have found that repetitive stimulation in the form of clicks or flashes can change the speed of the internal clock (see Chapter 1, section 1.2.2). Hockey (1970) suggested that noise acts as a kind of general stimulant which raises the level of arousal. Yoblick and Salvendy (1970) found that when participants reproduced filled time intervals (auditory tones, visual flicker, or tactile vibrations) they overestimated the duration of lower frequencies significantly more often than higher frequencies only with auditory stimuli. When the time intervals were filled with visual or tactile stimuli, participants estimated high and low frequencies similarly.

Intensity of stimuli was also shown to have an effect on time estimation by Delay and Mathey (1985) who investigated this using 10 male and 10 female undergraduates and instructed them to estimate 5, 10, 15 and 30 second intervals under five intensities of ambient noise (50, 60, 70, 80 and 90 dB). Findings showed that the interval estimates became shorter as the intensity of noise increased from 50 to 80 dB but became longer at 90 dB. The effects of noise intensity were most prominent in the two longest intervals. Again this supports the idea that the higher intensity stimulus (which is potentially more arousing) causes the internal clock rate to speed up, resulting in participants perceiving time as being lengthened. The explanation for the lengthening of time estimates at 90dB may lie in the theory discussed in section 5.2.2.

4.4.2 Information Processing Speed

One of the most investigated factors affecting RT is 'arousal' or state of attention, including muscular tension. RT is fastest with an intermediate level of arousal and deteriorates when the subject is either too relaxed or too tense (Broadbent, 1971; Freeman, 1933). That is, RT (performance) responds to arousal as shown in Figure 8. However, the inverted-U function has been criticised (i.e., Hancock & Ganey, 1982).

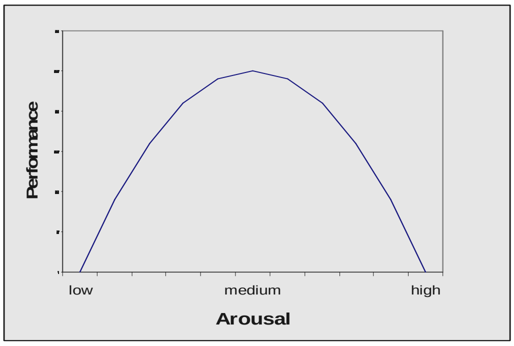


Figure 8: Inverted-U function of arousal on performance.

In a study carried out by Groves and Eason (1969) the relative contributions of arousal and attentional factors affecting the amplitude of the visually evoked cortical potential and RT latency were investigated. Participants were studied under the following four conditions: (1) passively watching a small, dim, intermittent flash; (2) reacting to each flash by releasing a lever, thereby giving a RT; (3) reacting to each flash within a specified period of time in order to avoid an uncomfortable shock to the fingers; (4) reacting to each flash while receiving occasional unavoidable shock. Findings demonstrated that the evoked potentials recorded during the avoidable shock condition (3) were significantly larger than during the other three conditions. RTs were routinely shorter during condition 3, followed by the no-shock (2) and then unavoidable shock (4) conditions. Since these studies demonstrate a relationship between arousal and RT, it is conceivable to suggest that the types of ‘arousing’ stimuli which appears to affect individuals’ time perception may also affect RT. It is suggested that clicks cause their effect on the internal clock because they are in some way arousing.

Perhaps the most persuasive arguement for the link between click rate and RT is that of Treisman et al. (1992) who argued that, if the perceptual and motor clocks have the same parameters, then the perceptual and motor interference patterns should be similar. To examine this, they presented participants with auditory clicks at different rates during the performance of motor actions and recorded the effect on response time. In this experiment a choice response based on a difficult discrimination and with a long movement path was employed, to produce a long response time (latency plus movement time) during which clicks could be given. The response required a hand movement of 28 or 30 cm from a fixed position to one of two small neighbouring targets, which required aiming under visual feedback and concurrent change in hand posture during the course of the movement. Clicks commenced at the onset of the response signal. Two response signals were employed that were thought unlikely to produce different mean response times. They were the appearance on the visual display unit of an asterisk slightly to the left or to the right of the midline. There were five conditions which differed only in the click rates presented. These were respectively, the 11 frequencies (at intervals of 0.5Hz) from 2.5 to 7.5Hz, from 7.5 to 12.5Hz, from 12.5 to 17.5Hz, from 17.5 to 22.5Hz and from 22.5 to 27.5Hz.

Inspection of the results shows that at a number of different click rates the different participants show similar features. Clicks caused interference in a systematic pattern with peaks in response time appearing at 9.5Hz and 10.0Hz. If the mean curve showing this describes an interference pattern in response and if it relates to a clock similar to or the same as the internal clock underlying time estimation, the two interference patterns should be related, given when the clock slows, time estimation will be shorter but response time longer. This predicts that they should be negatively correlated. Time estimation data was taken from experiment 1 in Treisman et al. (1990). There was indeed, a significant relation between response time and time estimation patterns. Concurrent sensory pulses were also shown to produce similar effects in a more complex task. In experiment 2, skilled typists were asked to type a passage of text while exposed to auditory click trains (between 8Hz and 13Hz). Results showed clear peaks at 9.5 and 11.5Hz, therefore, the peaks still occurred at or near the locations predicted by the interference pattern obtained in experiment 1. In sum then, the studies reported here, show a satisfactory degree of congruence with the response time results and time estimation data. It appears that interference patterns may occur that are similar for a range of motor and perceptual task (Treisman et al., 1992).

4.4.3 Conclusion: The Effect of Arousal on Both Time Perception and Information Processing

Since the common explanation for how clicks operate is that they are arousing, the experiments just discussed by Treisman et al. (1992) demonstrate a factor which simultaneously has an effect on both information processing (RT in this case) and the internal clock. Therefore, the study by Treisman et al. (1992) supports the notion of a link between these two processes.

4.5 Modality (Auditory and Visual)

Hearing is “the most privileged temporal sense” (“halten wir uns an das Gehor, als den bevorzugtesten zeitlichen Sinn”; Vierordt, 1868, p. 172).

4.5.1 Time Perception

Internal clock models consistent with the pacemaker-accumulator model of SET have also been used (Wearden, Edwards, Fakhri, & Percival, 1998) to account for the well-known modality effect in timing, that “tones are judged longer than lights” (i.e., Goldstone & Lhamon, 1974). (See Chapter 1, Section 1.2.2). Interestingly, shorter duration judgments of visual stimuli compared to auditory stimuli were found to be greater in the morning than in the afternoon as well as greater for the older compared to younger adults (Lustig & Meck, 2001). Treisman et al. (1990) also found that the auditory stimulus appears to have a greater subjective length than the visual stimulus, despite both being the same duration and also argued that the pacemaker of an internal clock runs faster during auditory than visual stimuli (Wearden et al., 1998). Similarly, Droit-Volet, Tourret and Wearden (2004) found that auditory stimuli were judged to be longer than visual stimuli in both 5-year-olds and 8-year-olds. Moreover, the auditory and visual stimuli produce a slope effect – not a bias effect. In other words, there was a bigger difference at longer durations. Future research may identify the physiological mechanism of human timing and disprove the notion of a pacemaker-accumulator internal clock. However, if a pacemaker-accumulator internal clock does not exist, the behavioural data definitely suggests that it does. Moreover, according to the findings of Glenberg, Mann, Altman, Forman and Procise (1989), reproduction of auditory rhythms is superior to that of visual rhythms.

Based on their study which showed that durations signalled by intermittent stimuli (visual flicker) are judged longer than visual steady ones (Ortega & Lopez, 2008), Ortega, Lopez and Church (2008) investigated the possibility of an auditory intermittency effect, in order to establish whether there exists an interaction between modality and intermittency effects. A temporal bisection task was employed and the duration range was created using two reference durations, a Short (S) duration of 200ms and a Long (L) duration of 800ms. The other durations given to compare to these references were 300, 400, 500, 600 and 700ms. Each testing phase consisted of randomly presenting these five intermediate durations as well as the two references and the task of the participant was to identify the durations as "Short" or "Long" according to their similarity to the S and L referents. Findings revealed that auditory steady stimuli and visual intermittent stimuli were judged as longer than visual steady ones. However, there was no evidence of an auditory intermittency effect, which effectively rejects the suggestion that there is an additive effect of modality and intermittency. The current findings suggest that the visual intermittency effect is greater than the modality effect, which implies that the clock can run at a potential minimum of three speeds: a slow one for the visual steady stimuli, followed by a faster speed for the auditory stimuli (steady and intermittent), with the visual intermittent stimuli evoking the fastest speed of the internal clock.

4.5.2 Information Processing Speed

Stimulus modality is an important factor in determining the reaction speed (Posner et al., 1976). Posner et al. (1976) found that when visual and auditory signals are presented simultaneously, participants generally respond to the visual input and are often unaware that an auditory signal has occurred. Therefore, it appears then that in many situations, visual input tends to dominate other modalities in perceptual and memorial reports and in speeded responses. Pascual-Leone, Brasil-Neto, Vall-Sole, Cohen and Hallett (1992) investigated the effect of different go-signals on the RT in nine normal human subjects trained to respond by rapidly flexing one arm. Comparison of the results obtained using the auditory, visual and somatosensory go-signals demonstrated that the RT to the auditory signals was shortest, followed by somatosensory and then visual. RTs were also inversely correlated with stimulus intensity. Jaskowski, Jaroszyk and Hojan-Jezierska (1990) also found that auditory stimuli are processed faster than visual stimuli. The difference between RTs for visual and auditory stimuli was about 40ms. Also, the auditory stimulus must be delayed to be perceived simultaneously with the visual one. Celebi (1978) found that the shortest RTs determined with light and sound were 150-200ms for light and 120-180ms for sound. Additionally, in a study carried out by Muller, Richter, Weisbrod and Klingberg (1991), simple RTs to clicks, flashes and numerical signals were measured in four groups of participants: 21 patients with mild pre-senile onset dementia of the Alzheimer type (PDAT, mean age 56 years), 14 patients with chronic cardiovascular disease and incipient cognitive deficit (CVD, mean age 55 years), 15 healthy older controls (mean age 53 years) and 16 younger controls (mean age 23 years). Findings revealed that the acoustic RTs were 20-25ms shorter than RTs to flash in the control groups and the CVD patients, but not shorter at all in the PDAT patients.

It is been demonstrated that an auditory warning signal (WS) speeds up the response more than a visual one (e.g., Bertelson & Tisseyre, 1969), especially when the foreperiod (FP) is relatively short. Sanders and Wertheim (1973) argue that besides factors such as time uncertainty, the FP effect is also largely dependent on the arousing quality of the signal or more accurately, the immediate arousal exerted by loud auditory stimulation, an idea tentatively presented by Bertelson and Tisseyre (1969). The most systematic outline of the idea is given by Posner et al. (1976), who suggested that auditory stimuli have an automatically alerting property that is almost totally absent in visual stimulation. It is obvious that automatic alerting and immediate arousal refer to one and the same thing. Consequently, it appears that when readiness to respond is low, loud auditory signals will compensate for it in the course of the reaction. Knowing this, it seems strange that formulations of this auditory RS superiority, with respect to the immediate arousal effect, have failed to be included in the literature on startle effects of loud auditory stimuli (Valls-Solé, Valldeoriola, Muñoz, Gonzalez & Tolosa, 1995).

Dufft and Ulrich (1999), after controlling for the psychological intensity of the warning signal (WS), found that participants respond faster to a visual response signal when an auditory accessory is presented at the same time._Hermelin (1964) found that trials with the auditory WS gave mean RTs about 30ms faster than trials with the visual WS, independent of FP duration. Moreover, Hermelin (1964) found that visual RTs were shorter when the preceding warning stimulus was a sound, than when it was a light. The mechanisms which give rise to these cross modality effects are by no means clear, however, Wearden et al. (1998) have put forth an explanation for why there are modality differences between auditory and visual stimuli. They argue that the pacemaker of the internal clock runs faster for the auditory than for the visual stimuli. The reflex study of Scheirs and Brunia (1982) provides especially strong evidence for the claim that an auditory warning signal exerts an immediate arousal effect on the peripheral motor system. These authors manipulated the intensity level of an auditory warning signal in a simple RT task and evoked a T-reflex (tendon) at various short intervals (0- 350ms) after the warning signal. They found that reflex amplitude increased with warning signal intensity but only in the auditory modality, not visual. Therefore, this may be another explanation for the observed modality differences.

4.5.3 Conclusion: The Effect of Modality on Both Time Perception and Information Processing

Wearden et al. (1998) clearly showed that auditory stimuli are judged as being longer than visual (light) stimuli. This demonstrates that auditory stimuli have a differential effect on the rate of the internal clock compared to visual stimuli. Wearden et al. (1998) argue that the pacemaker of a pacemaker-accumulator internal clock runs faster with auditory stimulus than with the visual stimuli. So the question is, is there a modality difference found with RT/information processing? Findings seem to suggest that there is. Jaskowski et al. (1990) demonstrated that auditory stimuli are processed faster than visual stimuli. Additionally, Bertelson and Tisseyre (1969) found that an auditory warning signal speeds up the reaction time response more than a visual one. Dufft and Ulrich (1999) even found that participants respond faster to a visual response signal when an auditory stimulus is presented simultaneously.

All these findings suggest that auditory stimuli appear to have more of an impact or are more dominant than visual stimuli. The fact that there are parallels in the effect of modality on both time perception and information processing suggests that the two are indeed linked in some way.

4.6 Anxiety/Mood States

4.6.1 Time Perception

Numerous studies have investigated the possible effects of varying moods, in particular stressful ones, on ones ability to estimate durations of time (see Chapter 1, section 'Stress and Arousal').

4.6.2 Information Processing Speed

Hainaut and Bolmont (2005) showed that reaction and movement time is also affected by anxiety or stress using a visual and auditory response-time task. Indeed, they demonstrated an effect of anxiety on auditory response-time tasks, suggesting that RT and movement time can be improved. Mood states and anxiety might alter performance in complex tasks whereas in more simple tasks such as stimulus-response, high anxiety could provoke bias in mechanisms of attention leading to better performances. Hainaut and Bolmont (2005) argue that the increased attention underlying anxiety and mood responses could have favored auditory response time by leading subjects to process stimuli more actively. In addition, state-anxiety and tension could have influenced muscular tension, enhancing the movement time in the auditory task. Because in a normal condition auditory stimuli are processed less actively than visual stimuli (Posner, Nissen & Klein, 1976), the general arousal induced by the anxiogenic condition could have led subjects to develop more attentional resources and to process consciously auditory stimuli as rapidly as visual stimuli (Hainaut & Bolmont, 2005).

Studies have also shown that individuals with depression display longer RT than control participants. Bonin-Guillaume et al. (2004) employed a two-choice visual RT task to determine which stages of processing are affected by depression in adults. Reaction time data suggest that depression spares the stage of stimulus pre-processing but affects the stage of motor adjustment. An analysis of the error rate leaves open the possibility that depression alters the stage of response selection. The notion that pre-processing is unaffected in depression is also supported by Azorin et al. (1995). Similarly, Giedke, Their and Bolz (1981) found that delayed RT of depressives seems to be a consequence of impaired selection, activation, or execution of the motor response rather than of delayed stimulus evaluation.

4.6.3 Conclusion: The Effect of Anxiety and Mood on Both Time Perception and Information Processing

As discussed in Chapter 1, Gil et al. (2009) demonstrated that a prolonged intense state of sadness, such as in depression, induces a slowing down in psychomotor functioning. Thus, the affective state of sadness in depressive individuals affects their time perception in such a way that they experience time as passing slowly. Consistent with Deffenbacher (1986), Watts and Sharrock (1984) found that 35 participants with arachnophobia retrospectively overestimated the duration of the short interval with the spider compared to the 18 participants without arachnophobia. Therefore, these studies lend support to the idea that fear speeds up the internal clock, increasing time-estimates. This is inconsistent with findings looking at the RT in individuals with depression. Bonin-Guillaume et al. (2004) found that individuals with depression display longer RTs than controls, consistent with much earlier findings by Martin and Rees (1966). This slowing down of information processing is inconsistent with the fact that their internal clock is running faster as argued by Gil et al. (2009). If their internal clock was running faster, the individuals with depression in the study by Gil et al. (2009) would have had longer subjective time in which to react. However, it is still possible that the internal clock and information processing are still linked. It may be that depression causes a much slower reaction time regardless of any clock speed change.

Another explanation was suggested by Azorin et al. (1995) who also found that individuals with depression have slower reaction time compared to controls. They were interested in investigating whether depression affects all stages of information processing or only some. They found that stimulus pre-processing is spared by depression. However, they found a deficit in response selection. Perhaps then, the slower reaction times are not due to a slowed internal clock, rather it may be a problem with the response selection in a task of reaction time.

4.7 Age

4.7.1 Time Perception

Exactly why “time flies” as we get older is far from conclusive. Baum, Boxley and Sokolowski (1984) investigated this comparing instituationalised and community dwelling elderly and found that faster time perceptions were associated with better psychological functioning (less clinical depression, enhanced sense of purpose and control and "younger" perceived age). The opposite subjective experience of time was found for elders with time "on their hands." Further, subjective time was also slower for many institutionalised elders. These findings are inconsistent with the idea that the subjective experience of time passing moves faster as we get older (suggesting a slowing down of the internal clock) (Wearden, Wearden & Rabbitt, 1997; McCormack, Brown, Maylor, Darby & Green, 1999; Wearden, 2005b). Wearden et al. (1997) investigated the ability of normal older participants (aged 60–79 years), with known scores on the Culture Fair Intelligence Test, on four timing tasks (i.e., temporal generalization, bisection, differential threshold, and interval production). Overall, Wearden et al. (1997) found that increasing age and decreasing IQ tended to be associated with increasing variability of judgments of duration. However, despite this, events could be timed on average accurately across the different tasks. There were some instances (e.g., bisection), where performance differences were negligible between older participants and students nearly 50 years younger used in other studies.

However, the findings by Baum et al. (1984) suggests that variability does exists amongst older persons with respect to whether they perceive time as moving fast or slow. This is inconsistent with earlier findings by Kline and Burdick (1980) using reproduction and production timing tasks. They found that other than time being perceived as shorter in the elderly, shorter estimates by both institutionalised and non-institutionalised elderly supporting the idea of a faster internal clock rate being “characteristic of older persons in general”. Carrasco, Bernal and Redolat (2001) also found that elderly adults internal clock speed appears to be faster. They investigated age-related differences in the reproduction of a short interval (10 s). The young adult and elderly adult groups had a mean age of 15 years and 79.1 years, respectively. They found that reproductions performed by elderly participants were shorter than those of younger ones, although there were no significant differences between the two age groups in the percentage of absolute errors or standard deviations.

One way to explain the difference between younger adults and older adults is to assume that duration judgments reflect only the rate of a pacemaker or other similar component of an internal clock. Theorists usually assume that a pacemaker that is not rate-compensated should operate more slowly in older adults (Wearden, 2005b). A slower pacemaker rate would shorten subjective duration. The findings by Wearden (2005b) are in the opposite direction. Perhaps the pacemaker runs faster in older adults, or perhaps older adults overcompensate for a slower pacemaker. These explanations are clearly post hoc, fairly implausible and difficult to test. Note that the finding that no significant age-related effects occurred in studies using the reproduction method does not effectively challenge the pacemaker-rate hypothesis. In this method, any individual differences in pacemaker rate present during the target duration are also present during the reproduction, effectively reducing the effect of such individual differences on the duration judgment ratio.

More recent support for Baum et al. (1984) came from Rammsayer (1993) who investigated the ability of three age groups (young adults (mean age = 25.1), middle-aged adults (mean age = 45.5) and older adults (mean age = 64.6)) in a task of duration discrimination. Participants were presented with two very brief auditorally marked intervals per trial and they were to judge which of the two had the longest duration. Findings showed that performance on this task was not dependant on age as all three age groups yielded a difference threshold of approximately 17ms. Rammsayer (1993) argues, therefore, that the ability to discriminate durations of very brief auditory intervals appears to be based on an underlying timing mechanism that does not slow down as we age. Moreover, Krampe, Engbert and Kliegl (2001) carried out a study investigating the accomplished young and older amateur pianists on the two bimanual rhythm tasks and found an age group by task dissociation for the variances of intervals with the same durations in both tasks. This finding is incompatible with the assumption that the central clock is slowed in older adults. There was no higher variability in older individuals' interval productions, inconsistent with the notion that age-related slowing affects the interval clock.

However, Block, Zakay and Hancock (1999) reviewed twenty experiments, all using a prospective paradigm, comparing duration judgments made by children versus adolescents and adults. Meta-analyses demonstrated substantial age-related differences. Compared to older participants, children make larger verbal estimates, comparable productions and shorter reproductions of duration. Children’s duration judgments also show greater interindividual variability. Significant age-related differences were also found in an earlier review of duration judgments made by younger and older adults where older adults’ estimates of duration were more variable compared to those of younger adults (Block, Zakay & Hancock, 1998). Further, it was found that older adults gave larger verbal estimates and made shorter productions of duration compared to the younger adults. Despite these differences in verbal estimation, no such age-related differences were found with reproduction of duration or in psychophysical slope relating judged and target duration. More support for Block et al. (1998; 1999) came from Vanneste, Pouthas and Wearden, (2001) who investigated the effect of age (young (20-30-year-old) and older (60-76-year-old) adults) on spontaneous motor tempo and found slower free-tapping rate in older subjects, assumed to reflect the slowing of internal clock in aging. However, rates were not relatively more variable in older adults (i.e., coefficients of variation, standard deviation/mean, did not differ between the older and young people).

Later, Baudouin, Vanneste and Isingrini (2004) attempted to replicate this finding of a decrease in the rate of the internal clock with age, by investigating the relationships between the two types of slowing observed in aging—the decline in general processing speed and the slowing of the spontaneous tempo. Baudouin et al. (2004), compared the performance of three age groups: young adults (ages 21 to 35), old adults (ages 66 to 80) and very old adults (ages 81 to 94) on tasks involving spontaneous motor tempo, processing speed (motor speed, geometric comparison test and digit-symbol task) and working memory (reading span, running span and alphabetical span). Findings supported previous finding (e.g., Vanneste et al., 2001) of spontaneous slowing down of motor tempo indicative of a decrease in clock speed as we age. The initial notion that if spontaneous motor tempo reflects the internal clock, it could be a mediator of the age-related decrease in working memory, as well as processing speed was not supported by the findings. However, processing speed was found to be a significant regulator of both working memory and the slowing of spontaneous motor tempo.

4.7.2 Information Processing Speed/Movement Time

As discussed in the previous section, it seems as if our internal clock slows down as we age. Perhaps, unsurprisingly, our information processing rate and memory performance may also deteriorate (Wearden, 2005b). This deterioration is gradual in the majority of non-pathological cases, so even in retrospective timing, an individual may be able to "recalibrate," over many years. However, this may not be the case. For instance, adults frequently report that "Christmas comes round quicker every year". There is an explanation for this. If we assume that an ordinary year contains some level of "storage" (X). As information processing rates decrease and memory losses increase with ageing, the amount of storage in a year is less (possibly much less) than X. As a result, the individual is surprised that a year has passed, since much less storage has occurred than they had anticipated.

Botwinick (1971) demonstrated that age differences in RT (elderly vs. young adults) were found to persist even when stimulus intensities were adjusted on an individual basis of reported loudness. Philip, Taillard, Quera-Salva, Bioulac and Akerstedt (1999) also showed that RT increases with age. They investigated the RTs of 294 drivers in two groups (less than 30 years and the other group 30 years and more). The task involved participants pressing a button as quickly as possible in response to the random presentation of a square during a highway driving video. Additionally, Fozard, Vercryssen, Reynolds, Hancock and Quilter (1994) investigated auditory RT data from 1,265 community-dwelling volunteers (833 males and 432 females) who ranged in age from 17 to 96. Repeated testing within participants (longitudinal analyses) over eight years showed consistent slowing and increased variability with age. A study carried out by Lewis and Brown (1994) found that age-related changes in the dynamics of muscle activation were, in part, responsible for longer RTs in the elderly.

Block, Zakay and Hancock (1999) carried out a meta-analytic review on the developmental changes in human duration judgments. They found that studies into the RT of children demonstrate that they are slower than young adults (e.g., Nettelbeck & Wilson, 1994), suggesting that their pacemaker rate may be slower than that of young adults. If this is the case and if duration judgments are directly proportional to pacemaker rate, children's verbal estimates should have been smaller, not larger, than those of older participants.

Even though it seems to have made the wrong prediction, the pacemaker rate hypothesis may still be viable. However, in order to learn to judge durations accurately, a child may need continually to recalibrate the translation between subjective duration units and verbal estimates. But the recalibration process may lag behind the actual increase in pacemaker rate. For example, if a child experiences a 10 second duration during which 100 subjective temporal units (e.g., pacemaker pulses) occur, he or she may store in reference memory the information ‘‘100 units = 10 sconds.’’ If the pacemaker rate increases throughout childhood, recalibration of reference memory information is needed, but this may lag behind the increase in pacemaker rate. For example, a 10 second duration now may contain 120 subjective temporal units, but the child has not yet revised the reference memory enough. Given no revision, he or she will judge a 10 second duration as being 12 seconds. For this reason, children may give overly large verbal estimates of durations and make overly short productions of durations. The present findings, in fact, are in that direction (although the effect size for productions is small and not significantly different from 0). Note that the pacemaker-rate hypothesis is not effectively tested by conditions using the method of reproduction, because any age-related difference in pacemaker rate or calibration during the target duration is also present during the reproduced duration. As such, a simple pacemaker-rate explanation is not able to handle the present finding of an age-related difference in reproduction magnitude.

4.7.3 Conclusion: The Effect of Age on Time Perception and Information Processing

In sum, despite some contradictory findings, there is substantial evidence that the rate of the internal clock slows down as we age, making subjective time appear to run at a faster rate. With respect to age-related slowing of the clock, the implication for such a model is that a faster (i.e. young) clock generates more pulses than a slower (i.e., old) clock to delineate the same target duration. Moreover, the overall variance of the target interval produced by the slower clock will be higher (Gibbon, Church & Meck, 1984) which may explain why variability in timing behaviour becomes greater as we get older (Wearden, 2005b).With respect to the studies investigating the effect of age on RT, consistent with other studies (i.e. Fozard et al., 1994), Philip et al. (1999) showed that RT increases with age. However, Lewis and Brown (1994) have suggested that this may be due to an age-related increase in motor reaction time (MRT), rather than a change in information processing rate.

Again, we see another factor which has an effect on both internal clock speed as well as information processing. The strongest argument for the speed of the internal clock in the elderly is by Wearden (2005b) who maintains that it is running at a slower rate compared to younger adults. If the internal clock is running slower then they would subjectively (to some degree) experience the world as running faster, giving rise to underestimations of duration. The fact that RT appears to be reduced in elderly adults is consistent with this slower rate of internal clock. If time is perceived as going faster, they will have less time to react and less information processing time. Again, this suggests a relationship between the internal clock and information processing. Although it could simply be that all brain processes decline with age.

4.8 Drugs and Parkinson's Disease: The Dopamine Hypothesis

4.8.1 Time Perception

Meck (1983) investigated whether drugs that affect dopamine metabolism, such as methamphetamine affect the speed of the internal clock in studies on rats. Findings demonstrate that methamphetamine results in a leftward shift in the psychophysical function when administered to rats trained under saline and produces a rightward shift when training under chronic methamphetamine is terminated. Therefore, supporting the idea that methamphetamine proportionally increases the clock reading for each physical stimulus duration. Evidence to suggest that dopamine plays a major role in determining the rate of temporal integration for time estimation (Meck, 1986) in humans comes from studies involving individuals with Parkinson's disease (PD). Humans with a damaged dopamine system, e.g. patients with Parkinson's disease, have impaired performance in time estimation tests (Malapani, Deweer & Gibbon, 2002). However, Wearden, Smith-Spark, Cousins, Edelstyn, Cody and O'Boyle (2009) argue that the large deficits seen in individuals with PD are due to the use of timed manual responses (e.g., Malapani et al., 2002). Wearden et al. (2009) used tasks involving no motor component (e.g., temporal bisection; temporal generalization; verbal estimation of duration) instead reflecting "central timing processes". In these tasks, PD patients demonstrate overall intact abilities to carry out such timing tasks. However, despite the lack of clear evidence suggesting that a damaged dopamine system results in poor timing abilities in humans, there is evidence for this in animal studies. Studies have found that the speed of an internal clock can be modified by the administration of DA receptor agonists or antagonists, with indirect agonist such as cocaine and methamphetamine increasing clock speed and antagonist such as haloperidol and raclopride decreasing clock speed (e.g., Cevik, 2003; Drew, Fairhurst, Malapani, Horvitz & Balsam, 2003; Meck, 1986).

4.8.2 Information Processing Speed

Dopamine is involved in a variety of motor and non-motor information-processing operations. Dopamine's contribution to human information processing has been shown in a variety of RT studies. Additionally, since timing deficits seen in patients with Parkinson's disease (PD) is thought to be the result of a decrease in clock speed, it is unsurprising then that impairments are also found in this group with respect to RT. Wilson (1925) was the first to obtain quantitative measures showing impairments of RT in PD. Across a wide variety of experimental paradigms, people with PD tend to have slower reactions compared with healthy adults of a similar age (e.g. Rafal, Inhoff, Friedman & Bernstein, 1987). Jahanshahi, Brown and Marsden (1993) have also found a slowed RT, not only in PD but also in patients with other disorders of the basal ganglia (Huntington's disease), as well as those with a disease sparing the basal ganglia (cerebellar disease).

The processing stages related to motor function are perhaps the most obvious stages in which to expect some degree of slowing in PD. After all, impaired motor activity is a defining feature of the disease. Even in tasks with minimal perceptual and decision requirements (e.g. simple RT task), PD patients tend to have slower reactions than control subjects (Heilman et al., 1976; Evarts et al., 1981). In addition, PD patients are especially slow and inaccurate at executing more complex movements (e.g. simultaneous or sequential movements), which presumably pose greater demands on motor processing compared with single element movements (Martin, Phillips, Iansek & Bradshaw, 1994). There is also evidence from transcranial magnetic stimulation studies to suggest that, in PD, a longer time is needed for the motor cortex to reach the threshold necessary for emitting an overt response (e.g. Pascual-Leone, Valls-Solé, Brasil-Neto, Cohen & Hallett, 1994b).

It is less clear whether processing stages prior to the motor system are affected by PD. Cooper et al. (1994) found that PD patients showed increasingly prolonged RTs as the CHOICE complexity of the decision increased. They concluded that cognitive speed is slowed in PD and that this slowing is proportional to the increase in decision complexity. Consistent, with these findings, Starkstein, Esteguy, Berthier, Garcia and Leiguarda (1989) found in a simple RT and movement time task during both “off” and “on” phases of medication, no significant differences. Thus, deficits in motor processing only became apparent when the motor requirements of the task were stringent. These findings of impairment on complex compared to simple RT tasks, is consistent with other studies (i.e., Cooper et al., 1994; Martin et al., 1994; Sanes, 1985; Temel, Blokland, Ackermans, Boon, van Kranen-Mastenbroek, Beuls, Spincemaille & Visser-Vandewalle, 2006). Kutukcu, Marks, Goodin and Aminoff (1999) also found a highly significant slowing of response time in both simple reacton time and choice reaction time tasks in patients with PD and that this delay is increased 3- to 5-fold with increase in task difficulty as judged by an increase in the response time to the same stimulus in normal participants.

Contrary to these findings of impairment with increasing task complexity (i.e., Pullman, Watts, Juncos & Sanes, 1990), other researchers have found no exaggerated slowness in PD patients when performing an increasingly complex stimulus task (Russ & Seger, 1995). Pascual-Leone et al. (1994a) found that PD patients are sometimes but not always slower than controls in choice RT tasks. Based on their findings with transcranial magnetic stimulation, Pascual-Leone et al. (1994a) suggested that ‘the main abnormality of PD patients in a RT situation is the abnormally slow build-up of premovement excitability’ (Pascual-Leone, Valls-Solé, Brasil-Neto, Cammarota, Grafman & Hallett, 1994a). The findings of Pascual-Leone et al. (1994a) are also supported by the findings of Pullman, Watts, Juncos, Chase and Sanes (1988) which also suggest that simple and choice RTs are differentially affected by L-dopa replacement, indicative of different neural mechanisms underlying each. Evarts, Teravainen and Calne (1981), consistent with Pascual-Leone et al. (1994a) and Pullman et al. (1988; 1990), found no selective impairment with a choice RT task in PD patients. Jahanshahi, Brown and Marsden (1992) found that medication state had no effect on movement time or the number of errors. Again suggesting that slowness in motor readiness and motor programming may not be specific to striatal dopamine deficiency but rather a non-specific concomitant of brain damage. Also, use of advance movement parameter information was not affected by withdrawal of dopaminergic medication.

4.8.3 Conclusion: The Effect of Drugs on Internal Clock and Information Processing Using Parkinson's Disease as a Human Biological Model

Numerous studies suggest that dopamine plays a major role in determining the rate of temporal integration for time estimation (Meck, 1986). However, the relationship between the dopaminergic system and internal clock speed has received criticism due to the lack of consistency of findings demonstrating effects of dompaminergic medication on timing performance (Matell, King & Meck, 2004; Holson, Bowyer, Clausing & Gough, 1996) and by pharmacological studies that showed that dopamine plays a role in attentional processing of information not simply the clock speed (Buhusi & Meck, 2002). The studies on the effect of dopamine on RT or information processing also show inconsistency. This lack of consistency in the literature highlights the fact that we cannot draw any conclusions here on the link between information processing and the internal clock.

4.9 Caffeine

4.9.1 Time Perception

Botella et al. (2001) argued that any effects of caffeine upon psychological time may possibly be attributable to its agonist effect on dopamine D2 receptors. Enhanced dopaminergic neurotransmission would, in theory, alter the pacemaker of a hypothetical internal clock (Treisman et al., 1992; Meck, 1996). Since amphetamine and methylphenidate are dopamine agonists it can be argued that the effects of caffeine on duration judgment should be similar to those of drugs (Gruber & Block, 2003). In addition, Gruber and Block (2003) found that caffeine slowed down the internal clock and shortened prospective duration timing for the participants in the caffeine condition, whereas, participants in the placebo condition made larger prospective verbal estimates of duration. In prospective judgments, participants know beforehand that they will be asked to make a judgment of some interval. Gruber and Block (2003) argued that rather than supporting the hypothesis that caffeine affects duration by increasing the internal clock rate as a result of dopamine D2 agonist properties, the findings are best explained as an increase in arousal. Such arousal leads to a narrowing of the focus of attention to the most salient task and encoding of more information. Therefore, compared to participants in the control condition, participants in the caffeine condition may have encoded more information about the secondary task involving the counting of polygon angles. As a result of this, they may also have encoded less information about the secondary task (attending to time) resulting in the shorter judgments of duration compared to controls. Smith and Tolla (1998) also argue that caffeine both increases general arousal and enhances attention. Moreover, Hogervorst, Riedel, Schmitt and Jolles (1998) found that the habitual use of large amounts of caffeine by middle-aged participants may be a means to overcome the age-related decreases in cognitive functioning that is caused by changes in information processing. Caffeine increased the number of words recalled by reducing the susceptibility to the distracting, auditory presented words but only in the middle-aged subjects because these participants are more sensitive to distraction and will benefit from the effect of caffeine on selective or focused attention (Hogervorst et al., 1998).

Additionally, Hogervorst et al. (1998) found that participants who were given a dose of 225 mg of caffeine consistently rated durations as longer than participants who had received a placebo, in perceived duration tasks. However, caffeine had no effect on remembered duration. Botella, Bosch, Romero and Parra (2001) postulated that caffeine at low or intermediate doses makes brain dopamine systems involved in the internal clock work in a similar way in males and females. This was demonstrated by the fact that in the control condition where participants were given decaffeinated coffee with 3 mg of caffeine, females made more accurate estimates of time intervals than males, whereas males demonstrated shorter RTs. Such gender differences were eliminated in participants who took doses of 75 and 150 mg of caffeine for the time estimation task and 150 mg for the RT task.

Stine, O’Connor, Yatko and Grunberg (2002) revealed also, that daily caffeine consumption is related to time perception. They looked at the link between regular caffeine consumption and time estimation. Participants were asked to complete questionnaires related to daily caffeine consumption then perform a 47 second time estimation exercise. Findings showed that individuals who reported moderate amounts of daily caffeine were more accurate in their perceptions of time than those who reported high amounts of daily caffeine intake or no daily caffeine consumption. However, although there were differences in the accuracy of time judgments between the groups, in contrast there was no effect of the level of daily caffeine consumption on ones perception of the rate of time passing (using the same 47 second time estimation task) which suggests that ones ability to estimate the duration of time is independent from the perception of the speed at which time passes (Stine et al., 2002). Such a conclusion is directly contradictory to the notion of the arousal-sensitive model of the internal clock theory.

4.9.2 Information Processing Speed

It has been well established that caffeine increases levels of arousal, so its effects of time perception can be assumed to be due to its effect on the rate of the internal clock. However, would the arousing capability of caffeine have an effect on RT as well? (e.g., Smith, Tola & Mann, 1999; Zwyghuizen-Doorenbos et al., 1990; Frewer & Lader, 1991). Studies have even suggested that the arousing effect can occur in the absence of caffeine. Mikalsen, Bertelsen and Flaten (2001) demonstrated that caffeine-associated stimuli can increase arousal.

Clubley, Bye, Henson, Peck and Riddington (1979) explored the effects of caffeine by employing an auditory RT test in which the participant pressed a microswitch as rapidly as possible in response to tones which had a mean interval of 7s and varied from 5 to 9 s. Findings showed that caffeine enhanced auditory vigilance, RT and tapping rates. Moreover, Franks, Hagedorn, Hensley, Hensley and Starmer (1975) investigated the effect of caffeine (300 mg/70 kg) on cognitive, perceptual and motor functions both alone and in combination with ethanol (0.75 g/kg) in 68 healthy student volunteers of both sexes. Caffeine alone tended to reduce simple auditory and complex RT, but had no effect on simple visual RT. Caffeine did not antagonise the ethanol-induced decrement in performance except in the RT tests.

Lieberman, Wurtman, Emde, Roberts and Coviella (1987) highlighted that, despite it being well known that caffeine appears to have stimulant-like behavioural effects on mood and performance, relatively few behavioural studies have examined this substance's acute effects when administered in a range of doses that include the low doses typically found in foods and over-the-counter drugs. So, Lieberman et al. (1987), investigated this by giving single doses of caffeine (32, 64, 128 and 256 mg) to 20 healthy male participants and assessed performance on an auditory vigilance and visual RT task. Although caffeine in all doses administered significantly altered performance on these two tests, a dose-response function was not apparent. Lastly, a greater sensitivity to caffeine's effects in older than in younger people has been reported previously (Swift & Tiplady 1988) and would not appear to reflect age related changes in caffeine disposition (Blanchard and Sawers 1983), at least in men. Indeed, Swift and Tiplady (1988) demonstrated a significant increase in tapping rate in the young, while the elderly showed improved attention, faster choice-RT and greater body sway on caffeine (Jarvis, 1993).

4.9.3 Conclusion: The Effect of Caffeine on Both Time Perception and Information Processing

Gruber and Block (2003) explain that the effects of caffeine on time estimation is due to the effect of its dopamine D2 agonist properties. They found that caffeine slowed down the internal clock as evidenced by participants who were administered caffeine underestimating duration on a prospective timing task. They then go on to say that the effects they found are due to arousal which leads to a narrowing of the focus of attention to the most salient task, an idea consistent with Smith and Tolla (1998). If this is the case, then surely the opposite findings would be produced, an overestimation of duration. However, if caffeine is arousing, then this would be expected to speed up the rate of the internal clock leading to overestimation of duration which is exactly what was found by Hogervorst et al. (1998). Further confusion is produced with the findings by Stine et al. (2002) who concluded that there is no effect of caffeine on the perception of duration, again inconsistent with the notion of an arousal-sensitive model of internal clock theory.

The findings of the effects on caffeine on RT performance (information processing) are more clear cut. Clubley et al. (1979) found that caffeine enhanced auditory vigilance and RT. Franks et al. (1975) also found that caffeine reduced simple auditory and complex RTs. Interestingly, they found no effect on simple visual RT. However, Lieberman et al. (1987) did find that caffeine improved visual RT, as well as auditory vigilance. Lastly, Swift and Tiplady (1988) also demonstrated reduced RT as well as a significant increase in tapping rate.

In sum, the effects of caffeine on information processing definitely point towards the idea that the arousal effects of caffeine are speeding up the internal clock (going with the study by Hogervorst et al., 1998) and enabling participants to react faster (indicative of a speeding up of information processing). It is possible though that caffeine speeds up any brain process, therefore, dissociative evidence would be more valuable here (see overall conclusion for more discussion on this).

4.10 Exercise

4.10.1 Time Perception

Jamin, Joulia, Fontanari, Giacomoni, Bonnon, Vidal and Cremieux (2004) argue that both exercise and hypoxia affect human ability to estimate time, an alteration thought to be induced by changes in subjects' level of arousal. Apnea induces cardiovascular changes and a decrease in oxygen uptake that indicate changes in physiological arousal. Jamin et al. (2004) investigated time estimation (TE) during brief periods of voluntary apnea to see whether there would be a relationship between TE and heart rate (HR), which is a physiological indicator of arousal. Participants comprised of two different groups of seven triathletes. To measure TE, the target time interval of either 20 or 30 seconds was presented and the participants were required to reproduce it under various conditions: initial baseline at rest, normal breathing with exercise (NE), Apnea with exercise (AE) and Apnea at rest (AR). In the NE condition, participants cycled at a constant cadence indicated by the bike's LCD screen at 30% of their individual aerobic power for 20 min before performing the TEs. Findings showed that reproduction for intervals was greater in the AR condition. Surprisingly, no difference was found between TEs performed during NE and AE. Since it has been shown that repetitive stimulation such as an auditory click added during TE affects timing (Penton-Voak et al., 1996) then perhaps the audible external tempo of the pedaling frequency may have altered the speed of the pacemaker (Penton-Voak et al., 1996). Since the cycling cadence was similar in NE and AE, it could have had an effect on participant's reproduction of durations in both conditions. Although the findings from this study must be interpreted with caution, the finding that the reproduction intervals were greater for the AR compared to both the NE and AE conditions (which involved exercise) may be due to the fact that the sound of the pedalling caused an increase in the rate of the internal clock (in the same way that click trains appear to do).

This is turn will lengthen participant's subjective sense of time passing, leading to shorter reproduction intervals.

Vercruyssen, Hancock and Mihaly (1989) evaluated performance on a 10-sec unfilled time interval estimation task before, during and after physical work on a cycle ergometer at relative intensities of 30 and 60% VO2max. Findings from their study on eleven healthy male participants revealed a significant increase in time estimation variability and a decrease in the mean estimated time intervals during exercise compared to non-exercise phases. These findings are part of a growing body of evidence which indicates that exercise and its severity has a substantive impact on perceptual and cognitive performance, particularly the ability to synchronize and anticipate the timing of events.

4.10.2 Information Processing Speed

An increasing amount of research is being conducted into the effect exercise has on cognition. Early theories of arousal and performance (Humphreys & Revelle, 1984; Pribram & McGuinness, 1975) based their ideas on arousal induced by cognitive demands. The notion of a relationship between increases in exercise intensity and changes in arousal was postulated by Davey (1973), who also argued that such a relationship would affect cognition. Further, that low, moderate and high intensities of exercise are synonymous with low, moderate and high levels of arousal. Based on Yerkes and Dodson's (1908) theory, Davey (1973) hypothesized that incremental exercise would have an inverted-U effect on cognitive performance which is consistent with the findings by McMorris, Hill, Sproule, Potter, Swain, Hobson and Holder (2005). Cooper (1973) suggested a psychoneuroendocrinological explanation for this exercise-cognition interaction. Cooper claimed that exercise results in increased brain concentrations of the neurotransmitters noradrenaline and dopamine, which enhance cognitive performance. Indeed, McMorris, Collard, Corbett, Dicks and Swain (2008) argue that exercise produces a greater availability of the neurotransmitters noradrenaline and dopamine, which are involved in the activation of several areas of the brain including the prefrontal cortex and basal ganglia. These areas of the brain play large roles in working memory, learning and RT.

Collardeau, Brisswalter and Audiffren (2001) investigated the effect of increased arousal induced by a prolonged exercise on simple RT performance during a running task.

Analysis showed a significant impairment in simple RT performance during the first treadmill run only. After this first run a significant effect of exercise duration on simple RT was observed. After 40-min. of exercise, a significant improvement in RT during exercise was recorded. These results suggest that a simple cognitive performance could be improved during exercise, despite the negative effect of the dual task. This improvement in RT could be explained mainly by an increase in arousal induced by a prolonged exercise. Davranche and Audiffren (2004), consistent with the findings from a later study (Audiffren, Tomporowski & Zagrodnik, 2008), also demonstrated the role of exercise on arousal. They explored the facilitating effects of moderate physical exercise on the reaction process in order to try and establish the link between physiological and cognitive processes. Sixteen participants with specific expertise in decision-making sports performed a double task consisting of choice RT while cycling. Findings showed that moderate-intensity exercise (50% maximal aerobic power) improves cognitive performance (on a choice RT task) and that low-intensity exercise (20% maximal aerobic power) enables participants to compensate the negative dual-task effect.

Improving on previous qualitative and quantitative analyses of the literature on the link between fitness and cognition (i.e., Etnier, Salazar, Landers, Petruzzello, Han & Nowell, 1997; Etnier, Nowell, Landers & Sibley, 2006), Colcombe and Kramer (2003) conducted a meta-analytic study to investigate the hypothesis that aerobic fitness training enhances the cognitive vitality of healthy but sedentary older adults. The primary finding was that fitness training increases performance, irrespective of the type of cognitive task, the training method, or participants' characteristics. Dietrich and Sparling (2004) reviewed the literature and found that in most studies, cognitive ability was examined at least 10–15 min after the exercise had finished, presumably to control for arousal levels as well as a number of other possible physiological confounds (e.g., Magnié, Bermon, Martin, Madany-Lounis, Suisse, Muhammad & Dolisi, 2000). However, findings from neuroimaging studies on a wide range of brain functions suggests that a delay of even a few minutes would be sufficient to normalise any exercise induced changes in neural activity. Very few studies were found to test for cognitive functions during exercise (e.g., Arcelin, Delignieres & Brisswalter, 1998; Brisswalter, Collardeau & Arcelin, 2002; for recent reviews see, Tomporowski, 2003). Specifically, the findings by Arcelin et al., (1998) were consistent with the notion that information processing rate is differentially affected by exercise, since decreases in RT were found with acute exercise.

However, Tomporowski and Ellis (1986) have emphasised the limitation of conclusions based on these studies, by pointing out the variety of cognitive tasks used across studies making comparison of studies almost impossible. Results from a study carried out by Dietrich and Sparling (2004) are indicative of the notion that during endurance exercise different cognitive functions are affected to different degrees. Specifically, they found exercise produced deficits that are selective for cognitive function typically attributed to functional systems that rely on the prefrontal cortex (Dietrich, 2006). Future research should also include methods to equate participants based on their level of physical fitness prior to evaluating the effects of exercise on mental functioning.

4.10.3 Conclusion: The Effect of Exercise on Time Perception and Information Processing

There has been little study carried out on the effects of exercise on timing abilities. The few studies that have been carried out enable us to tentatively suggest that that exercise may have an effect on humans' ability to estimate time. For instance, Vercruyssen et al. (1989) found that participants demonstrated greater variability in their time estimates and decreased estimates of time intervals during exercise. This suggests that the internal clock is being slowed down during exercise. Exercise is generally considered to be arousing (LeDuc, Caldwell Jr & Ruyak, 2000), so this suggests an effect going in the opposite direction to what we would expect based on findings from the literature that arousal leads to an increase in the speed of the internal clock. This conflict of findings supports the notion that more studies are required to enable us to interpret this with more confidence.

Findings from studies looking at the effect of exercise on information processing show that simple cognitive performance can be improved during exercise (i.e., Collardeua et al., 2001, Davranche & Audiffren, 2004). The exercise was argued to increase arousal. If this was indeed the case, then the findings on timing are inconsistent with the notion that the exercise caused the rate of the internal clock to speed up which lead to an increase in information processing as evidence by reduced RTs while exercising.

4.11 Overall Conclusion

The timing and RT literature was explored to see whether they are subserved by the same mechanism. Various factors were looked at to see what effect they had on both information processing (as measured by RT) and time perception. Many factors were found to suggest a link between information processing and time perception, for instance: attention, stimulus intensity, arousal, stimulus modality, age, caffeine and exercise. The effect of modality was also explored and studies showed that auditory stimuli appear to be more dominant than visual stimuli. Also, parallels in the effect of modality on both time perception and RT suggest the two are linked. Of particular relevance was the study carried out by Treisman et al. (1992) which clearly highlighted a factor which *simultaneously* had an effect on both internal clock speed and information processing. The next step is to carry out an investigation into whether click trains can also affect both internal clock speed and information processing, simultaneously. If an effect on both is demonstrated, this would further strengthen the argument for a link between these two processes.

It is crucial to point out here that logically we have to acknowledge the fact that there can always be some manipulation (s) that can show a sharp distinction, in this case, between the internal clock and information processing. All we can really do is *accumulate* a weight of evidence that these two processes are linked. The models proposed in Chapter 1, section 1.4.7, are parsimonious models poised to explain the potential relationships between information processing and the internal clock. There always remains the possibility that a much more complex model is more representive of the actual process. However, a parsimonious explanation at this stage in our understanding of the underlying process of clicks is warranted. These notions also apply to the experiments carried out in this thesis. Even if the experiments carried out in this thesis generally point towards a relationship between the internal clock and information processing, caution must be taken in the conclusions drawn from this lack of dissociative evidence between these two processes.

Chapter 5

Exploration of the Parametrics of the Effect of Clicks on Tasks of Reaction Time

It has previously been shown that clicks can reduce reaction time (i.e., Jones et al., 2010). However, what has not been explored is the parametrics of clicks which seems the next logical step in trying to understanding the nature of clicks and how they operate. In particular, how long the effect of clicks on reaction time lasts. This is explored by the experiments in Chapter 5. The findings from the studies exploring the parametrics of clicks will further our understanding of the nature of clicks on reaction time.

5.1 Experiment 1a and b - 1, 2 and 4 Choice Reaction Time Task with Set Delays and Clicks versus No-Clicks

Research conducted in the time perception lab at The University of Manchester has shown that clicks speed up reaction times on a 1, 2, 4 choice reaction time task (Jones et al., 2010). However, Experiment 1a took the findings of Jones et al. (2010) further by investigating how long this effect lasts by using gap durations of either 500, 2,000 or 5,000ms after the clicks and before the presentation of the response cue as opposed to the random delay (randomly selected between 300 and 1,200ms) which was used previously. So, Experiment 1a is effectively investigating the effect of clicks over time. In the task, half the trials were preceded by 5 seconds of clicks and the other half 5 seconds of no-clicks. On each trial, the five seconds of either clicks or no-clicks was then followed by a delay of 500, 2,000 or 5,000ms after which a cross appeared in one of four presented boxes and participants were asked to make a response as quickly and accurately as possible to this cross. There are three response types, one choice, a two choice and a four choice (the one choice being the easiest and the four choice being the hardest). Experiment 1b is exactly the same experimental design as Experiment 1a but uses much longer gap durations of 5,000, 7,500 or 10,000ms. From the findings of previous studies (Penton-Voak, et al., 1996; Burle et al., 1999; Burle et al., 2001), it was expected that on trials preceded by clicks, reaction times would be reduced on each of the three response types. So the present experiments explored the parametrics of the clicks by investigating the time course of the effect (how robust it is over time) which has not previously been addressed. If clicks are shown to work even after a long delay, then this will be a first and important confirmation of the effect of clicks on reaction time that was first demonstrated by Jones et al. (2010).

5.1.1 Method

Participants

For Experiment 1a, thirty-eight undergraduate students from the University of Manchester participated in exchange for course credit, which was not contingent on performance. Thirty participants took part and received £5 compensation which was not contingent on performance in Experiment 1b.

Apparatus

A Dell PC computer controlled all experimental events. The computer stereo speaker produced the auditory stimuli and the visual stimuli and instructions were displayed on the computer screen. The experiment was created using an E-Prime program (Psychology Software Tools Inc.). All reaction-time responses were made on an E-Prime Serial Response box.

Procedure

For Experiment 1a, each participant served in an experimental session consisting of three choice types (1, 2 or 4 choice). There were three blocks, each consisting of fifty-four trials with 27 click and 27 no-click trials randomly intermixed. In each block there were 18 trials of each of the three choice types (1, 2 or 4), producing 9 trials in each experimental condition. Half of the 18 trials for each of the three choice types being preceded by no-clicks, the other half being preceded by clicks. There were three gap duration types (500, 2000 and 5000ms). Each of these three gap duration types were presented 18 times. Therefore, there were 162 trials in total. In all conditions, participants were instructed to respond as quickly as possible (and as accurately, in the choice conditions) to the onset of the black cross.

At the beginning of each session, instructions appeared on the screen and participants were then asked to press the space bar to commence the first trial. On each trial 4 boxes with a black outline and a white centre (80 pixels wide by 60 pixels high) appeared on the screen in a horizontal line. Each trial began with a 700Hz tone of 25ms duration followed by a 5 second period, either filled by silence or by a series of clicks, depending on the session type. This was then followed by a subsequent 700Hz tone presented for 25ms. Following the second tone, there was a gap duration of either 500, 2,000 or 5,000ms. After which, a small black cross (formed by two lines 11 pixels in length) appeared in the middle of one of the four boxes. The participant was instructed to react as quickly and accurately as possible by pressing the appropriate button on the response box. After each response was made, participants were asked to press the space bar for the next trial to begin. In the first block type (the ‘one choice’ condition), participants were asked to respond as fast as possible by pushing any one of the four buttons on the response box when the cross appeared in the center of any one of the boxes presented on the screen. In the second block type (the ‘two choice’ condition) participants were asked to respond on the far left key of the response box (marked 1) when the cross appeared in either of the two left-hand boxes and the far right key (marked 4) if the cross appeared in either of the two right-hand boxes. In the third block type (the ‘four choice’ condition) participants responded to the appropriate key for the appropriate box, i.e. key 1 for the left hand box, key 2 for box appearing second from the left, etc.. Participants were instructed when a new block type was beginning via instructions on the monitor and were asked to press the space bar to commence the first trial for the block. The order of response types were counter-balanced across participants. Throughout the experiment the participants rested their dominant hand on the response box with their fingers resting on each of the response keys.

In Experiment 1b, the only difference was that following the second tone, there was a gap duration of either 5,000, 7,500 or 10,000ms rather than 500, 2,000 or 5,000ms.

5.1.2 Results

Experiment 1a

The mean reaction time responses and standard errors for each of the experimental conditions are shown in Figure 9. Descriptive analysis reveals that the mean reaction time for trials preceded by clicks was less than that of the trials preceded by no-clicks, 485.92ms (SE = 14.99) and 507.12ms (SE = 17.4), respectively. The reaction times also became longer the more complex the choice type. For choice type 1, the mean reaction time was 412.01ms (SE = 16.37). For choice type 2, mean reaction time was 510.58ms (SE = 16.2) and lastly the mean reaction time for choice type 4 was 566.98ms (SE = 18.03). The reaction times for each of the three gap durations appears to have no significant difference (gap duration 500ms, mean reaction time 500.44ms (SE = 16.23); gap duration 2,000ms, mean reaction time 488.79ms (SE = 16.64) and gap duration 5,000ms, mean reaction time 500.34ms (SE = 15.86). Inspection of Figure 9 suggests than on trials preceded by clicks, reaction times were faster. For each of the three choice types, reaction time was reduced on trials preceded by clicks. However, this was only the case when the gap duration was either 2,000 or 5,000ms, not with the shortest gap duration of 500ms. What is interesting is the fact that there was no effect of gap duration type (500, 2,000 and 5,000ms), on the effect of clicks.

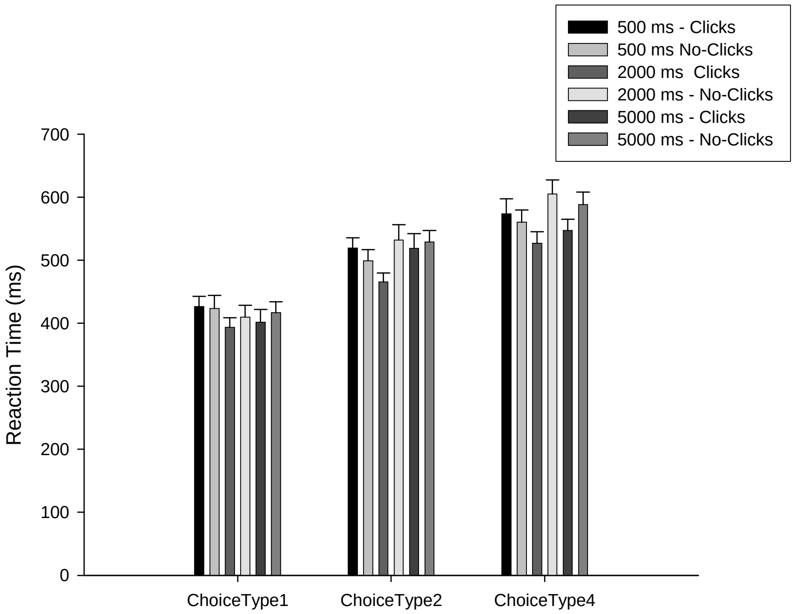


Figure 9: Mean reaction times plotted against choice condition (one, two or four) for the click (5Hz) and no-click conditions of Experiment 1a. Vertical lines show standard error of the mean.

These findings were confirmed by the statistical analysis. Three participants were removed from the data as a result of incorrectly carrying out the task. This was determined by the fact that they failed to carry out the appropriate choice type response for blocks and proceeded to get a large proportion of incorrect responses. Repeated measures analysis of variance (ANOVAs) were used with one factor being number of choices (1, 2 or 4), the second factor being gap duration (500, 2,000 and 5,000ms) and the third being the presence or absence of clicks. There were significant main effects of clicks versus no-clicks, $F(1,37) = 8.03$, $p < .05$, $\eta_p^2 = .18$, MSE = 9572.65, confirming an effect of clicks on reaction time. There was no significant main effect of gap duration, $F(2,74) = 2.08$, $p = .13$, $\eta_p^2 = .053$, MSE = 4900.76, indicating that reaction time had not been reduced by the gap durations used. There was also a significant main effect of choice type, $F(2,74) = 115.72$, $p < .001$, $\eta_p^2 = .76$, MSE = 12122.14, which is what we would expect. Namely, that reaction time increased the more complex the choice type. There was a significant interaction between gap duration and clicks/no-clicks, *F*(2,74) = 15.61, $p < .001$, $\eta_p^2 = .3$, MSE = 3960.09, indicating that the effect of clicks/no-clicks was dependent upon gap duration. However, there was no interaction between gap duration and choice type, *F*(4,148) = 2.18, $p = .08$, $\eta_p^2 = .06$, MSE = 2973.83, suggesting that gap duration is not dependent on choice type. There was also no significant interaction between clicks/no-clicks and choice type, *F*(2,74) = 2.12, $p = .13$, $\eta_p^2 = .05$, MSE = 4552.74, suggesting that the effect of clicks/no-clicks is not dependent on choice type. There was, however, a significant three-way interaction between gap duration, clicks/no-clicks and choice type, *F*(4,148) = 2.77, $p < .05$, $\eta_p^2 = .07$, MSE = 3205.74, indicating that the effect of clicks/no-clicks was dependent upon both gap duration and choice type.

Figure 10 shows more clearly the effect of clicks for each gap duration across the three choice type responses. Reaction times from the click condition trials were subtracted from the reaction times from the silence condition trials. This gives a much better representation of the effect of the clicks. Figure 10 confirms again that clicks resulted in a reduced reaction time for all choice types but only with a gap duration of 2,000 or 5,000ms.

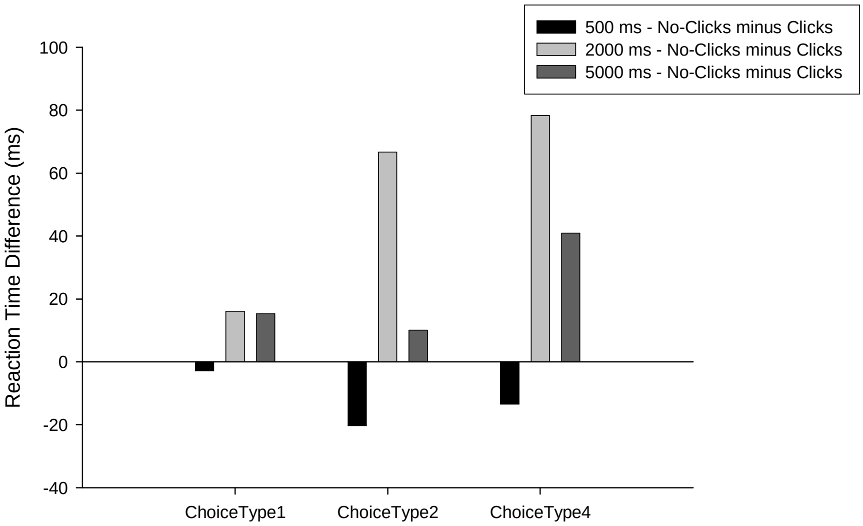


Figure 10: Mean reaction time for the no-click minus click condition across all choice types and gap durations of Experiment 1a.

Experiment 1b

The mean reaction time responses and standard errors for each of the experimental conditions are shown in Figure 11. Descriptive analysis reveals that the mean reaction time for trials preceded by clicks is less than that of the trials preceded by no-clicks, 608.04ms (SE = 40.54) and 545.49ms (SE = 31.32), respectively. The reaction times also became longer the more complex the choice type. For choice type 1, the mean reaction time was 523.73ms (SE = 42.57). For choice type 2, mean reaction time was 566.37ms (SE = 33.61) and lastly the mean reaction time for choice type 4 was 640.19ms (SE = 34.64). The reaction times for each of the three gap durations appears to have no significant difference (gap duration 5,000ms, mean reaction time 592.85ms (SE = 34); gap duration 7,500ms, mean reaction time 580ms (SE = 39.31) and gap duration 10,000ms, mean reaction time 557.44ms (SE = 36.19). Inspection of Figure 11 suggests that, firstly, the response times for all choice types and gap durations are reduced with clicks. Therefore, Experiment 1b provides even stronger support than Experiment 1a for the idea that clicks reduce reaction time, since all nine condition types demonstrated this effect as opposed to six out of nine conditions in Experiment 1a. Moreover, overall response times increase across the three choice types, with response type 3 having the highest reaction times. These suggestions were supported by the statistical analysis.

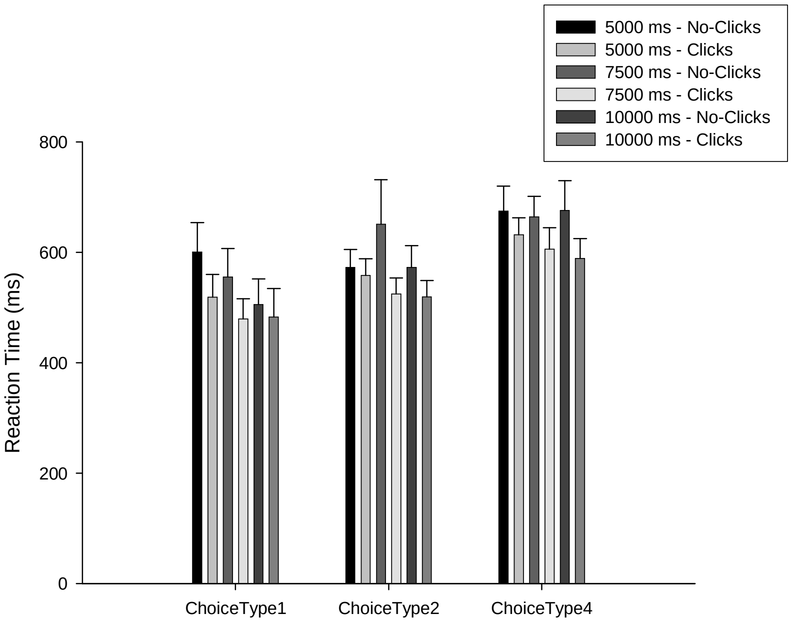


Figure 11: Mean reaction times plotted against choice condition (one, two or four) for the click (5Hz) and no-click conditions of Experiment 1b. Vertical lines show standard error of the mean.

Repeated measures analysis of variance (ANOVAs) were used with one factor being number of choices (1, 2 or 4), the second factor being gap duration (5,000, 7,500 and 10,000ms) and the third being the presence or absence of clicks. There was a significant main effect of clicks, $F(1,29) = 14.98$, $p < .05$ ($p = .001$), $\eta_p^2 = .34$, MSE = 35266.65, confirming an effect of clicks on reaction time. There was no significant main effect of gap duration, $F(2,58) = 2.38$, $p = .1$, $\eta_p^2 = .08$, MSE = 24314.59, indicating that reaction time was not dependent on the gap durations used. There was a significant main effect of choice type, $F(2,58) = 17.28$, $p < .001$, $\eta_p^2 = .37$, MSE = 624877.9, indicating increased reaction time with increasing choice difficulty which is what we would expect. There was no significant interaction between gap duration and clicks/no-clicks, $F(2,58) = 1.28$, $p = .29$, $\eta_p^2 = .04$, MSE = 16038.48, indicating that the effect of clicks/no-clicks was not dependent upon gap duration. There was also no interaction between gap duration and choice type, $F(4,116) = 1.12$, $p = .35$, $\eta_p^2 = .04$, MSE = 18779.98. There was no significant interaction between clicks/no-clicks and choice type, $F(2,58) = .02$, $p = .98$, $\eta_p^2 = .001$, MSE = 15949.65, indicating that the effect of clicks/no-clicks was not dependent on choice type. There was a non-significant three-way interaction between gap duration, clicks/no-clicks and choice type, $F(4,116) = 1.08$, $p = .37$, $\eta_p^2 = .04$, MSE = 23326.82.

Figure 12 shows more clearly the effect of clicks for each gap duration across the three choice type responses. Reaction times from the click condition trials were subtracted from the reaction times from the no-clicks condition trials. This gives a much better representation of the effect of the clicks which are producing a faster reaction time in all conditions. Figure 12 confirms again that clicks produce a reduced reaction time on all three choice type responses. However, no trend is evident, in terms of delay duration.

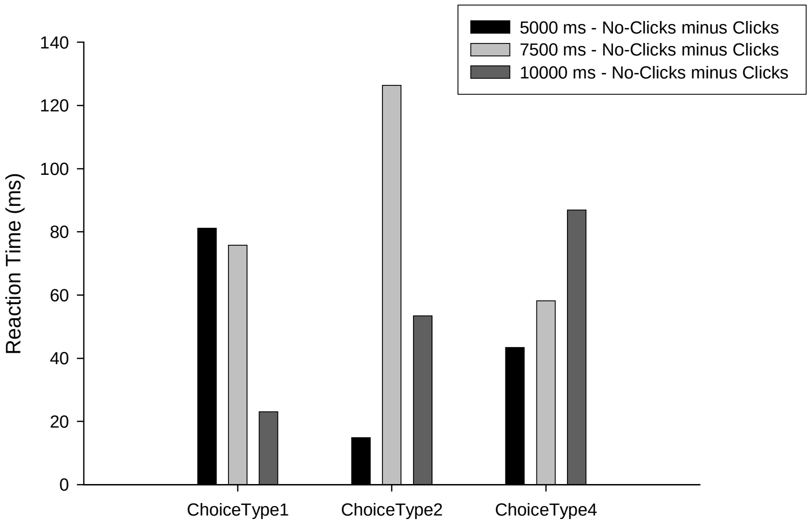


Figure 12: Mean reaction times for the no-click minus click conditions for all choice types and gap durations of Experiment 1b.

5.1.3 Discussion

In Experiment 1a, both the results from Figure 9 and 10 and the ANOVA analysis, clearly demonstrate two effects. First, there was a significant effect of choice type on reaction time, with reaction time increasing significantly with the number of choices. Second, this increase was found for both clicks and silence trials. This finding is unsurprising as it a classic finding by Hick (1952) who argued that “Information is definitely related to reaction time, within the duration of one perceptual-motor act”. However, such a classic finding in this study does demonstrate that the choice reaction time task used here does seem to produce results that are consistent with the “normal” or expected response. Consistent with previous findings by Jones et al. (2010), there was a significant effect of clicks, with click trains in general reducing reaction time response. Specifically, six of the nine conditions demonstrated this reduced reaction time with clicks. The most important finding was the fact that there appears to be no significant effect of gap duration (500, 2,000 and 5,000ms). In other words, that the effect of clicks were not reduced over time (with respect to the gap durations used in the present experiment). Only with a gap duration of 500ms is there no evidence of a reduced reaction time on trials preceded by clicks.

Consistent with Experiment 1a, Experiment 1b found no significant effect of gap duration and a significant effect of both clicks and choice type. A significant effect of choice type is not surprising. However, the effect of clicks demonstrated was unique as it has only ever previously been found by Jones et al. (2010). Therefore, this effect of clicks has now been confirmed by two experiments. What is of further interest is the fact that the reduction of reaction time due to clicks lasts as long as 10,000ms. Further studies are required to determine when the effect of clicks actually wears off. Experiment 1b provided even stronger support for the notion that clicks reduce reaction time, since all nine condition types demonstrated this effect as opposed to six out of nine conditions in Experiment 1a.

Previous studies have demonstrated that preceding a stimulus with a click train results in the participants judging the duration of the stimulus as longer than if it were preceded by silence (Penton-Voak et al., 1996; Burle & Cassini, 2001; Penton-Voak et al., 1996). Both Experiment 1a and b, take this a step further by not only confirming that click trains make stimulus duration appear longer and also decrease reaction time (as shown by Jones et al., 2010) but that this effect is persistent up to a 10 second duration/delay. The potential criticism that the effect of clicks is due to the end of the click train indicating to the participants that they will now be asked to make a reaction time response was eliminated by the inclusion of a cue (a tone) that signified the end of the clicks and no-clicks 5 second interval.

However, a potential problem with the design of this study is the presence of expectancy effects. During the three different gap durations the participants experience (either 500, 2,000 and 5,000ms or 5,000, 7,500 and 10,000ms), they may learn quite quickly to increasingly expect the cross with increasing gap duration. Particularly in the case of the 10,000ms delay, which is sufficiently long to cause the participants to prepare to respond towards the end of this duration, thus biasing the results. In order to reduce the effect of this, Experiment 1c introduced a random delay after the three different types of gap durations. A tone signified the end of the gap duration, after which a random delay of somewhere between 300 and 1,200ms took place. At the end of this random delay, the cross appeared in one of the four boxes and participants were asked to respond. If an effect of clicks was found this would provide further and more robust evidence that the clicks do improve reaction time response and that this effect persists over time, as suggested by Experiments 1a and b.

5.2 Experiment 1c - 1, 2 and 4 Choice Reaction Time Task with Modification for Expectancy Effects

As in Experiments 1a and b, this experiment also addressed the research question of the parametrics of clicks but it also controlled for possible expectancy effects that may have been present. Experiment 1c used the same methodology as Experiment 1a, with the exception of there being a random delay (between 300ms and 1,200ms) inserted between the gap duration (of either 500, 2,000 or 5,000ms) and the presentation of the cross. The reason for this modification was that the results found in Experiment 1a may have been affected by a bias introduced by expectancy effects. So, as the gap duration approached its termination, participants were getting prepared to make a response. This effect would be especially marked on the longer gap duration of 5,000ms. Findings were expected to be consistent with Experiment 1a, namely, that on trials preceded by clicks the reactions time would be reduced. An effect of clicks in Experiment 1c would help reduce this possible criticism of expectancy confounds, lending further support to the effect of clicks on reaction time and show that this effect is consistent over time as well as supporting the findings from previous studies (i.e., Penton-Voak, et al., 1996; Burle et al., 1999; 2001).

5.2.1 Method

Participants

Thirty-one undergraduate students from the University of Manchester participated in exchange for course credit, which was not contingent on performance. Fifteen participants were recruited via the research volunteer website and were compensated with £5 for their participation, which was not contingent on performance.

Apparatus

See Apparatus for Experiment 1a.

Procedure

This experiment was similar to Experiment 1a apart from the addition of a random delay (between 300ms and 1,200ms) after the gap duration of either 500, 2,000 or 5,000ms.

5.2.2 *Results*

The mean reaction time responses and standard errors for each of the experimental conditions are shown in Figure 13. Descriptive analysis reveals that the mean reaction time for trials preceded by clicks is less than that of the trials preceded by no-clicks, 510.5ms (SE = 36.21) and 473.18ms (SE = 21.54), respectively. The reaction times also became longer the more complex the choice type. For choice type 1, the mean reaction time was 438.44ms (SE = 31.43). For choice type 2, mean reaction time was 489.96ms (SE = 24.42) and lastly the mean reaction time for choice type 4 was 547.13ms (SE = 31.31). The reaction times for each of the three gap durations appears to have no significant difference (gap duration 500ms, mean reaction time 492.81ms (SE = 16.23); gap duration 2,000ms, mean reaction time 496.58ms (SE = 29.54) and gap duration 5,000ms, mean reaction time 486.14ms (SE = 24.68). Inspection of Figure 13 suggests that, as in Experiment 1a, reaction times appear to be faster on trials preceded by click trains compared to silence (no-clicks). Again, as in Experiment 1b, this effect of clicks was found in all nine conditions. There also appears to be a significant effect of choice type (1, 2 or 4). However, it is not clear whether there is a significant effect of gap duration (500, 2,000 and 5,000ms). Subsequent statistical analysis was performed to investigate this.

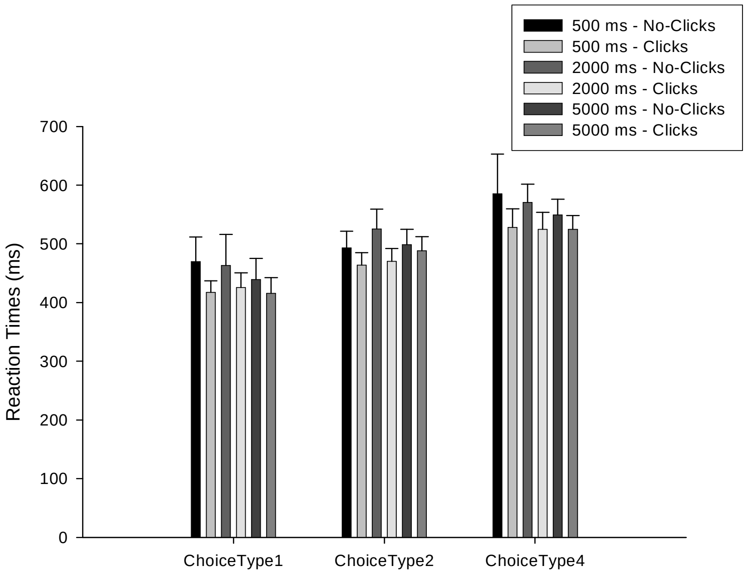


Figure 13: Mean reaction times plotted against choice condition (one, two or four) plus random delay for the clicks and no-clicks conditions of Experiment 1c. Vertical lines show standard error of the mean.

Repeated measures analysis of variance (ANOVAs) were used with one factor being number of choices (1, 2 or 4), the second factor being gap duration (500, 2,000 and 5,000ms) and the third being the presence or absence of clicks. The main effect of clicks just failed to reach statistical significance, $F(1,30) = 3.81$, $p = .06$, $\eta_p^2 = .11$, MSE = 51077.56. So clicks almost demonstrate an effect on reaction time. There was no significant main effect of gap duration, $F(2,60) = .99$, $p = .38$, $\eta_p^2 = .03$, MSE = 5238.73, indicating that the reaction time had not been reduced over time (based on the gap durations used in the present experiment). There was a significant main effect of choice type, $F(2,60) = 33.65$, $p < .001$, $\eta_p^2 = .53$, MSE = 16341.15, which again is the classic finding. There was no significant interaction between either gap duration and clicks/no-clicks, $F(2,60) = 1.05$, $p = .36$, $\eta_p^2 =.03$, MSE = 10535.83 or gap duration and choice type, $F(4,120) = .9$, $p = .47$, $\eta_p^2 = .03$, MSE = 7036.18. There was also no significant interaction between clicks/no-clicks and choice type, $F(2,60) =.18$, $p =.84$, $\eta_p^2 =.006$, MSE = 7818.83. Finally, there was also no significant three-way interaction between gap duration, clicks/no-clicks and choice type, $F(4,120) = 0.32$, $p = .87$, $\eta_p^2 = .01$, MSE = 6546.69.

Figure 14 shows more clearly the effect of clicks for each gap duration across the three choice type responses. Reaction times from the click condition trials were subtracted from the reaction times from the silence condition trials, providing a better representation of the effect of the clicks. Figure 14 confirms again that clicks produce a reduced reaction time on all three choice type responses, although in this experiment the effect just failed to reach overall significance (p = .06). From the graph, there appears to be some suggestion that the effect of clicks on reaction time is being reduced by gap duration even if not significant.

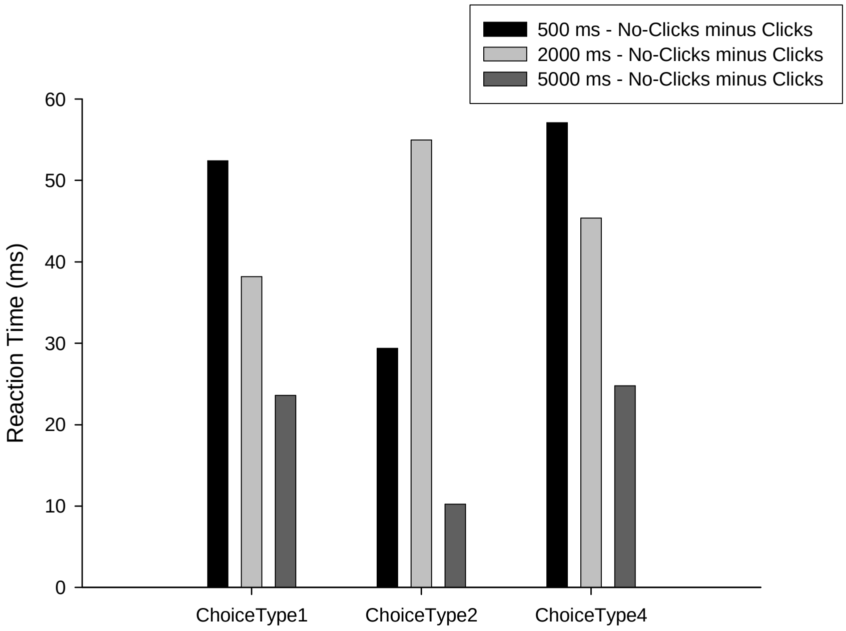


Figure 14: Mean reaction times for each gap duration across the three choice type responses by subtracting the mean reaction times for the click condition trials from the no-click condition trials of Experiment 1c.

5.2.3 Discussion

Consistent with Experiment 1a and b, was the non-significant effect of gap duration. Experiment 1c also found a significant effect of choice type, consistent with the finding from Experiment 1a and b. Compared to Experiment 1a and b, the effect of clicks was not as strong, since the effect of clicks just approached statistical significance. However, the present study still supports the findings from Experiment 1a and b, as the overall pattern suggests that the effect of clicks in reducing reaction time was not reduced by gap duration.

5.3 Overall Conclusion

Overall, Experiment 1a and b demonstrated that click trains reduce reaction time on a 1, 2 and 4 choice reaction time task, compared to trials preceded by silence. Experiment 1a used gap durations after the presentation of the clicks of 500, 2,000 and 5,000ms. Only with a gap duration of 500ms was there no evidence of a reduced reaction time on trials preceded by clicks. Experiment 1b used longer durations than Experiment 1a (namely, 5,000, 7,500 and 10,000ms) and found even stronger evidence for the idea that clicks reduce reaction time since all nine conditions demonstrated this effect. This shows that the effect of clicks persists over time, exactly how long for merits further study.

This unique effect of clicks has only ever been demonstrated by Jones et al. (2010). A possible criticism of Experiment 1a and b is the potential presence of expectancy effects. This is of particular importance with the longest gap duration of 10,000ms. Towards the end of this gap duration, participants will prepare to respond, thus bringing potential bias into the results. In order to reduce this, Experiment 1c used the same gap durations as Experiment 1a with the addition of a random delay between the gap duration and the presentation of the cross participants have to respond to. Consistent with Experiment 1a and b was the non-significant effect of gap duration, again demonstrating that the click effect is persistent over time. However, the clicks' effect on reaction time was not as strong as in Experiment 1a and b, since it was found to *just* approach statistical significance. Lastly, the graph from Experiment 1c does suggest that the effect of clicks is being reduced by duration even if it is not significant.

In sum, the findings from Experiment 1 suggest that there may be a link between information processing and the internal clock. Previous studies have already demonstrated that clicks have an effect on the internal clock (i.e., Jones et al., 2010; Penton-Voak et al., 1996). The present experiments have demonstrated that the clicks also have an effect on information processing which is consistent with the notion that there is a link between this process and the internal clock. Here we found that clicks increased the rate of information processing as evidenced by a decrease in the reaction time response with clicks compared to silence. Since clicks also lengthen subjective duration of time (i.e., Jones et al., 2010), then it may be that the reduction in reaction time was due to the fact that participants had longer *subjective* time in which to react. Determining whether these effects take place *simultaneously* on both the internal clock and information processing is explored in Chapter 9.

Chapter 6

Exploring the Effect of Replacing Clicks with White Noise on Tasks of Reaction Time, Mental Arithmetic and Verbal Estimation

The next set of experiments explored the second research question, namely, is the facilitatory effect on information processing and on internal clock speed specific only to repetitive auditory stimulation? In order to explore this, the same experiments using clicks (Experiments 1a and Jones et al., 2010) were repeated. Only this time the clicks were replaced with white noise. We already know that clicks speed up the internal clock (i.e., Penton-Voak et al., 1996). We have also seen from the experiments carried out in this thesis so far, that clicks can also increase information processing rate as evidenced by a reduced reaction time on trials preceded by clicks compared to trials preceded by no-clicks. Anecdotal as well as experimental evidence suggests that there is a link between the internal clock and information processing (Binkofski & Block, 1996; Jones et al., 2010). Also, later in this thesis (Chapter 9), we investigate whether clicks can *simultaneously* speed up the brain and internal clock speed. However, it might be that the effect of clicks on both information processing and internal clock speed is merely a coincidence. In particular, maybe the effect of clicks on information processing has nothing to do with any changes it may have on the internal clock. This would support the model proposed in Chapter 1, section 1.4.7, figure 4. In order to investigate this issue, we need to replace clicks with something that has been found to have no effect on internal clock speed and then go on to explore whether it has any affect on information processing rate. Essentially, this would explore whether having any pre-stimulus event would have the effect that clicks have demonstrated. Perhaps, the clicks work simply because they are alerting or arousing and then any noise stimulus would induce the same effect as a result.

In order to answer these questions, we first replaced clicks with white noise to see whether it had any effect on internal clock speed. Experiment 2a explored this using a task of verbal estimation. If white noise has no effect on verbal estimates, then it provides an even better control because it has no effect on the internal clock. Experiment 2b and c then went on to see whether white noise had any effect on information processing. If white noise has an effect on information processing, then it would suggest it is not mediated by the internal clock (since it was previously found not to effect internal clock speed). This would also indicate that the effect of clicks is independent from the internal clock. It is important to point out here that it is possible that the clicks and white noise have different underlying mechanisms and therefore, clicks may still be mediated by internal clock speed. On the other hand, if white noise does not have an effect on information processing, then it would suggest that there is something special about the clicks. It is not simply any pre-stimulus event that produces the effect. Instead, the repetitive nature of the clicks would appear to be the crucial component.

6.1 Experiment 2a - The Effect of White Noise in a Task of Verbal Estimation

There is much research to suggest that click trains can increase verbal estimates of duration, thus supporting the notion of the internal clock which suggests under some situations the pacemaker can be speeded up (e.g., Penton-Voak et al., 1996). However, it is not clear whether such an effect can occur on verbal estimations using white noise. Experiment 2a also provided a control for the study by Penton-Voak et al. (1996). In the Experiment, on each trial participants were presented randomly with one of ten different stimulus durations (77, 203, 348, 461, 582, 767, 834, 958, 1,065 and 1,183ms). Upon hearing one of the tones on each trial, participants were required to give their verbal estimation of the duration of the tone by typing in their estimate on the keyboard. On half the trials, participants heard five seconds of white noise and on the other half, five seconds of silence preceding the tone to be estimated. Previous studies have shown that preceding tones or visual stimuli by trains of clicks increased their subjective duration (Burle & Cassini, 2001; Penton-Voak et al., 1996). If the effect of clicks is due to the repetitive nature of the stimulation, then it would be expected that on the trials preceded by white noise, the verbal estimates would be the same as those preceded by silence. White noise is continuous rather than pulsing – so it may not provide the repetitive stimulation given by clicks. As discussed in the introduction to this chapter, Experiment 2a is the first stage in exploring whether any pre-stimulus event would show the same effect as clicks (Jones et al., 2010).

6.1.1 Method

Participants

Seventeen undergraduate students from the University of Manchester participated in exchange for course credit, which was not contingent on performance.

Apparatus

See apparatus for Experiment 1a.

Procedure

At the beginning of each session, instructions appeared on the computer screen, participants were requested to press the space bar to commence the first trial when ready There were two trial conditions (white noise and no-noise). In the white noise condition participants were instructed to look at a fixation cross in the centre of the screen and to begin the trial by pressing the spacebar. Participants were then presented with a 25ms tone (700Hz), followed by a five second period of white noise at 5Hz. A further 25ms tone (700Hz) ended the white noise, which was followed by a random delay between 300 and 1200ms. The fixation cross remained on the screen throughout this process. The tone (500Hz) to be estimated was then presented. There were ten different stimulus durations presented in a random order across trials (77, 203, 348, 461, 582, 767, 834, 958, 1,065 and 1,183ms). After presentation of the test tone, participants were asked to type their estimate of the duration of the tone on the keyboard. Once a response had been made the participants began the next trial after a prompt to press the spacebar when ready to continue.

In the no-noise condition, trials were performed in an identical manner, with the exception that five seconds of no-noise were used in place of the five seconds of white noise. Forty ‘white noise’ trials and forty 'no-noise' trials were presented in a random order across the experimental session. Each of the possible durations of tone occurred 4 times in each condition ('white noise' and 'no-noise').

6.1.2 Results

Verbal estimates

Data from one participant was discarded as all their estimates were less than 10ms. Thus the verbal estimates from sixteen participants were analysed. Figure 15 shows mean verbal estimates (in milliseconds) plotted against stimulus duration for both the ‘white noise’ and ‘no-noise’ conditions. Descriptive analysis showed that the mean verbal estimate for the silence and white noise conditions were 1013.21ms (SE = 128.3) and 1058.04ms (SE = 146.3), respectively. Inspection of Figure 15 suggests than mean estimates increased as an approximately linear function of actual stimulus duration in both conditions. Furthermore estimates of stimulus duration do not appear to differ for the stimuli preceded by white noise than for those preceded by silence. These suggestions were supported by the subsequent statistical analysis.

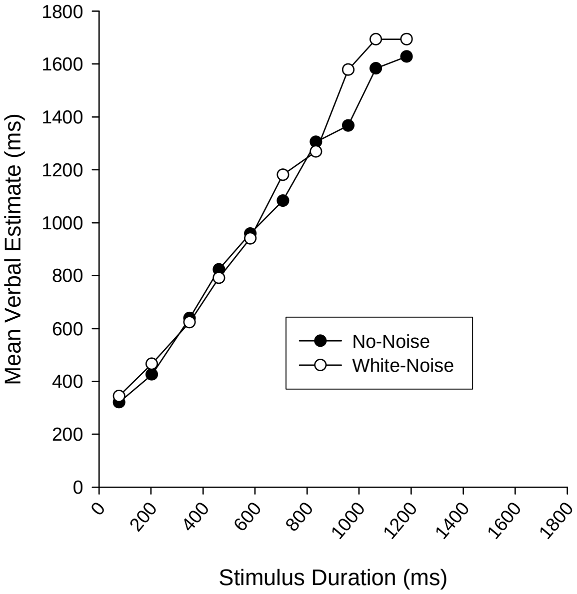


Figure 15: Mean verbal estimates plotted against stimulus duration for the white noise and no-noise conditions of Experiment 2a.

A repeated measures analysis of variance (ANOVAs) was used with one factor being the presence or absence of white noise and the second factor being stimulus duration (77, 203, 348, 461, 582, 767, 834, 958, 1,065 and 1,183ms). There was no significant main effect of white noise/no-noise on estimates, $F(1,15) = 1.87$, $p = 0.19$, $\eta_p^2 = .11$, MSE = 85892.15, which suggests that white noise had a similar effect as no-noise on verbal estimates. There was a significant main effect of stimulus duration, $F(9, 135) = 42.91$, $p < .001$, $\eta_p^2 = .74$, MSE = 172714.93, indicating that with increasing stimulus duration participants estimates of duration were greater. There was no significant white noise/no-noise x stimulus duration interaction, $F(9, 135) = 1.07$, $p < .39$, $\eta_p^2 = .07$, MSE = 46503.5.

Linear contrasts were not carried out here as there was no significant effect of white noise on verbal estimations which is the primary interest. Overall, these results indicate that there was no significant effect of condition on either the intercept or slope of the functions, therefore we did not continue with a slope and intercept analysis based on individual linear regressions.

6.1.3 Discussion

Findings showed that the presence or absence of white noise had no effect on estimates of stimulus duration. This gives rise to the proposition that there is something special about clicks in their effect on the internal clock. It is simply not just any pre-stimulus noise which is causing the effects we have seen. As discussed in the introduction, these findings also strengthen the notion of a relationship between the internal clock and information processing. Another question is what is the nature of operation of the clicks? In other words, what drives the effect of clicks that we have seen? The common explanation is that they are arousing and this idea is explored in later experiments (Experiments 7a, b, c and Experiment 8). Additionally, could it be that the actual repetitive nature of the clicks is the key. This is investigated in Chapter 8, where the frequency and duration of the clicks are manipulated to see whether this has any differential impact on tasks of both reaction time and verbal estimation.

6.2 Experiment 2b - 1, 2 and 4 Choice Reaction Time Task comparing White Noise and No-Noise Manipulations

Experiment 1 showed that click trains made response times faster, implying a speeding up of information processing. These findings were consistent with previous studies (Jones et al., 2010; Burle et al., 1999; Burle et al., 2001). However, the question is, would any pre-stimulus noise show the same effect which click trains do? As a control, Experiment 2b used the same 1, 2, 4 choice reaction time task as Experiment 1a, only it replaced clicks with white noise. There were no set gap durations just a random delay of anything between 300 and 1,200ms. Experiment 2a showed that white noise appears to have no effect on internal clock speed. The present experiment investigated whether white noise has any effect on information processing. Establishing whether white noise has an effect on information processing is an important step in understanding whether the click effect is due to its repetitive nature and also in attempting to understand whether the click effect on reaction time is mediated by the internal clock (see introduction of this chapter for more detailed discussion of this research question).

6.2.1 Method

Participants

Nineteen undergraduate students from the University of Manchester participated in exchange for course credit, which was not contingent on performance.

Apparatus

See Apparatus for Experiment 1a.

Procedure

Identical to Experiment 1a, only Experiment 2b replaced the clicks condition with white noise.

6.2.2 Results

Overall error rate in the choice reaction time conditions was extremely low: out of 1140 trials only 22 (1.91%) were error trials and these were excluded before data analysis. Mean reaction times for the white noise and no-noise conditions and the three different block types (1, 2 and 4 choice types) are plotted in Figure 16. Descriptive analysis reveals that the mean reaction time for trials preceded by white noise was slightly less than that of the trials preceded by no-noise, 495.94ms (SE = 27.87) and 510.21ms (SE = 26.73), respectively. The reaction times also became longer the more complex the choice type. For choice type 1, the mean reaction time was 427ms (SE = 30.76). For choice type 2, mean reaction time was 498.22ms (SE = 25.63) and lastly the mean reaction time for choice type 4 was 584ms (SE = 39.02). Inspection of the data suggests that (a) reaction times increased markedly as the number of choices increased and (b) there was little or no difference between the reaction times for the white noise and no-noise conditions for the choice type 1 and 2. Inspection of Figure 16 suggests little or no effect of white noise on reaction time which was supported by subsequent statistical analysis.

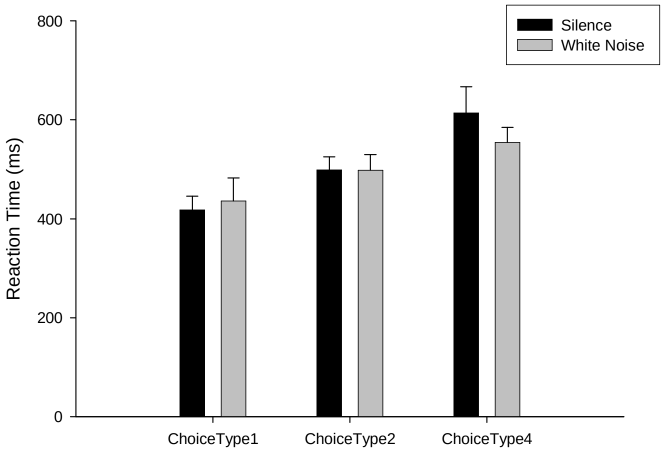


Figure 16: Mean reaction times plotted against choice condition (one, two or four) for the white noise and no-noise conditions of Experiment 2b. Vertical lines show standard error of the mean.

Figure 17 shows more clearly the effect of white noise for each gap duration across the three choice type responses. Reaction times from the white noise condition trials were subtracted from the reaction times from the silence condition trials. This gives a much better representation of the effect of the white noise. Figure 17 shows that white noise had a fairly large effect only when participants were carrying out the four choice type response. It had a very small effect on the two choice type response task and a negative effect during the one choice type response. So, during the one choice type response condition, white noise actually increased participants reaction time compared to the silence trials in the same choice type condition. However, none of these differences turned out to be supported by subsequent statistical analysis.

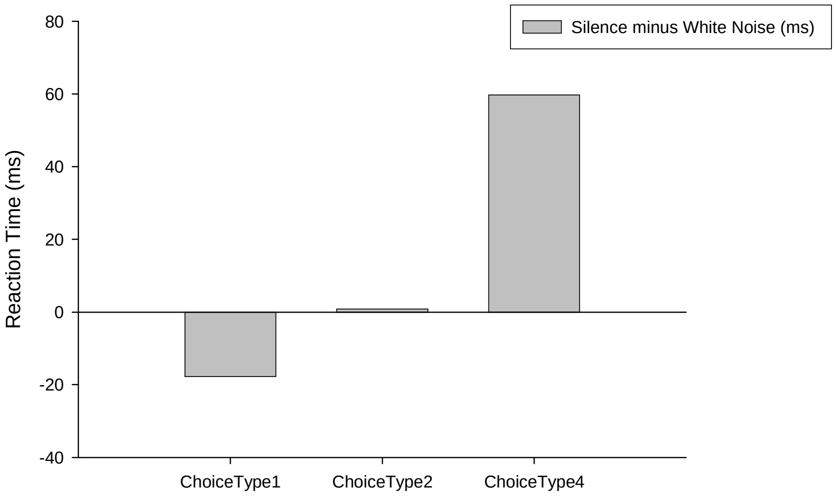


Figure 17: Mean reaction time for the silence condition minus the white noise condition for the three choice types of Experiment 2b.

Repeated measures analysis of variance (ANOVAs) were used with one factor being the presence or absence of white noise and the second factor being choice type (1, 2, or 4). There was a significant main effect of choice type, $F(2,36) = 11.38$, $p < .001$, $\eta_p^2 = .39$, MSE = 20639.06, the typical effect. However, there was no significant main effect of the presence or absence of white noise, $F(1,18) = .78$, $p = .39$, $\eta_p^2 = .04$, MSE = 7477.94, indicating that the effect of white noise and no-noise on reaction time were not significantly different. There was also no significant white noise/no-noise x choice type interaction, $F(2,36) = .95$, $p = .40$, $\eta_p^2 = .05$, MSE = 16419.4.

6.2.3 Discussion

Again, as in Experiments 1 a, b and c, reaction time on this task increased significantly with the number of choices. This effect was found on trials preceded by both white noise and no-noise. Overall however, no effect of white noise was found. This suggests that the effect of speeding up of information processing is unique to click trains (*repetitive* stimulation) as opposed to any noise stimulation giving rise to some arousal to produce the effect previously observed (i.e., Experiments 1a, b and c; Jones et al., 2010). The research question that this experiment addressed was whether the facilitatory effect on information processing is specific only to repetitive auditory stimulus. The finding from the current experiment suggests that it is not simply the presence of *any* pre-stimulus event that produces the effect that clicks have shown on reaction time. As this experiment shows, the reduced reaction time due to clicks appears to be unique to this particular stimulus since when we replaced the clicks with white noise in the same experiment, no difference was found in the reaction time of trials preceded by no-clicks compared to white noise. So it suggests that it is the *repetitive* nature of the clicks that gives rise to the observed effects. It is important to point out here that there could always be some non-repetitive stimuli that does produce the same effect as clicks on reaction time that has not been tested yet.

In sum, the fact that white noise was found to have no effect on reaction time suggests that there is something unique about the clicks. Thus strengthening the theory that the effect of clicks on reaction time/information processing is mediated by the internal clock.

6.3 Experiment 2c - The Effect of White Noise on Mental Arithmetic

Experiment 1 clearly demonstrated the facilitatory effect of clicks on a low-level perceptual-motor time task. What is of interest now, is whether the same effect would be found on a more challenging reaction time task in which longer response latencies would be expected. Jones et al. (2010) sought to address this question using a mental arithmetic task. The overall methodology of this experiment by Jones et al. (2010) was identical to that of Experiment 1c, with the exception of a mathematical addition problem complete with potential answer being presented in one of the four boxes rather than a cross. Participants were instructed to decide whether the answer given on the screen was correct or not as quickly and accurately as possible. Two levels of task complexity were used by changing the number of items to be added. So the easy problems required the addition of two items, whereas the more difficult sums required the addition of three. Overall, participants' response times on the arithmetic task were significantly reduced by clicks, but only when click frequency was 5Hz (See Jones et al., 2010 for more details about this study). However, would any pre-stimulus cue demonstrate this same effect?

In order to explore this, Experiment 2c adopted the same mental arithmetic task as Jones et al. (2010) only in this experiment clicks were replaced with white noise. If white noise speeds up information-processing rates, we would expect the reaction times to the math problems to be shorter than when they are preceded by silence. However, no effect of white noise was found in Experiment 2b, which used a choice reaction time task. Perhaps this can be explained by the relative ease of the task in Experiment 2b and the effect might be found when a more complex task is involved. However, it must be pointed out here that clicks did demonstrate the effect using the easier task. Again if white noise was found not to have an effect then this would imply that the effect of clicks on information processing (reaction time) may be mediated by the internal clock. Thus, strengthening the idea of a link between the internal clock and information processing.

6.3.1 Method

Participants

Twenty-eight undergraduate students from the University of Manchester participated in exchange for course credit, which was not contingent on performance.

Apparatus

See Apparatus for Experiment 1a. White noise was used for the noise trials.

Procedure

The participants completed eighty trials, twenty in each condition (*easy* task/no-noise, *easy* task/white noise, *hard* task/no-noise, *hard* task/white noise). The trials were either preceded by white noise or by an equivalent period without white noise. There were two trial conditions (white noise and no-noise) and two further sub conditions of *easy* and *hard* sums. In the white noise condition, participants were asked to look at a fixation cross in the center of the screen and to begin the trial by pressing the spacebar. Participants were then presented with a 25ms tone (700Hz), followed by a 5 second period of white noise. A further 25ms tone (700Hz) ended the white noise, which was followed by a random delay between 300 and 1,200ms. The fixation cross remained on screen throughout this process. A display then appeared on the monitor in place of the cross, presenting participants with an addition problem composed of either a correct or an incorrect addition (such as ‘2 + 9 = 11’ or ‘2 + 9 = 13’). Participants had to respond whether the sum was correct or incorrect by pressing ‘Y’ (for correct answers) or ‘N’ (for incorrect answers) on the keyboard. Participants were instructed at the beginning of the experiment to keep one finger on each of these two keys throughout the trials. Incorrect responses were accompanied by feedback (a ‘beep’) to maintain the participants’ focus. Once a response had been made the trial was over and participants began the next trial after a prompt to press the spacebar when ready to continue.

In the no-noise condition, trials were performed in an almost identical manner, with the exception that five seconds of silence were used in place of the five seconds of white noise. The addition problems themselves were randomly generated by E-Prime, which either displayed the correct answer to the sum, or an incorrect random answer drawn from a distribution of integer values that fell within 4 of the correct answer. The probability of either condition arising (correct or incorrect) on each trial was 0.5. There were two experimental conditions, *easy* and *hard*. In the *easy* condition the additions were comprised of two single digits (of random numbers generated between 1 and 9) and an answer (e.g. ‘5 + 6 = 11’, or ‘5 + 6 = 14’) whereas *hard* additions involved a three single-digit additions (e.g. ‘5 + 6 + 2 = 13’, or ‘5 + 6 + 2 = 11’). Thus, there were four experimental conditions; ‘*easy* white noise’, ‘*easy* no-noise’, ‘*hard* white noise’ and ‘*hard* no-noise’. Participants received 10 trials in each experimental condition (40 in total), the ordering of which was randomised throughout the experiment to counter such effects as task learning and experimental fatigue. Participants’ response time and accuracy was measured on all trials.

6.3.2 Results

The mean response times and standard errors for each of the experimental conditions are shown in Figure 18. Descriptive analysis reveals that the mean reaction time for trials preceded by white noise was slightly less than that of trials preceded by no-noise, 2027.81ms (SE = 101.65) and 2040.37ms (SE = 97.95), respectively. It is unsurprising that the reaction times for the *easy* condition was less than that of the *hard* condition, 1488.99ms (SE = 77.42) and 2579.19ms (SE = 126.02), respectively. Inspection of the data suggests that, firstly, the response times for all of the *hard* arithmetic problems were clearly longer than for the *easy* ones. Secondly there appeared to be no difference in reaction time in the white noise trials relative to the no-noise trials. These suggestions were supported by the statistical analysis.

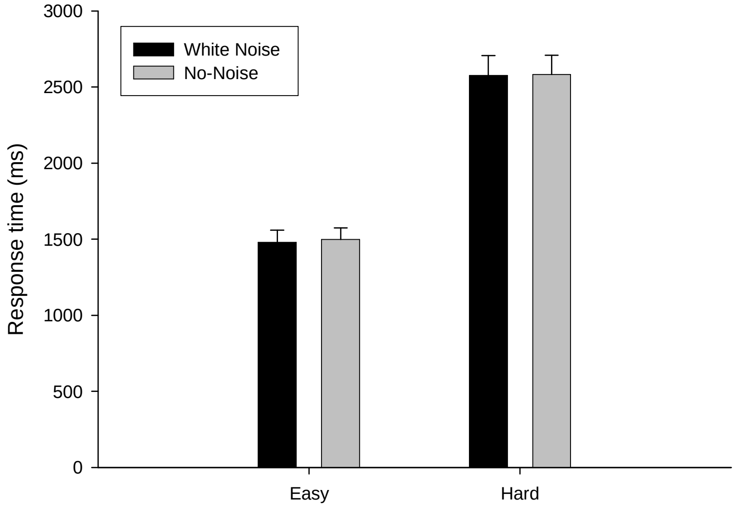


Figure 18: Mean reaction times plotted against difficulty condition (*easy* and *hard*) for the white noise and no-noise conditions of Experiment 2c. Vertical lines show standard error of the mean.

Repeated measures analysis of variance (ANOVAs) were used with one factor being the presence or absence of white noise and the second factor being task difficulty (*easy* and *hard*). There was a main effect of task difficulty, $F(1,27) = 251.02$, $p < .001$, $\eta_p^2 = .9$, MSE = 132577.27, which is consistent with the expected effect that reaction times would be longer for the *hard* condition compared to the *easy* condition. However, there was no main effect of white noise/no-noise, $F(1,27) = .19$, $p = .67$, $\eta_p^2 = .01$, MSE = 23548.4, which confirms that white noise had no effect on reaction times. There was no task difficulty x white noise/no-noise interaction, $F(1,27) = .05$, $p = .82$, $\eta_p^2 = .00$, MSE = 23267.39.

6.3.3 Discussion

Unlike click trains, white noise appears to have no effect on reaction times when participants are asked to make a yes or no decision as to whether the sum they are given is correct or not. This is consistent with the findings from Experiment 2b, which also used white noise on a simpler choice reaction time task and found no effect. We have seen now that white noise does not affect internal clock speed, nor does it affect information processing rate in two different tasks. Therefore, this supports the unique nature of clicks and stresses the importance of the repetitive nature of the stimuli in producing its effect. It is not merely any pre-stimulus event that can produce the observed effects on internal clock speed and information processing. The findings from the three white noise experiments also strengthens the idea that the click effect on information processing is mediated by the internal clock. If white noise *had* an effect on information processing, then it would suggest that is was not mediated by the internal clock (since it was previously found not to affect internal clock speed, Experiment 2a). Therefore, if white noise *had* demonstrated an effect on information processing, then you could argue that the effect was due to the arousing or alerting nature of the white noise stimulus and therefore, the same could be argued to explain the effect of clicks. However, as we have seen, it is the *repetitive nature* of the clicks that seems to be important in driving the speed of both the internal clock and information processing.

Chapter 7

Exploring the Effect of Actively Processing Click Trains compared to Passively Processing Click Trains

The main purpose of Experiment 3a and b in this section was to further explore the relationship between information processing and the internal clock. It does this by introducing a third pre-stimulus noise condition which manipulates how the clicks are processed by the participant. Experiment 3a employs a 1, 2 and 4 choice reaction time task and Experiment 3b employs a verbal estimation task. In both experiments, half the participants took part in an experimental condition in which they were asked whether there was a shift in the pitch of the clicks for both click conditions (normal clicks, clicks with a change in pitch shift). Therefore, participants in this instance have to actively process the clicks in order to determine whether there was indeed a change in pitch, this is the ‘Ask’ experiment. In the ‘Don’t Ask’ experiment, the participants were never asked to report whether there was a shift in pitch of the clicks. There was also a third noise condition in both experiment groups (Ask and Don’t Ask), namely, no-clicks. Experiment 3a explored the effect of click processing on information processing, while Experiment 3b explored the effect on the internal clock. If this change in how the clicks are processed showed an effect in both experiments in the Ask experimental group, then it would strengthen the idea of a link between information processing and the internal clock. However, if the active processing of clicks only demonstrated an effect in one experiment and not the other, then it would weaken the idea that there is a link. However, in this instance, it could still be possible that there is a strong link between the two and that perhaps actually having to *process* the clicks interferes with normal information processing, leaving the internal clock processes spared.

The following two experiments also explored the role of arousal and attention in mediating the effect of clicks on both internal clock speed and information processing. Wearden, O’Rourke, Matchwick, Min and Maeers (2009) using a task-switching paradigm, explored the use of a pre-stimulus event that *itself*, requires processing followed by the subsequent time judgment task. Zakay and Block (2004) postulate that (p. 324) since task-switching requires attentional resources, the task-switching paradigm allows the unique investigation into the impact of attention on time perception. Wearden et al. (2009) investigated the effect of a task-switch on estimates of the duration of six tones (77, 203, 461, 767, 958 and 1,183ms). They were either presented alone (“no-numbers” condition), or after the addition of rapidly presented digits (“numbers” condition). There were two groups and they differed in the difficulty of the addition task. In the “Easy” group, participants were required to add up digits ranging from 1 to 5. The “difficult” group had to add up digits ranging from 10 to 15. Findings showed that preceding a tone with a pre-stimulus event which involves processing to generate a later response can, but not always, cause underestimation of the tonal duration. In the “easy” group, the pre-stimulus event had no significant effect. However, in the “difficult” addition, duration estimates were significantly reduced. Additionally, the underestimation of tonal duration became greater with increasing stimulus durations, indicating a slope effect. Therefore, a task-switching deficit was found when participants were required to process a pre-stimulus event before the timing judgment.Wearden et al. (2009) argue that these findings may be explained by a reduction in the pacemaker speed with task-switching, consistent with the “attentional gate” model (Block & Zackay, 1996; Monsell, 2003). The effect of task-switching on the attentional gate results in less pulses passing per unit of time after a pre-stimulus event which subsequently produces underestimation of duration.

Experiments 3a and 3b of this thesis attempt to explore these ideas further using processing of clicks as the task-switching experimental condition as opposed to addition tasks used by Wearden et al. (2009) in the task of verbal estimation. Also we explore this effect on reaction time (information processing) *as well as* verbal estimation (internal clock speed) (Experiment 3a and 3b, respectively). The findings may go someway to explaining the underlying mechanisms of the effect of clicks, specifically, whether attention and/or arousal are involved.

7.1 Experiment 3a - The Effect of Processing versus Passively Experiencing Clicks in a 1, 2 and 4 Choice Reaction Time Task

Experiment 3a examined whether the active processing of the clicks had any effect on reaction time compared to conditions where the participant passively listens to clicks or is simply presented with no-clicks. In order to do this, a 1, 2 and 4 choice reaction time experiment (used previously, Jones et al., 2010) was employed.

7.1.1 Method

Participants

Thirty-two participants took part and were compensated with 3 course credits for their time and effort which was not contingent on performance.

Apparatus

See apparatus for Experiment 1a.

Procedure

Experiment 3a was identical to Experiment 1a, only in this experiment each participant served in only one of two experimental groups both of which consisted of three block types (1, 2 or 4 choice) and each block consisted of ninety trials (30 click, 30 no-click and 30 clicks with a pitch shift trials randomly intermixed). One of the experimental groups (Ask) involved the participant being asked after each click trial (both clicks and click shift conditions) whether there was a pitch shifted click. In the click-change condition, a pitch shift of 750Hz in the clicks occurs. The click rate was always 5Hz and the pitch shift randomly occurred somewhere between the 4th to the 22nd 'click' (inclusive), The other experimental group (Don’t Ask) was the opposite, in that participants were not asked after either click group whether there was a pitch shifted click. So, participants in the ‘Ask’ group also had a presentation of a screen after they made their reaction time response which asked them whether there was a pitch shift change in the clicks. To which they responded by pressing ‘Y’ for yes or ‘N’ for no. Participants were instructed when a new block type was beginning via instructions on the monitor and were asked to press the space bar to commence the first trial for the block. Throughout the experiment the participants rested their dominant hand on the response box with their fingers resting on each of the response keys.

7.1.2 Results

<u>Ask Vs Don’t Ask</u>

Figure 19 shows mean reaction time plotted against choice for all conditions from the Ask and Don’t Ask experiments. Inspection of the figures clearly reveals that the mean reaction times for all of the Ask conditions were higher than those for the Don’t Ask group at all three choice levels.

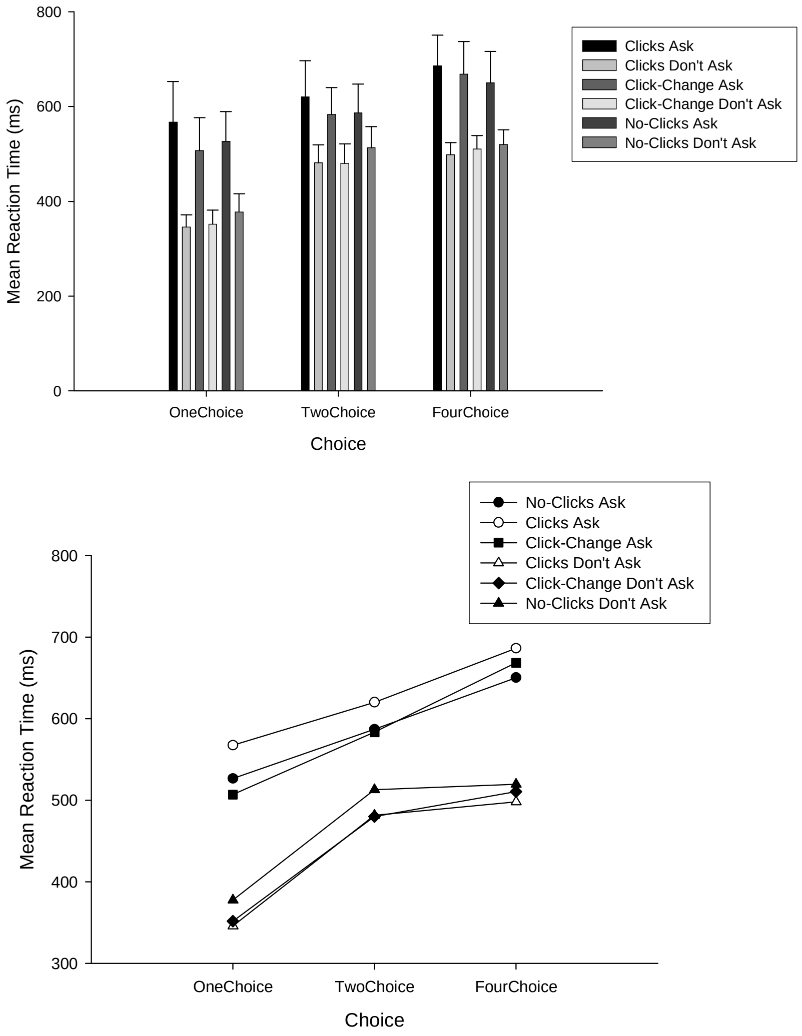


Figure 19 (Top): Mean reaction time plotted against choice for the Ask and Don't Ask experiments. **(Bottom):** Mean reaction time plotted against choice for all conditions from the Ask and Don't Ask experiments. Both figures for Experiment 3a.

We then performed a repeated measures analysis of variance (ANOVAs) with choice (1, 2 or 4) and noise type (clicks, no-clicks and click-change) as within subject factors and instruction (Ask or Don't Ask) as the between subjects factor. There was significant main effect of choice, *F*(2,58) = 13.32, $p < .001$, $\eta_p^2 = .32$, MSE = 37236.62 and a significant main effect of instruction, *F*(1,29) = 4.50, $p < .05$, $\eta_p^2 = .89$, MSE = 332002.85. These two main effects suggest that reaction time increased with choice type complexity and with instruction (Ask and Don't Ask). There was no significant effect of noise type, *F*(2,58) = 1.49, $p = .23$, $\eta_p^2 = .05$, MSE = 4479.04, which suggests that overall reaction time did not differ between the three noise types. There was a significant noise type x instruction interaction, *F*(2,58) = 5.68, $p < .01$, $\eta_p^2 = .16$, MSE = 4479.04, which suggests that the effect of noise type was dependent on type of instruction. There were no other significant two or three way interactions. The data from the Ask and Don't Ask experiments were then analysed separately.

<u>Ask Condition</u>

The data from all sixteen participants was analysed. Figure 20 shows the mean reaction time plotted against choice condition for the no-clicks, clicks and click-change conditions. Descriptive statistics show that the mean reaction times for the 1, 2 and 4 choice types were 533.61ms (SE = 70.84), 596.79ms (SE = 63.59) and 668.28ms (SE = 66.11), respectively. That reaction time increased with task difficulty is not surprising. Of interest are the mean reaction times for the three noise conditions for each choice type. For choice type one, the mean reaction times for no-clicks, clicks and click-change were 526.58ms (SE = 62.78), 567.32ms (SE = 85.32) and 506.93ms (SE = 69.75), respectively. For choice type two, the mean reaction times for no-clicks, clicks and click-change were 587.02ms (SE = 60.43), 620.05ms (SE = 76.61) and 583.3ms (SE = 56.93), respectively. Lastly, for choice type four, the mean reaction times for no-clicks, clicks and click-change were 650.31ms (SE = 66.32), 686.17ms (SE = 64.46) and 668.36ms (SE = 68.67), respectively. Inspection of the figures suggest that mean reaction time increased with choice, also that the mean reaction time was higher for the clicks condition compared to the click-change and no-clicks conditions at all three choice levels. There appears to be little or no difference between the no-clicks and click-change conditions. Further statistical analyses were performed to determine whether there are any significant differences between the different conditions.

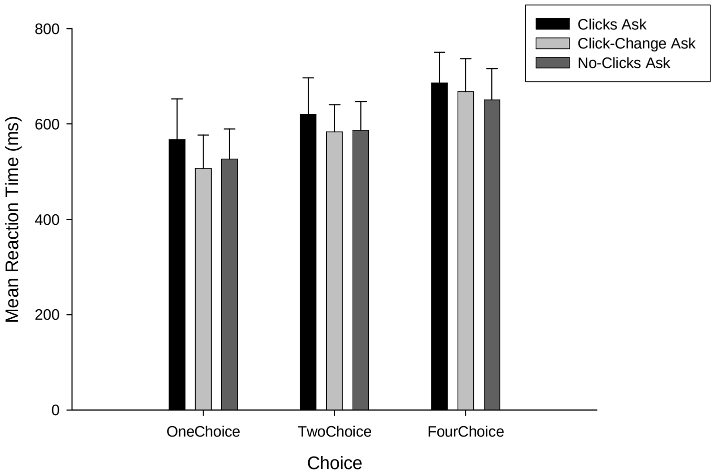


Figure 20: Mean reaction time plotted against choice condition for the no-click, clicks and click-change conditions of Experiment 3a.

A repeated measures ANOVA was conducted with two factors, choice (with three levels; 1, 2 or 4 choice) and noise type (with three levels, clicks, click-change, no-clicks) as within subject variables. There was a significant main effect of choice, $F(2,30) = 3.73$, $p < .05$, $\eta_p^2 = .2$, MSE = 58400.77. There was also a significant main effect of noise type, $F(2,30) = 3.44$, $p < .05$, $\eta_p^2 = .19$, MSE = 6536.8. There was no significant choice x noise type interaction, $F(4,60)= .55$, $p = .70$, $\eta_p^2 = .04$, MSE = 4022.81.

Paired-samples *t* tests were then performed, examining the differences in reaction times between the no-clicks, clicks and click-change in each choice type. For choice type one, the results (Bonferroni corrected) indicated no significant difference, $t(15) = -1.03$, $p = .96$ between the no-clicks and clicks conditions. There was also no significant difference, $t(15) = 2.18$, $p = .14$, between the clicks and click-change conditions or between the click-change and no-clicks conditions, $t(15) = .72$, $p = 1.46$. A paired-samples *t* test was also performed in the same way for choice type two. The results indicated no significant difference, $t(15) = -1.3$, $p = .64$, between the no-clicks and clicks conditions. There was also no significant difference, $t(15) = 1.21$, $p = .73$, between the clicks and click-change conditions or between the click-change and no-clicks conditions, $t(15) = .2$, $p = 2.52$. Again, paired-samples *t* tests were carried out for choice type four. The difference between the no-clicks and clicks condition was approaching significance, $t(15) = -2.59$, $p = .06$. There was no significant difference between the clicks and click-change conditions, $t(15) = 1.29$, $p = .65$. Lastly, there was no significant difference, $t(15) = -1.86$, $p = .25$, between the click-change and no-clicks conditions. These findings strongly suggest that having to process the clicks suppresses the typical effect that clicks normally have on reaction time, namely, making response times faster. Neither the click-change nor the clicks conditions demonstrated this effect.

Don’t Ask Condition

Figure 21 show the mean reaction time plotted against choice condition for the no-clicks, clicks and click-change conditions. Descriptive statistics show that the mean reaction times for the 1, 2 and 4 choice types were 358.38ms (SE = 30.42), 491.48ms (SE = 40.47) and 509.37ms (SE = 28.24), respectively. That reaction time increased with task difficulty is not surprising. Of interest are the mean reaction times for the three noise conditions for each choice type. For choice type one, the mean reaction times for no-clicks, clicks and click-change were 377.57ms (SE = 38.28), 345.76ms (SE = 25.25) and 351.81ms (SE =

29.4), respectively. For choice type two, the mean reaction times for no-clicks, clicks and click-change were 512.82ms (SE = 44.78), 481.59ms (SE = 37.46) and 480.04ms (SE = 41.39), respectively. Lastly, for choice type four, the mean reaction times for no-clicks, clicks and click-change were 519.67ms (SE = 31.6), 497.91ms (SE = 25.9) and 510.54ms (SE = 28.63), respectively. The data from one participant was removed from the analysis as the reaction times indicated that they had not attended to the task. This participant's lack of attention to the task was evidenced by notably large reaction times. The data from the remaining 15 participants was analysed. Inspection of these figures suggests that mean reaction time increased with choice. It also appears that the reaction times for the silence condition are higher across all three choice conditions compared to clicks and click-change conditions and there appears to be little or no difference between the click and click-change conditions at any choice level. Further statistical analysis was performed to determine whether there were any significant differences between the different conditions.

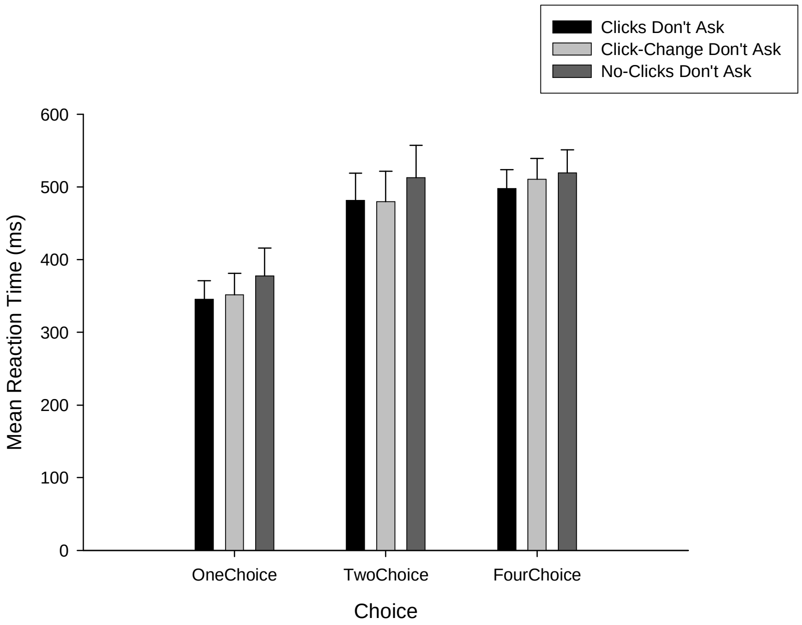


Figure 21: Mean reaction time plotted against choice condition for the no-click, clicks and click-change conditions of Experiment 3a.

A repeated measures analysis of variance (ANOVAs) was conducted with two factors, choice (with three levels; 1, 2 or 4 choice) and noise type (with three levels, clicks, click-change, no-clicks) as within subject variables. There was a significant main effect of choice, $F(2,28) = 21.03$, $p < .001$, $\eta_p^2 = .6$, MSE = 14560.75. There was also a significant main effect of noise type, *F*(2,28) = 4.42, $p < .05$, $\eta_p^2 = .24$, MSE = 2274.29. There was no choice x noise type interaction, *F*(4,60) = .79, *p* = .53, $\eta_p^2 = .05$, MSE = 723.42. Responses were also examined for their speed across different conditions. Paired-samples *t* tests were performed, examining the differences in reaction times between the no-clicks, clicks and click-change conditions in each choice type. For choice type one, the results (Bonferroni corrected) indicated no significant difference, *t*(14) = 1.75, *p* = .31 between the no-clicks and clicks conditions. There was also no significant difference, *t*(14) = -.64, *p* = 1.6, between the clicks and click-change conditions or between the click-change and no-clicks conditions, *t*(14) = 2.08, *p* = .17. A paired-samples *t* test was also performed in the same way for choice type two. The results indicated no significant difference, *t*(14) = 1.77, *p* = .3, between the no-clicks and clicks conditions. There was also no significant difference, *t*(14) = .12, *p* = 2.71, between the clicks and click-change conditions or between the click-change and no-clicks conditions, *t*(14) = 2.63, *p* = .06. Again, paired-samples *t* tests were carried out for choice type four. There was no significant difference, *t*(14) = 2.12, *p* = .16, between the no-clicks and clicks condition or between the clicks and click-change conditions, t(14) = -1.66, p = .35. Lastly, there was no significant difference, *t*(14) = .81, *p* = 1.29, between the click-change and no-clicks conditions. These findings suggest there is no difference between the noise conditions across all three choice types.

7.1.3 Discussion

Findings from the Ask vs Don’t Ask analysis showed that there was a significant effect of choice type and a significant overall effect of instruction (Ask vs Don’t Ask) on reaction time. There was no significant effect of noise type (clicks, no-clicks & click-change) when taking the Ask and Don’t Ask groups together. For the Ask condition separately, reaction time increased with choice type complexity (1, 2 or 4 choice). Repeated measures analysis showed that there was no difference between the click-change and no-clicks condition and between the clicks and no-clicks. Findings did show a significant difference between the clicks and the click-change. However, further analysis revealed that there were *no* significant differences between the no-clicks, clicks and click-change conditions. For the Don’t Ask group, reaction time increased with choice type complexity (1, 2 or 4 choice). Repeated measures analysis showed that there was a significant main effect of noise type. However, as found in the Ask group, further analysis revealed there were *no* significant differences between the no-clicks, clicks and click-change conditions. Lastly, reaction times were longer across all conditions in the Ask group which strongly suggests that this manipulation of the clicks had an effect on information processing.

These findings suggest that having to process clicks in the pitch shift condition actually mitigates the effect of clicks in the non-pitch shift condition to such a degree that reaction times actually becomes longer than if normal clicks were not present at all. This is consistent with the findings of Wearden et al. (2009) who found that a task-switching condition resulted in a slowing down of the internal clock. If we apply the results by Wearden et al. (2009) to the present study, we can perhaps explain the findings of the Ask experiment condition by arguing that the processing clicks condition resulted in a reduced pacemaker speed. Plus, that this reduced pacemaker speed was strong enough to cause the reverse effect on reaction time that clicks have previously been found to have (i.e., Jones et al., 2010). This can perhaps also explain why there was no beneficial effect of clicks in the Don't Ask group. Perhaps, even just the presence of a change/manipulation of the clicks in the click-change condition is enough to reduce pacemaker speed in both click conditions but to a lesser extent compared to the Ask group. It is also possible that participants are attending to (consciously processing) the click changes themselves in the Don't Ask condition.

A possible explanation for the difference in the effect of the controlled processing (Ask condition) and the automatic processing (Don't Ask condition) is that the Ask condition may have increased the duration of the response (RT) because the conscious processing of the clicks interfered with the speed at which each of the five stages of reaction time were completed. Classically, reaction time is decomposed in stages of processing. Theios (1975) proposed a decomposition of five stages: stimulus detection, identification, stimulus-response association, response programmation and execution. Roberts and Sternberg (1992) argued that since there is no temporal overlap between the five stages of processing, the reaction time is therefore the sum of the durations of these five stages. In other words, increased reaction time is a result of an increase in the duration of one or more of these five stages. In this respect, processing of clicks may have increased the duration of one or more of these five stages during processing.

In sum, having to process the clicks in the Ask group produced greater reaction times across all conditions compared to the Don't Ask group. So clicks did not have the typical effect of reducing reaction time (i.e., Jones et al., 2010; Chapter 5, Experiment 1a and b). This suggests that the Ask/Don't Ask manipulation had much greater effect than any difference between the noise conditions. Clicks were also found to have no beneficial effect on reaction time in the Don't Ask group, compared to the no-clicks and click-change conditions. Although there was a trend for the no-click conditions to be slower than the click conditions, this was not borne out by t-test analysis. Experiment 3a, therefore, shows that this manipulation of clicks impacts on information processing.

7.2 Experiment 3b - The Effect of Processing versus Passively Experiencing Clicks in a Task of Verbal Estimation

Experiment 3a shows that the processing of clicks and the presence of a click change manipulation is enough to eliminate the beneficial effect of clicks that have previously been demonstrated (i.e., Jones et al., 2010). However, this was found on a 1, 2 and 4 choice reaction time task, so demonstrating such a manipulation affects information processing. The question is whether it also affects the internal clock which would strengthen the idea of a link between these two processes. Experiment 3b, therefore, used a task of verbal estimation to investigate this.

7.2.1 Method

Participants

Ninety-four undergraduate students from the University of Manchester participated in exchange for course credit, which was not contingent on performance. Forty-seven in each experimental group (Ask versus Don't Ask).

Apparatus

See Apparatus for Experiment 1a.

Procedure

At the beginning of each session, instructions appeared on the computer screen, participants were requested to press the space bar to commence the first trial when ready There were three trial conditions (click, click-change and no-click). In the click condition participants were instructed to look at a fixation cross in the centre of the screen and to begin the trial by pressing the spacebar. Participants were then presented with a 25ms tone (700Hz), followed by a 5-s period of clicks at 5Hz (each click was 10ms long). A further

25ms tone (700Hz) ended the clicks, which was followed by a random delay between 300 and 1200ms. The fixation cross remained on screen throughout this process. The tone (500Hz) to be estimated was then presented. There were 10 different stimulus durations presented in a random order across trials (300, 478, 567, 656, 745, 834, 923, 1,012, 1,101 and 1,300ms). After presentation of the test tone participants were asked to type their estimate of the duration of the tone on the keyboard. Once a response had been made the participants began the next trial after a prompt to press the spacebar when ready to continue. Participants in the ‘Ask’ group also had a presentation of a screen after they entered their response which asked whether there was a pitch shift change in the clicks, they responded pressing ‘Y’ if they did or ‘N’ if they did not. As in Experiment 3a, in the click-change condition, a pitch shift of 750Hz in the clicks occurs. The click rate was always 5Hz and the pitch shift randomly occurs somewhere between the 4th to the 22nd 'click' (inclusive), Lastly, participants were given a range from which they could select their verbal estimates. This range was between 250 and 1,350ms. If participants made a response outside of this range, they were reminded of the range and were not able to continue until they had entered a ‘correct’ response.

7.2.2 Results

Ask Vs Don’t Ask

Figure 22 shows mean reaction time plotted against choice for all conditions from the Ask and Don’t Ask experiments. Inspection of Figure 22 reveals that the mean verbal estimates do not differ across the three noise condition between both experimental groups (Ask versus Don’t Ask).

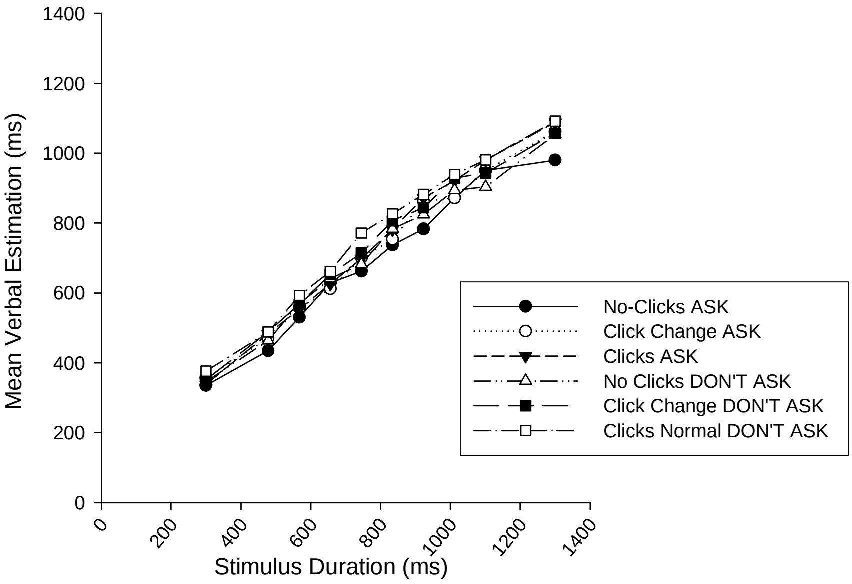


Figure 22: Mean verbal estimates for each of the ten stimulus durations plotted for the three noise conditions for the two experimental conditions (Ask versus Don't Ask) of Experiment 3b.

For the sake of completeness we performed a repeated measures analysis of variance (ANOVAs) with stimulus duration and noise type (no-clicks, click-change, clicks) as within subject factors and instruction (Ask or Don't Ask) as the between subjects factor. There was significant main effect of noise type, $F(2,184) = 25.64$, $p < .001$, $\eta_p^2 = .22$, MSE = 177723.83. There was also a significant main effect of stimulus duration, $F(9,828) = 412.95$, $p < .001$, $\eta_p^2 = .82$, MSE = 34117.98. However, there was no significant noise type x instruction interaction, $F(2,184) = .46$, $p = .63$, $\eta_p^2 = .01$, MSE = 177723.83. Also, there was no significant stimulus duration x instruction interaction, $F(9,828) = .68$, $p = .73$, $\eta_p^2 = .01$, MSE = 34117.98. There was no significant noise type x stimulus duration x instruction three way interaction, $F(18,1656) = 1.34$, $p = .15$, $\eta_p^2 = .01$, MSE = 11089.13. With the between subjects variable, instruction, there was a main effect, $F(1,92) = 2196.84$, $p < .001$, $\eta_p^2 = .96$, MSE = 677249.56.

The data from the Ask and Don't Ask experiments were then analysed separately.

<u>Process (Ask)</u>

Clicks Vs Click-Change Vs No-Clicks

Figure 23 shows the mean verbal estimates for each condition plotted against actual stimulus duration. Descriptive statistics show that the mean verbal estimates for the no-clicks, click-change and clicks conditions were 691.4ms (SE = 22.29), 720.02ms (SE = 22.88) and 734.5ms (SE = 22.27), respectively. Inspection of the figure suggest that mean verbal estimates increased linearly with the duration of the stimulus. Secondly, the figure suggests that there is a difference between the mean estimates for the three conditions. Specifically, that the participants appear to give longer verbal estimates of duration for the trials preceded by clicks and click change compared with the trials preceded by no-clicks. These suggestions were supported by the subsequent statistical analyses.

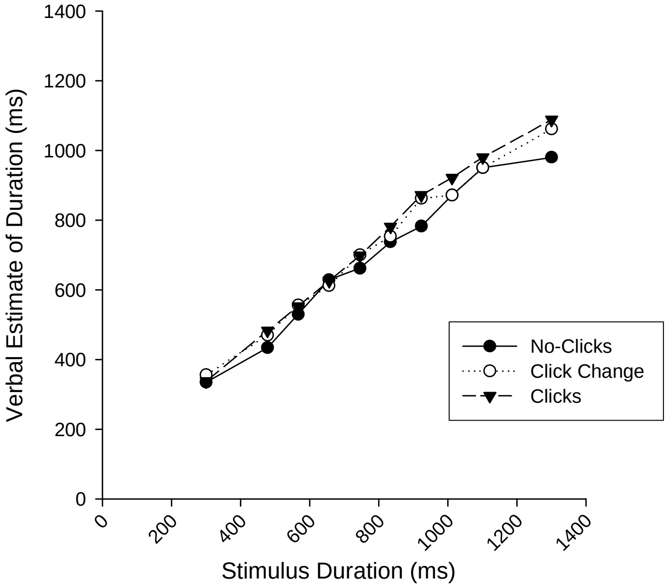


Figure 23: The relationship between the mean verbal estimates of duration (ms) against the actual stimulus durations (ms) for the Ask (Process) experiment of Experiment 3b.

The data were analysed in two ways, firstly the mean estimate data was investigated. Secondly linear regression for each individual participant for each condition were calculated and the slope and intercept values were analysed.

Mean Verbal Estimates Analysis

Clicks Vs Click-Change Vs No-Clicks

A repeated measures analysis of variance (ANOVAs) with noise type (clicks, click-change, no-clicks) and stimulus duration (the 10 different stimulus durations) as within subject factors was carried out. There was a significant main effect of noise type, $F(2,92) = 18.35$, $p < .001$, $\eta_p^2 = .29$, MSE = 12325.21. There was a significant main effect of stimulus duration, $F(9,414) = 211.97$, $p < .001$, $\eta_p^2 = .82$, MSE = 33649.44. There was also a noise type x stimulus duration interaction, $F(18,828) = 1.68$, $p < .04$, $\eta_p^2 = .04$, MSE = 12288.39.

Another repeated measures analysis of variance (ANOVAs) with noise type (no-clicks and click-change) and stimulus duration (the 10 different stimulus durations) as within subject factors was conducted. There was a significant effect of noise type, $F(1,46) = 15.06$, $p < .001$, $\eta_p^2 = .25$, MSE = 12784.39. There was a significant effect of stimulus duration, $F(9,414) = 162.99$, $p < .001$, $\eta_p^2 = .78$, MSE = 27579.37. There was also a noise type x stimulus duration interaction, $F(9,414) = 2.03$, $p < .05$, $\eta_p^2 = .04$, MSE = 12018.69.

Further, a repeated measures analysis of variance (ANOVAs) with noise type (click and no-clicks) and stimulus duration (the 10 different stimulus durations) as within subject factors was conducted. There was a significant main effect of noise type, $F(1,46) = 27.51$, $p < .001$, $\eta_p^2 = .37$, MSE = 15868.25. There was also a significant main effect of stimulus duration, $F(9,414) = 201.42$, $p < .001$, $\eta_p^2 = .81$, MSE = 23857.59. There was also a noise type x stimulus duration interaction, $F(9,414) = 2.27$, $p < .05$, $\eta_p^2 = .05$, MSE = 12715.55.

Lastly, a repeated measures analysis of variance (ANOVAs) with noise type (clicks and click-change) and stimulus duration (the 10 different stimulus durations) as within subject factors was conducted. There was a significant main effect of noise type, $F(1,46) = 5.92$, $p < .05$, $\eta_p^2 = .11$, MSE = 8323. There was also a significant main effect of stimulus duration, $F(9,414) = 177.1$, $p < .001$, $\eta_p^2 = .79$, MSE = 28150.32. There was no noise type x stimulus duration interaction, $F(9,414) = .73$, $p = .68$, $\eta_p^2 = .02$, MSE = 12130.92. Having found a significant effect of noise type x stimulus duration interaction, linear regression analyses were then performed on the slopes and intercepts of each participant.

Linear Regression Analysis – Process (Ask)

Slope Values

Individual linear regressions for each participant for each condition were then calculated. Figure 24 shows the mean slope values for each condition. Descriptive analysis showed that the mean slope values for the no-clicks, click-change and clicks condition were, .71 (SE = .04), .73 (SE = .04) and .77 (SE = .04), respectively. Inspection of Figure 24 suggests that there may be significant differences between the slope values of the conditions. This suggestion was supported by subsequent statistical analysis.

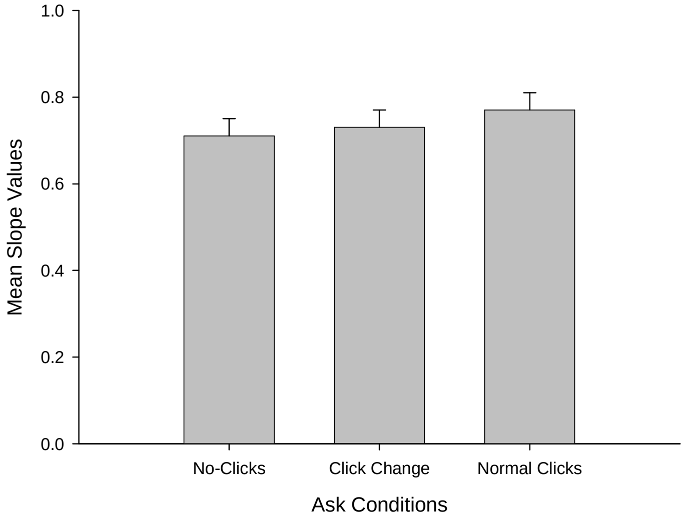


Figure 24: Mean slope values plotted against condition (no-clicks, click-change and clicks) of Experiment 3b.

A repeated measures ANOVA with one factor; noise type (no-clicks, click-change, clicks) was conducted on the mean slope values. There was a significant main effect of noise type, $F(2,92) = 4.13$, $p < .05$, $\eta_p^2 = .08$, MSE = .01.

Paired-samples *t* tests found no significant difference between the slope of the no-click condition and the click-change condition, $t(46) = -.62$, $p = .54$. However, there was a significant difference between the slope of the no-click condition and the click condition, $t(46) = -3.23$, $p < .05$ and between the two click conditions, $t(46) = -2.16$, $p < .05$.

Intercept Values

Figure 25 shows the mean intercept values for each condition. Descriptive statistics showed that the mean intercept values for the no-clicks, click-change and clicks conditions were, 129.23ms (SE = 25.51), 141.84ms (SE = 32.93) and 121.39ms (SE = 29.51), respectively. Inspection of Figure 25 suggests that there may be a significant difference between the intercept values of any of the conditions. This suggestion, however, was not supported by subsequent statistical analysis.

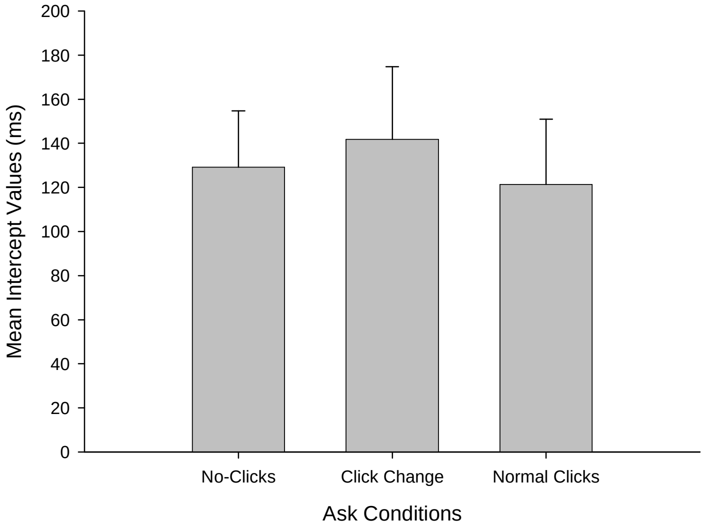


Figure 25: Mean intercept values (ms) plotted against condition (no-clicks, click-change, clicks) of Experiment 3b.

A repeated measures ANOVA with one factor, noise type (no-clicks, click-change, clicks) was conducted on the mean intercept values. There was no significant main effect of noise type, $F(2,92) = .61$, $p = .55$, $\eta_p^2 = .01$, MSE = 8257.18.

Paired-samples *t* tests found no significant difference between the intercept of the no-click condition and the click-change condition, $t(46) = -.56$, $p = .58$, between the intercept of the no-click condition and the click condition, $t(46) = .46$, $p = .65$ and between the two click conditions, $t(46) = 1.31$, $p = .2$.

Non-Process (Don't Ask)

Figure 26 shows the mean verbal estimates for each condition plotted against stimulus duration. Descriptive statistics show that the mean verbal estimates for the no-clicks, click-change and clicks conditions were 716.05ms (SE = 22.29), 735.39ms (SE = 22.88) and 760.78ms (SE = 22.27), respectively. Inspection of the figure suggest that mean verbal estimates increased linearly with the duration of the stimulus. Secondly, the figure suggests that estimates were higher for the two click conditions. This suggestion was supported by subsequent statistical analyses.

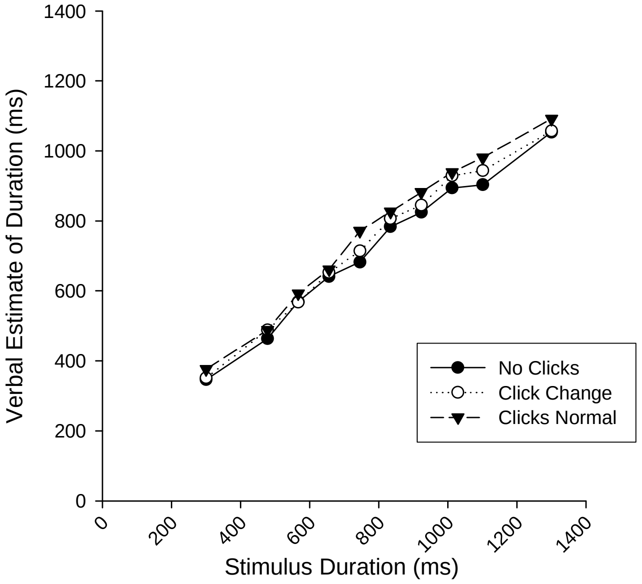


Figure 26: The relationship between the mean verbal estimates of duration (ms) against the actual stimulus duration (ms) for the Don't Ask (non-process) experiment of Experiment 3b.

The data were analysed in two ways, firstly the mean estimate data was analysed. Secondly linear regression for each individual participant for each condition were calculated and the intercept values, not slope values, were analysed.

Mean Verbal Estimates Analysis

Clicks Vs Click-Change Vs No-Clicks

A repeated measures analysis of variance (ANOVAs) with noise type (no-clicks, click-change, clicks) and stimulus duration (the 10 different stimulus durations) as within subject factors was conducted. There was a significant main effect of noise type, $F(2,92) = 10.23$, $p < .001$, $\eta_p^2 = .18$, MSE = 23122.45. There was also a significant main effect of stimulus duration, $F(9,414) = 201.8$, $p < .001$, $\eta_p^2 = .81$, MSE = 34586.52. However, there was no significant noise type x stimulus duration interaction, $F(18,828) = .82$, $p = .68$, $\eta_p^2 = .02$, MSE = 9889.87. The non-significant noise type x stimulus duration interaction suggests that there is no slope effect between the no-click and click conditions.

Another repeated measures ANOVA with noise type (no-clicks and click-change) and stimulus duration (the 10 different stimulus durations) as within subject factors was carried out. There was no significant main effect of noise type, $F(1,46) = 2.55$, $p = .12$, $\eta_p^2 = .05$, MSE = 34480.42. There was a significant main effect of stimulus duration, $F(9,414) = 177.4$, $p < .001$, $\eta_p^2 = .79$, MSE = 25612.39. However, there was no noise type x stimulus duration interaction, $F(9,414) = .5$, $p = .88$, $\eta_p^2 = .01$, MSE = 9679.31.

Further, a repeated measures ANOVA with noise type (click and no-clicks) and stimulus duration (the 10 different stimulus durations) as within subject factors was conducted. There was a significant main effect of noise type, $F(1,46) = 32.97$, $p < .001$, $\eta_p^2 = .42$, MSE = 14259.88. There was also a significant main effect of stimulus duration, $F(9,414) = 176.65$, $p < .001$, $\eta_p^2 = .79$, MSE = 26377.62. However, there was no noise type x stimulus duration interaction, $F(9,414) = 1.29$, $p = .24$, $\eta_p^2 = .03$, MSE = 9888.41.

Lastly, a repeated measures analysis of variance (ANOVAs) with noise type (clicks and click-change) and stimulus duration (the 10 different stimulus durations) as within subject factors was conducted. There was a significant main effect of noise type, $F(1,46) = 7.35$, $p < .05$, $\eta_p^2 = .14$, MSE = 20627.05. There was also a significant main effect of stimulus duration, $F(9,414) = 175.97$, $p < .001$, $\eta_p^2 = .79$, MSE = 207072.89. There was no noise type x stimulus duration interaction, $F(9,414) = .67$, $p = .74$, $\eta_p^2 = .01$, MSE = 10101.88.

As there were no significant interactions between noise type and duration, only linear regression analysis on the intercept values across all participants was performed.

Linear Regression Analysis – Non-process (Don't Ask)

Intercept Values

Figure 27 shows the mean intercept values for each condition. Descriptive statistics showed that the mean intercept values for the three noise conditions (no-clicks, click-change and clicks) were, 153.59ms (SE = 36.96), 161.39ms (SE = 35.06) and 172.2ms (SE = 37.53). Inspection of Figure 27 suggests that there was a significant difference between the intercept value of the no-click condition and that of the two click conditions (click-change, clicks). Further, clicks appear to result in greater mean intercept values than the click-change condition. However, these suggestions were not supported by subsequent statistical analysis.

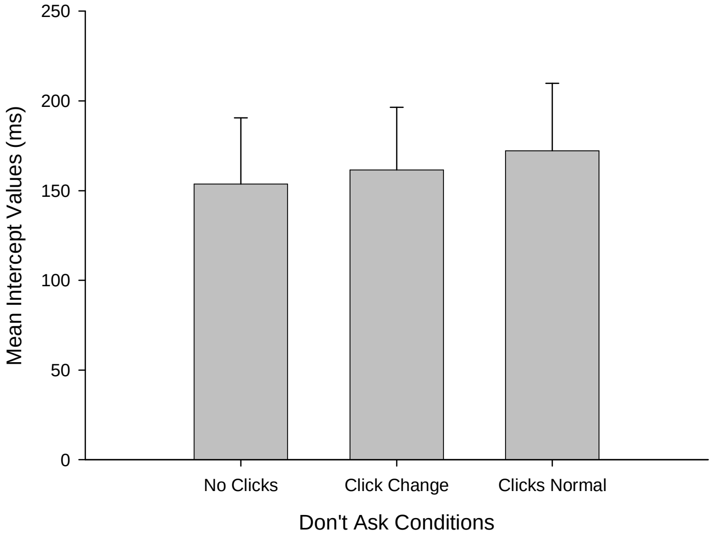


Figure 27: Mean Intercept values (ms) plotted against condition (no-clicks, click-change, clicks) of Experiment 3b.

A repeated measures ANOVA with one factor, noise type (no-clicks, click-change, clicks) was conducted on the mean intercept values. There was no significant main effect of noise type, $F(2,92) = .64$, $p = .53$, $\eta_p^2 = .01$, MSE = 6445.78.

7.2.3 Discussion

In the Ask versus Don't Ask analysis, there was a significant effect of noise type, instruction and stimulus duration. However, there was no significant noise type x stimulus duration interaction. All other interactions were also non-significant. In the Ask condition separately, repeated measures analysis revealed a significant difference between the following conditions: no-clicks versus click-change, clicks versus no-clicks and clicks versus click-change. Both clicks conditions resulted in greater verbal estimates compared to no-clicks. Therefore, unlike in Experiment 3a, the click manipulation (having to process the clicks in the Ask condition to determine whether there was a pitch shift) did not reduce the effect of clicks. In addition, in the Ask condition, there was no significant difference between the slope of the no-click condition and the click-change condition. However, there was a significant difference between the slope of the no-click condition and the click condition and between the two click conditions (clicks and click-change). In the Don't Ask condition, repeated measures analysis revealed a significant difference between the click versus the no-click conditions and the clicks versus the click-change conditions. However, there was no significant difference between the no-click versus the click-change conditions. In the Don’t Ask condition, there were no significant differences in the slopes between the three conditions (no-click, click-change and click).

The pattern of results so far are rather complex, in sum, unlike Experiment 3a, the click processing manipulation had no detrimental effect on the typical effect produced clicks. Both click types increased verbal estimates of duration in both the Ask and Don’t Ask groups although we found no interaction in the Don’t Ask condition, which at the moment has no explanation. A greater overestimation of duration was found with the clicks compared to the click-change condition. These effects with clicks show that this processing manipulation had no effect on the internal clock, despite having demonstrated an effect on information processing in Experiment 3a. This weakens the idea of a link between information processing and the internal clock. However, as mentioned earlier, it still remains a possibility that there *is* a strong relationship between these two processes. Perhaps, having to process the clicks caused a relocation or division of processes that only caused a detrimental effect to information processing leaving the internal clock process spared. With such an explanation for the findings, it still remains possible that there is a link between the two as demonstrated by the white noise studies in Chapter 6.

An alternative explanation may be that the act of having to attend to and process the clicks only affects information processing because it does not operate in the supposed accumulative fashion as the internal clock. The accumulative process of the internal clock can be carried out unconsciously. For example, in the case, where someone has to retrospectively say how long they felt some event had lasted for. Generally, people tend to be fairly accurate in their estimates. Consistent with the first explanation, perhaps the fact that information processing in the form of reaction time task is in itself a conscious process (compared to the internal clock) is why when given another conscious task (click processing), information processing is affected in such instances. In effect, there is a ‘processing overload’. Despite the complexity in the findings, in the Ask condition, the clicks still produce their normal effect on reaction time.

Chapter 8

The Effect of Frequency and Duration Manipulation of Click Trains

8.1 Experiment 4a - Manipulation of Frequency and Duration in a 1, 2 and 4 Choice Reaction Time Task

As we have seen, previous studies have found that repetitive stimulation (in the form of flashes or clicks) can create a subjective lengthening of stimulus duration (e.g., Treisman et al., 1990; Jones et al., 2010). It has also been shown that repetitive stimulation in the form of click trains can also enable participants to react faster in a 1, 2 and 4 choice reaction time task (Jones et al., 2010). However, existing studies in the literature, which have used click trains as a form of repetitive stimulation (e.g., Burle & Casini, 2001), typically use a click train frequency of 5Hz for five seconds (25 stimulations/clicks). There has been no systematic investigation into whether modifying the frequency and number of stimulations/duration has any effect on individual's verbal estimation of duration or reaction time. For instance, simply changing the frequency that is delivered to participants is not enough to investigate the effect since each frequency will vary in the number of stimulations that is presented over the 5 seconds. For example, 5Hz for five seconds produces 25 stimulations while 12Hz for five seconds produces 60 stimulations. Such differences were controlled for in this study. For example, in the case above, a condition was created in which the 12Hz tone was delivered for 2.08 seconds giving 25 stimulations. In order to explore this, the following two experiments were carried out. Experiment 4a manipulated the frequency and duration of the clicks in a 1, 2 and 4 choice reaction time task and Experiment 4b explored the same manipulation of clicks in a task of verbal estimation. Therefore, Experiment 4a explored the effect of click frequency and duration manipulation on information processing speed, while Experiment 4b explored the effect of the same manipulation on internal clock speed. Most importantly, if an effect of these manipulations was only found on the verbal estimation task but not on the RT task, then it would weaken the notion of a relationship between the internal clock and information processing or at least the idea that clicks exert their effect on both by the same mechanism.

8.1.1 Method

Participants

Thirty-two undergraduate psychology students took part for course credits which were not contingent on performance.

Apparatus

This experiment was similar to Experiment 1a apart from the varying durations and frequencies of the clicks delivered. A 700Hz tone of 25ms duration signaled the start of the trial and was followed by a 2.08 to 12.5 second period, filled by clicks of certain duration and frequency. Another 700Hz tone was then presented for 25ms. Following the second tone, there was a gap duration randomly selected from between 300 and 1,200ms. After which, a small black cross (formed by two lines 11 pixels in length) appeared in the middle of one of the four boxes.

Procedure

Each participant served in an experimental session consisting of three choice types (1, 2 or 4 choice). There were three blocks, each consisting of 70 trials. In each block, all seven sound conditions (see below) were presented 10 times each. Therefore, there were 210 trials in total. Each trial began with a 700Hz tone of 25ms duration followed by one of seven conditions: 2Hz, 5Hz, 7Hz and 12Hz with numbers of stimulations delivered being constant at 25 (the duration of each of these conditions being 12.5, 5, 3.57 and 2.08 seconds, respectively) and 2Hz, 7Hz and 12Hz delivered for 5 seconds (with the numbers of stimulation being 10, 35 and 60, respectively). This was then followed by a subsequent 700Hz tone presented for 25ms. Following the second 700Hz tone, there was a random delay (between 300 and 1,200ms) before a small black cross (formed by two lines 11 pixels in length) appeared in the middle of one of the four boxes. The reaction time task, thereafter, is similar to Experiment 1c (see Procedure/Methodology in Experiment 1c).

8.1.2 Results

The mean response times and standard errors for each of the experimental conditions are shown in Figure 28. Descriptive statistics showed that the mean reaction time for choice type one, two and four were 339.89ms (SE = 15.15), 382.85ms (SE = 9.92) and 443.53ms (SE = 10.86). Collapsing across choice type, the mean reaction times for the seven conditions (2Hz, 5Hz, 7Hz and 12Hz for 5 seconds and 2Hz, 7Hz and 12Hz for 12.5, 3.57 and 2.08 seconds) were 384.95ms (SE = 9.99); 387.56ms (SE = 11.05); 390.88ms (SE = 12.89); 385.66ms (SE = 10.52); 400.41ms (SE = 14.93); 382.62ms (SE = 9.25) and 389.22ms (SE = 10.19). Inspection of the data suggests that, firstly, the response times for all choice types are similar across all seven sound conditions. Moreover, overall response times increased across the three choice types, with response type three having the highest reaction times. These suggestions were supported by the statistical analysis.

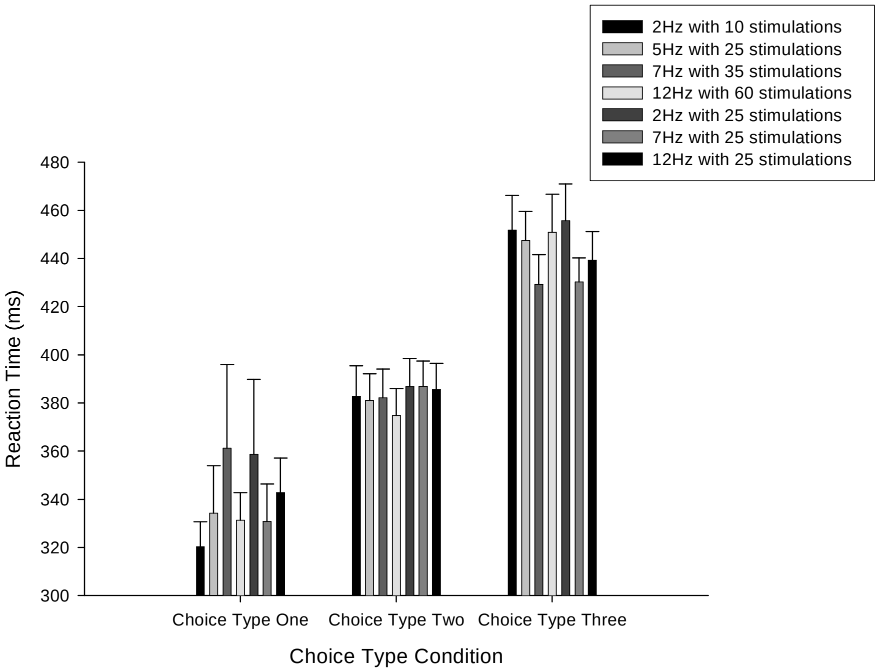


Figure 28: Mean reaction times plotted against choice condition (one, two or four) for all seven click sound conditions of Experiment 4a. Vertical lines show standard error of the mean.

A repeated measures ANOVA was used, with one factor being choice type with three levels (1, 2 or 4), another being the click sound condition (with seven levels, one for each condition). There was a significant main effect of choice type, $F(2,62) = 31.64$, $p < .001$, $\eta_p^2 = .51$, MSE = 19195.06. However, there was no significant main effect of click sound condition, $F(6,186) = .75$, $p = .61$, $\eta_p^2 = .02$. MSE = 4334. There was also no significant interaction between choice type and click sound condition, $F(12,372) = 1.08$, $p = .37$, $\eta_p^2 = .03$. MSE = 3895.5.

8.1.3 Discussion

The difference between the three choice types was significant. Response times increased across the three choice types, with response type three having the highest reaction times. However, overall, there was no significant effect of click sound condition on reaction time. These findings suggest that the frequency of the clicks is irrelevant and that it is perhaps simply the presence of repetitive stimulation that is driving the effect of clicks. This is inconsistent with findings by Treisman et al. (1990) and Burle and Casini (2001). However, it supports the findings by Jones et al. (2010) which showed no differential effect of clicks on reaction time when presented at either 5Hz or 25Hz.

8.2 Experiment 4b - Manipulation of Frequency and Duration in a Verbal Estimation Task

8.2.1 Methods

Participants

Thirty-four undergraduate psychology students took part for course credits which was not contingent on performance.

Apparatus

See apparatus for Experiment 1a.

Procedure

Throughout the experiment, participants heard clicks trains of varying frequency and duration and their task was to estimate the duration of a tone (500Hz) presented after these varying click trains. The following instructions were given to participants on the computer screen…”You will hear clicks trains of varying frequency and duration. Your task is to estimate the duration of the tone following the click train. Please press enter to begin”. There were ten different durations of the 500Hz tone (300, 478, 567, 656, 745, 834, 923, 1,012, 1,101 and 1,300ms). Each of these ten different durations was presented twice after each of the following seven conditions which began and ended with a 700Hz tone for a 25ms duration: 2Hz, 5Hz, 7Hz and 12Hz with numbers of stimulations delivered being constant at 25. The duration of each of these conditions being 12.5, 5, 3.57 and 2.08 seconds, respectively. In addition, 2Hz, 7Hz and 12Hz delivered for 5 seconds with the numbers of stimulations being 10, 35 and 60, respectively. Each of these seven conditions was presented twenty times, giving a total of one hundred and forty trials.

After the presentation of the tone, participants were presented with the following instructions: “Please type in your estimate of the duration of the tone. Your response must be between 250 and 1350ms. Press enter when finished”. If the participants made a response outside this given range, they were reminded of this and asked to re-type a response. When the participant had pressed enter another instruction appeared on the screen….“Press spacebar for next trial”. After the participants pressed spacebar for next trial, there was a delay of 2,000ms before the presentation of the clicks and tone.

8.2.2 Results

Figure 29 shows the mean verbal estimates for each condition plotted against stimulus duration. Inspection of the figure suggest that mean verbal estimates increased linearly with the duration of the stimulus, in all conditions.

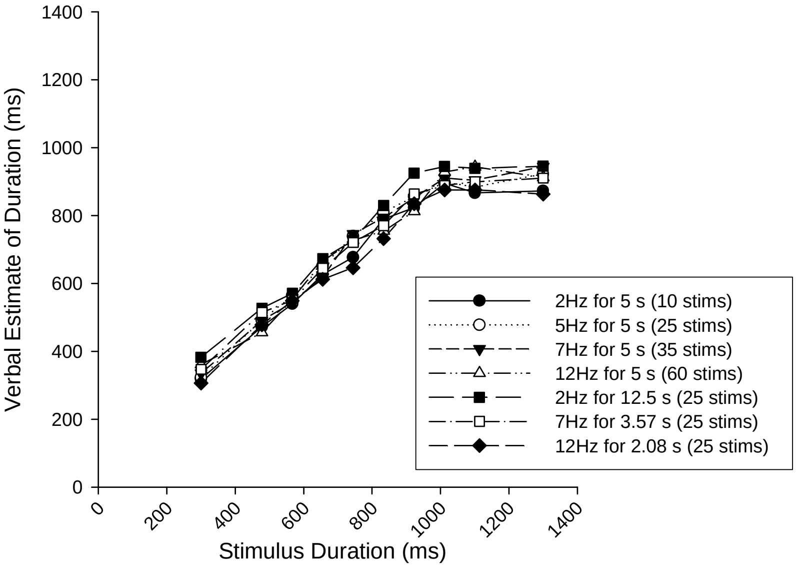


Figure 29: The relationship between the mean verbal estimates of duration (ms) against the actual stimulus duration (ms) for all seven conditions in Experiment 4b

A repeated measures ANOVA with click type (2Hz, 5Hz, 7Hz and 12Hz for 5 seconds and 2Hz, 7Hz and 12Hz for 12.5, 3.57 and 2.08 seconds, respectively) and stimulus duration (the 10 different stimulus durations) was used. There was a significant main effect of click type, $F(6,198) = 4.44$, $p < .001$, $\eta_p^2 = .12$, MSE = 36818.72. There was a significant main effect of stimulus duration, $F(9,297) = 127.42$, $p < .001$, $\eta_p^2 = .79$, MSE = 73818.17. However, there was no click type x stimulus duration interaction, $F(54,1782) = .89$, $p = .69$, $\eta_p^2 = .03$, MSE = 14543.71.

Duration Constant Analysis

In order to disentangle the effects of frequency, the data was split to create two separate lines of analysis. The first selected the four conditions in which the duration of the clicks was constant, namely, five seconds. The second (see section Number of Stimulations Constant Analysis) selected the four conditions in which the number of stimulations presented by the clicks remains constant, namely, twenty-five stimulations. Figure 30 shows the mean verbal estimates for duration constant condition plotted against stimulus duration. Descriptive statistics revealed that the mean verbal estimates for these four conditions (2Hz, 5Hz, 7Hz and 12Hz for 5 seconds) were 687.91ms (SE = 27.55), 713.74ms (SE = 26.94), 713.47ms (SE = 27.35) and 711.1ms (SE = 27.69), respectively.

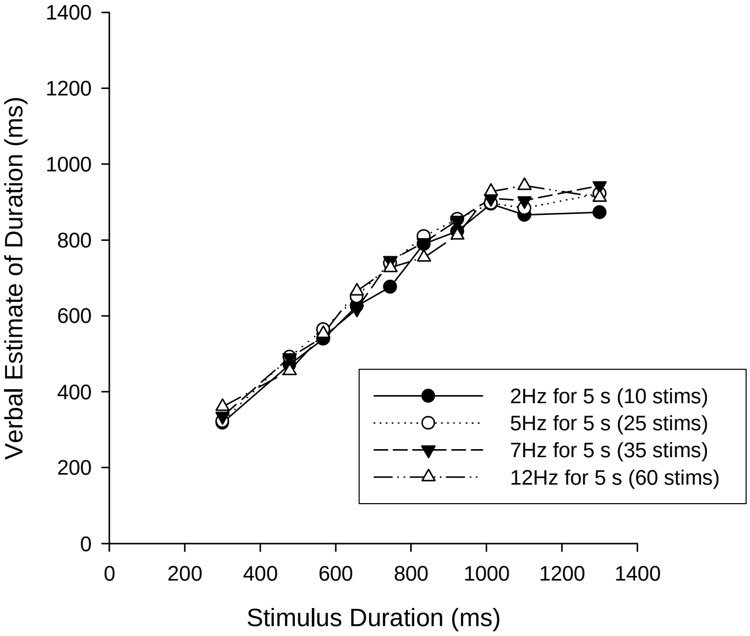


Figure 30: The relationship between the mean verbal estimates of duration (ms) against the actual stimulus duration (ms) for the conditions in which duration of presented clicks is constant (five seconds) of Experiment 4b.

A repeated measures ANOVA with click type (2Hz, 5Hz, 7Hz and 12Hz for 5 seconds) and stimulus duration (the 10 different stimulus durations). There was no significant main effect of click type, $F(3,99) = 2.08$, $p = .11$, $\eta_p^2 = .06$, MSE = 25449.31. There was a significant main effect of stimulus duration, $F(9,297) = 109.47$, $p < .001$, $\eta_p^2 = .77$, MSE = 50139.45. However, there was no click type x stimulus duration interaction, $F(27,891) = .96$, $p = .53$, $\eta_p^2 = .03$, MSE = 15301.1. This suggests that the duration is important in driving the effects of clicks.

Number of Stimulation Constant Analysis

Figure 31 shows the mean verbal estimates for the conditions in which the number of stimulations presented by the clicks is constant (25 stimulations) plotted against stimulus duration Descriptive statistics revealed that the mean verbal estimates for these four conditions (2Hz, 5Hz, 7Hz and 12Hz for 12.5, 3.57 and 2.08 seconds) were 746.03ms (SE = 28.4), 713.74ms (SE = 26.94), 710.53ms (SE = 29.06) and 677.06ms (SE = 32.46), respectively. From these means, it seems as though the effect of clicks reduces as the duration of the clicks becomes shorter, strongly indicating the importance of the duration.

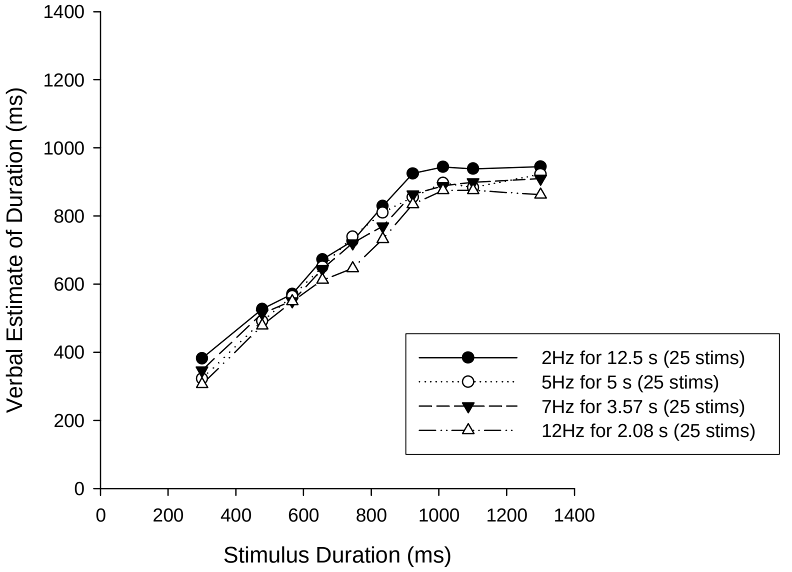


Figure 31: The relationship between the mean verbal estimates of duration (ms) against the actual stimulus duration (ms) for the conditions with 25 stimulations of Experiment 4b.

A repeated measures ANOVA was used with one factor being click type (2Hz, 5Hz 7Hz and 12Hz for 12.5, 5, 3.57 and 2.08 seconds, respectively) and the other being stimulus duration (the 10 different stimulus durations). There was a significant main effect of click type, $F(3,99) = 5.5$, $p < .01$, $\eta_p^2 = .14$, MSE = 49092.09 and a significant main effect of stimulus duration, $F(9,297) = 111.93$, $p < .001$, $\eta_p^2 = .77$, MSE = 47372.37. However, there was no click type x stimulus duration interaction, $F(27,891) = .66$, $p = .91$, $\eta_p^2 = .02$, MSE = 13794.44. This supports the suggestion from the results of the previous analysis (looking at the effect of frequency controlling for duration), which highlighted the importance of the duration in driving the effects. Since there was no significant interaction, linear regression analysis was carried out only on the intercept values.

Linear Regression Analysis

Intercept Values

Figure 32 shows the mean intercept values for each condition. Inspection of Figure 32 suggests that there was no significant difference between the intercept values of any of the conditions. This suggestion was supported by subsequent statistical analysis.

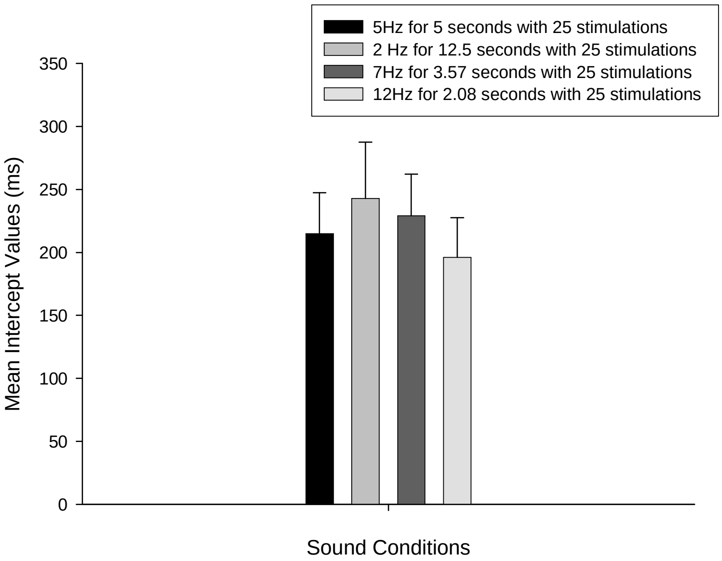


Figure 32: Mean intercept values (ms) plotted against condition (2Hz, 5Hz 7Hz and 12Hz for 12.5, 5, 3.57 and 2.08 seconds, respectively) of Experiment 4b.

A repeated measures ANOVA with one factor, click type (5Hz for 5 seconds; 2Hz for 12.5 seconds; 7Hz for 3.57 seconds and 12Hz for 2.08 seconds all with 25 stimulations) was conducted on the mean intercept values. There was no significant main effect of click type, $F(3,99) = 1.12$, $p = .34$, $\eta_p^2 = .03$, MSE = 12146.85.

8.2.3 Discussion

Overall, the findings show a significant effect of click type condition. There was a significant effect of stimulus duration since the mean verbal estimates increased linearly with the duration of the presented stimulus. However, in order to disentangle the effects of frequency on verbal estimates, the conditions were split into two sections and analysed separately. Findings showed no difference between the conditions in which the duration of the presented clicks is constant for a duration of five seconds. However, there was a difference between the conditions in which the number of stimulations presented by the clicks is controlled for across the four difference frequencies (2, 5, 7 and 12Hz). However, subsequent follow-up demonstrated no significant intercept effects. The main finding of no main effect of frequency manipulation is consistent with Experiment 4a. The findings highlight instead the importance of duration in producing the effect of clicks on verbal estimates. So the effect of clicks is stronger the longer they are presented for consistent with the idea that the clicks work though the process of non-specific entrainment of brain waves, supporting the findings of Will and Berg (2007) (See Chapter 2, section 2.9).

Chapter 9

The Effect of Clicks on Memory Recall and Time Estimation *Simultaneously*

9.1 Experiment 5 - The Effect of Clicks on both Memory Recall and Verbal Estimation

As noted earlier, previous studies have shown that preceding both tones or visual stimuli by trains of clicks increases their subjective duration (Burle & Cassini, 2001; Penton-Voak et al., 1996). In a previous study (Jones et al., 2010), we demonstrated that clicks could also speed up reaction time. Additionally, we also investigated whether it is possible to encode more information in some objective time period *t* when the internal clock is running faster and hence the subjective time elapsed is increased. An adapted version of the classical Sperling (1960) task was used in which either five seconds of clicks or no-clicks preceded a 3x4 matrix which was presented for a duration of either 300 or 500ms. In principle, the click trains should increase the speed of the pacemaker, so that the subjective period for which the matrices are presented should seem longer to the participant. If the participant experiences the matrix for longer, s/he may be able to extract more information on trials where the pacemaker is sped up compared to trials without the click manipulation. Indeed, it was found that participants recalled more letters correctly from matrices that were preceded by clicks as opposed to those that were not.

However, a potential oversight of this previous study (Jones et al., 2010) is that it did not investigate participants’ subjective estimations of the duration of the matrices. So even though clicks were found to enable participants to correctly recall more letters, indicative of them having more time in which to process the letter matrix, no tests of subjective duration were carried out. It is impossible to conclude therefore that, participants experienced the matrices as lasting for subjectively longer whilst simultaneously experiencing an increase in information processing speed, since time estimations were not investigated. The current experiment therefore explored both recall memory and time estimation using the same adapted Sperling task, in a dual task design.

Essentially, the main question that the current experiment attempted to investigate was whether information processing speed is determined directly by clock speed. The experiment had two conditions, one in which participants were asked to estimate the duration of the stimulus (a 3 x 4 matrix consisting of 12 letters) and another in which they were asked to recall as many letters as they could from the matrix. Effectively, the condition in which participants were asked to estimate the stimulus duration measured clock speed and the condition in which participants were asked to recall letters measured information processing speed. It is hypothesised that on trials preceded by clicks, participants will estimate the stimulus matrix as lasting subjectively longer than on trials preceded by silence. Also, participants will correctly recall more letters on trials preceded by click compared to silence. It is well known that clicks cause increases in verbal estimates (Penton-Voak et al., 1996; Jones et al., 2010). The inclusion of the verbal estimate condition enabled us to investigate whether, in the click conditions, increases in internal clock speed are *proportional* to information processing speed. So, for instance, if there is a 20% increase in verbal estimates, the number of letters recalled is 4.2 (as opposed to say 3.5 when there are no clicks).

Although an association may be found between information processing rate and internal clock speed in the current experiment, the question of cause and effect remain a problem as the relationship between the two, if any, is difficult to disentangle. In other words it may be that during situations in which time appears to slow down, this enables the brain to process more information. On the other hand, it may be that a higher rate of information processing causes greater estimates of subjective time instead. Kail and Salthouse (1994) have argued that processing speed can be compared to the clock speed of a microcomputer: “for an individual with a higher clock speed, all processing takes place at a faster rate than for individuals with a lower clock speed”. This argument suggests that an increase in the rate of processing directly results in an increase in the speed of the internal clock.

9.1.1 Method

Participants

Fifty participants took part and were compensated with £5 for their time and effort. This was not contingent on performance.

Apparatus

See apparatus for Experiment 1a.

Procedure

There were 160 trials in total, with four blocks in each consisting of 40 trials. Two blocks involved recalling as many letters as possible from the stimuli and the other two involved estimating the duration of the stimuli. The order of the blocks was counterbalanced across participants. In each block, 20 trials were preceded by 5 seconds of no-clicks (silence) and the other 20 were preceded by 5 seconds of clicks (the order of which was counterbalanced across participants).

At the beginning of each session, instructions appeared on the computer screen, participants were requested to press the space bar to commence the first trial when ready. There were two trial conditions (clicks and no-clicks). In the recall condition, participants were instructed to look at a fixation cross in the centre of the screen and to begin the trial by pressing the spacebar. Participants were then presented with a 25ms tone (700Hz), followed by a 5 second period of clicks at 5Hz. A further 25ms tone (700Hz) ended the clicks, which was followed by a random delay between 300 and 1200ms. A matrix stimulus was then presented, which consisted of 12 letters (4 x 3). There were three main stimulus (the matrix) durations of interest presented in a random order across trials (300, 400 and 500ms). These three durations were randomly mixed among other durations as follows: either randomly between 100 and 200ms; randomly between 200 and 300ms; randomly between 500 and 800ms and lastly, randomly between 800 and 1,000ms. In each 40 trial block (20 being silence and the other 20 being clicks), each of the three durations of interest (300, 400 and 500ms) were presented eight times giving a total of twenty-four trials of interest in each block (a total of 96 across entire experiment).

After the presentation of the matrix, participants were asked to type as many of the letters from the matrix as they could recall on the keyboard. Once a response had been made the participants began the next trial after a prompt to press the spacebar when ready to continue. Only correctly recalled letters were used in the analysis. In the verbal estimation condition, the same procedure was used as in the recall condition. The only difference was that, instead as being asked to recall as many of the letters as they could from the matrix stimulus, participants were asked to type on the keyboard their estimate of the duration of the matrix, choosing from a range of 50 to 1,250ms.

9.1.2 Results

Verbal Estimation: Internal Clock Speed

Figure 33 shows mean verbal estimates plotted against stimulus duration for the click and no-click conditions of the current experiment. Across all durations, the mean verbal estimates for the clicks and no-clicks conditions were 487.9ms (SE = 33.1) and 544.49ms (SE = 36), respectively. The mean verbal estimates for the presentation durations of 300, 400 and 500ms were 370.91ms (SE = 32.05), 512.97ms (SE = 34.82) and 664.72ms (SE = 42.01), respectively. Inspection of Figure 33 suggests that mean estimates increased as an approximately linear function of actual stimulus duration in both conditions. Furthermore estimates of stimulus duration appear to differ for the stimuli preceded by clicks compared to those preceded by no-clicks. Moreover, the difference between the estimates for the two conditions appears to increase as the duration of the tone to be estimated increases, indicative of a slope effect. The internal clock therefore, running faster in the click condition than the silence condition. These suggestions were supported by subsequent statistical analysis.

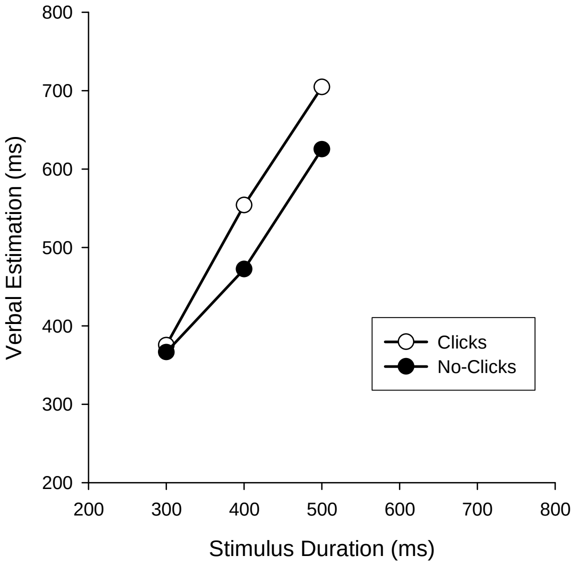


Figure 33: Mean verbal estimates plotted against stimulus duration for the click and no-click conditions of Experiment 5.

Figure 34 shows more clearly the increase in verbal estimates due to clicks compared to no-clicks. Across all three presentation durations, on trials preceded by clicks, there is an increase in verbal estimates. This effect is more pronounced for the longer 400 and 500ms durations. The fact that the difference between the trials preceded by clicks versus no-clicks becomes greater the longer the duration (a slope effect) demonstrates that the effect is multiplicative and it is not simply a bias effect.

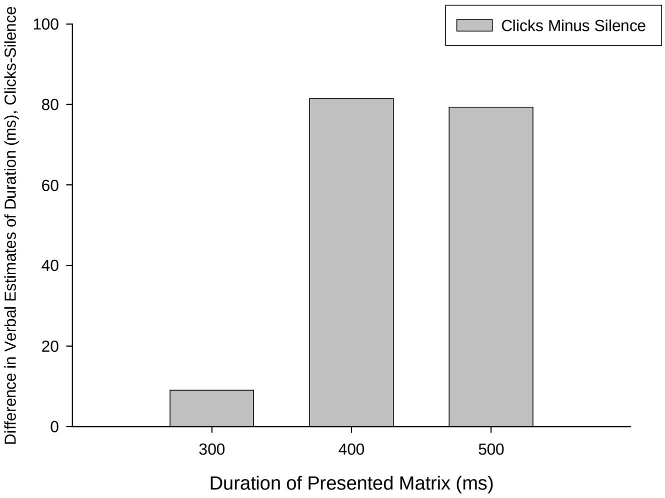


Figure 34: The mean verbal estimates for the click trials minus verbal mean estimates from the no-click trials, for each of the three presentation durations of Experiment 5.

A repeated-measures ANOVA was used with one factor being the presence or absence of clicks (clicks and no-clicks) and the other being stimulus duration (300, 400 and 500ms) showed a significant main effect of clicks on estimates, $F(1,49) = 10.81$, $p < .05$, $\eta_p^2 = .18$. MSE = 22209.33. There was also a significant main effect of stimulus duration, $F(2,98) = 67.52$, $p < .001$, $\eta_p^2 = .58$. MSE = 31972.47. However, there was a borderline significant click/no-clicks x stimulus duration interaction, $F(2,98) = 2.92$, $p = .06$, $\eta_p^2 = .06$. MSE = 14523.05.

After the repeated measures, paired-samples *t* tests were conducted. A repeated measures t-test showed that the difference between the estimates of duration for no-click and clicks in the condition of a 300ms presentation duration was not significant, $t(49) = -.43$, $p = .67$. However, the difference between the estimates of duration for the no-click and clicks in the condition of a 400ms presentation duration was significant, $t(49) = -2.69$, $p < .05$. The difference between the estimates of duration for the no-click and click condition of 500ms duration was also significant, $t(49) = -3.02$, $p < .05$.

In sum then, for the 400 and 500ms stimuli durations, the difference between the estimates for the click and no-click conditions are significant. Estimates of duration are greater for the stimuli that are preceded by clicks compared to the stimuli preceded by no-clicks when the stimulus durations were 400 and 500ms.

Memory Recall: Information Processing Speed

The mean number of correctly recalled letters for the click and no-click conditions were 3.93 (SE = .07) and 4 letters (SE = .07), respectively. The mean number of correctly recalled letters for the three presentation durations of 300, 400 and 500 were 3.77 (SE = .07), 3.99 (SE = .07) and 4.14 letters (SE = .08), respectively. Figure 35 shows the number of letters correctly recalled plotted against the duration of presentation of the stimuli for both click and no-click conditions. Inspection of Figure 35 suggests that number of correctly recalled letters increased as an approximately linear function of actual stimulus duration in both conditions. Furthermore, the number of correctly recalled letters appears to differ for the stimuli preceded by clicks compared to those preceded by no-clicks. The difference between the number of letters correctly recalled for the two conditions appears to increase as the duration of the presentation increases, indicative of a slope effect indicating that the clicks are both having an effect on the internal clock and information processing. Specifically, by speeding up the internal clock as well as increasing the rate of information processing. The suggestion that the number of letters correctly recalled differs between the two conditions was supported by subsequent statistical analysis.

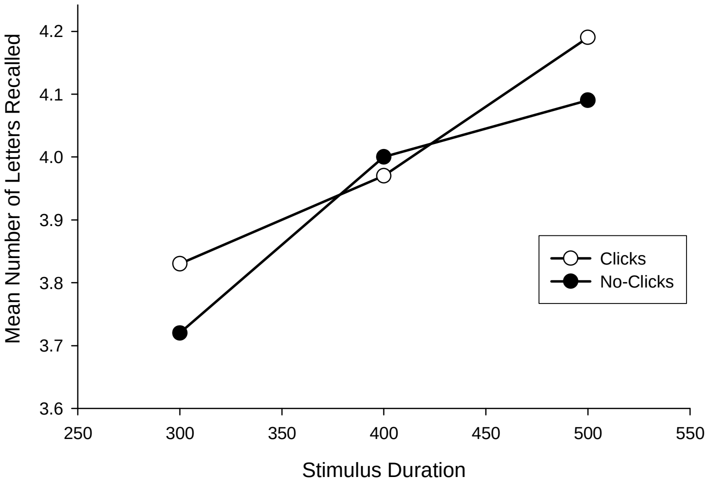


Figure 35: Number of letters correctly recalled plotted against the duration of presentation of the stimuli for both click and no-click conditions of Experiment 5.

Figure 36 shows more clearly the increase in the amount of correctly recalled letters due to clicks compared to no-clicks. At the 300 and 500ms presentation durations, on trials preceded by clicks, there is an increase in amount recalled.

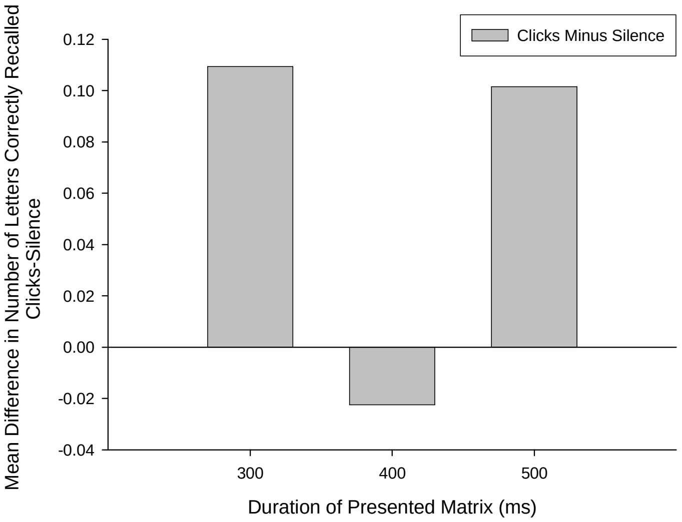


Figure 36: Mean number of correctly recalled letters for the no-click trials are taken away from the click trials, for each of the three presentation durations of Experiment 5.

A repeated measures ANOVA was used with one factor being presence or absence of clicks (clicks or no-clicks) and the other being stimulus duration (300, 400 and 500ms) showed a significant main effect of clicks on recall, $F(1,49) = 4.51$, $p < .05$, $\eta_p^2 = .08$. MSE = .07. There was also a significant main effect of stimulus duration on recall, $F(2,98) = 36.89$, $p < .001$, $\eta_p^2 = .43$. MSE = .09. However, there was no significant click/no click x stimulus duration interaction, $F(2,98) = 2.26$, $p = .11$, $\eta_p^2 = .04$. MSE = .06.

After the repeated measures, paired-samples *t* tests were conducted. A repeated measures t-test showed that the difference between the amount of correctly recalled letters for no-clicks and clicks in the condition of a 300ms presentation duration was significant, $t(49) = -2.33$, $p = .02$. However, the difference between the amount of correctly recalled letters for the no-clicks and clicks in the condition of a 400ms presentation duration was not significant, $t(49)= .43$, $p = .67$. The difference between the amount of correctly recalled letters for the no-clicks and click condition of a 500ms duration was significant, $t(49) = -2.01$, $p < .05$.

In sum then, for the 300 and 500ms stimuli durations, the difference between the amount of correctly recalled letters for the click and no-click conditions was significant. More letters were correctly recalled for the stimuli that were preceded by clicks compared to the stimuli preceded by no-clicks when the stimulus durations were 300 and 500ms.

Proportionality between Memory Recall and Verbal Estimation

For the memory recall condition, all the mean values for each participant for the click trials were subtracted from all the mean values for the no-click trials. This resulted in a difference value for the effect of clicks compared to no-clicks on memory recall performance. The same procedure was carried out for the time estimation condition. Figure 37 shows the individual participant's mean change in time estimation (ms) plotted against the mean change in the amount of letters correctly recalled (memory recall). Inspection of Figure 37 shows only a very slight linear relationship between these two variables.

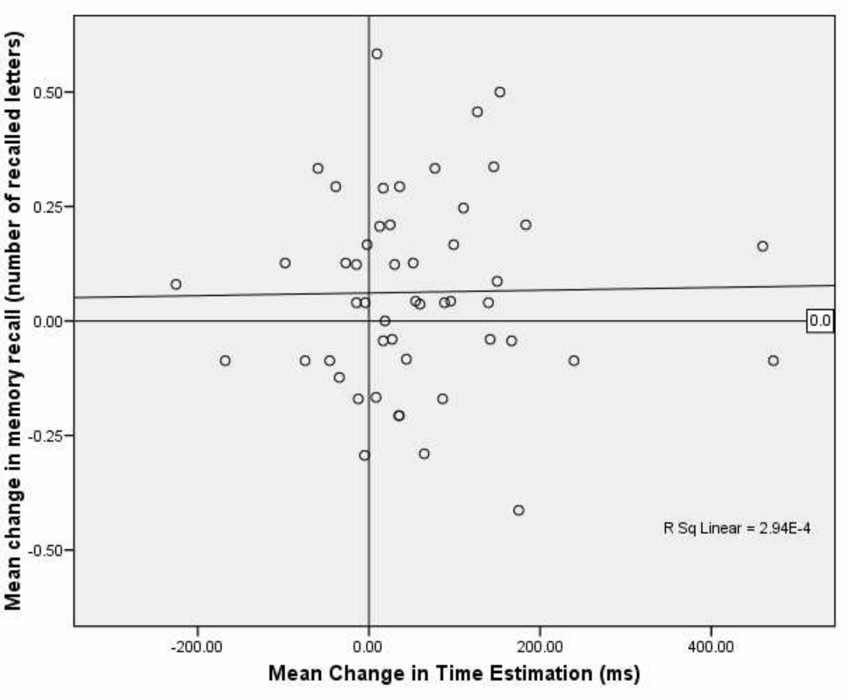


Figure 37: Individual participant's mean change in time estimation (ms) plotted against the mean change in memory recall (the amount of letters successfully recalled) of Experiment 5.

In Figure 37, the dots appear to be scattered quite randomly and the line of best fit is indicating little or no proportionality between the two variables. Thus, suggesting that there is no relationship between the mean change in time estimation and the mean change in memory recall. Further analysis using Pearson's *r*, showed that there was a non-significant positive correlation between mean change in memory recall (no. of letters) and the mean change in time estimation (ms) (*r* = .017, *N* = 50, *p* = .91), with only .00029% of the variation explained. Therefore, there is clearly no linear relationship between these two variables.

9.1.3 Discussion

In the verbal estimation task, clicks increased participants' verbal estimations of the stimulus matrix when it was presented for the longer 400 and 500ms only. In the memory recall task, clicks enabled participants to recall more letters when the stimulus matrix was presented for 300 and 500ms but not 400ms. Generally then, supporting previous studies (i.e., Penton-Voak et al., 1996) clicks appear to lengthen subjective duration as evidenced by longer estimates of the duration of the presented matrix.

More interestingly, clicks generally enabled participants to process more information as shown by more correctly recalled letters. This finding is even more interesting if we consider the unusual visual stimuli employed in this study. The matrix is not the usual type of visual stimulus used in timing studies/speeding up the internal clock studies. However, there appears to be no correlation between whether a participant experiences time as being subjectively longer and whether they are able to process and encode more information. This would suggest then that in the click conditions, increases in internal clock speed are not proportional to information processing speed. So, for instance, there is no link between say a 20 % increase in verbal estimates and the increase in the number of letters recalled.

This study replicated our previous findings (Jones et al., 2010), which demonstrated that participants recall more letters from the matrix on trials preceded by clicks compared to no-clicks, thus demonstrating that clicks can increase the rate of information processing. However, since the previous study did not incorporate a time estimation condition, it was not known whether participants experienced both a lengthening of subjective time as well as the increase in memory recall of the letters as a result of the click stimulus. The current experiment adopted the same experimental design but explored both memory recall and time estimation and found that subjective time estimation was indeed greater in trials preceded by clicks. Therefore, it appears that clicks speed up both the hypothetical internal clock and the rate of information processing in this task. This suggests then, that there was a lengthening of subjective time in our previous study also. The fact that both information processing and the internal clock were affected simultaneously by the clicks provides us with further evidence that a link between the two may exist.

The research question that this experiment addressed was whether clicks affect information processing rate and internal clock speed simultaneously, since previous studies have only looked at the effect of clicks on these two processes separately (i.e., Jones et al., 2010; Penton-Voak et al., 1996). Findings from this dual paradigm revealed that when clicks speed up information processing, there is a simultaneous lengthening of subjective duration. Therefore, it suggests that when participants experience a subjective lengthening of duration, this may enable them to process more information in this perceived longer time available to them.

In conclusion, although there is some evidence here to suggest that an increase in the speed of the internal clock can occur simultaneously with an increase in information processing, there was no evidence of a correlation between the two. However, this does not rule out the possibility of a relationship between the two. Here, we have seen that both processes are affected by clicks simultaneously. What is of interest now is establishing the exact nature of this relationship. Based on Chapter 1, section 1.4.7, there are two possible models that can be used to explain the relationship, namely the models represented in Figure 3 and 5. Whether the internal clock rate caused the increased rate of information processing or vice versa cannot be concluded from this study alone and therefore more research is needed to explore the directionality (if any) of this relationship. It is possible that information processing rate and the speed of the internal clock may even operate independently of each other.

Chapter 10

The Effect of Clicks on Memory Decay

10.1. Experiment 6 – The Effect of Clicks on Memory Decay

Previous experiments (i.e., Jones et al., 2010) have found improved recall performance (including other psychological processes such as reaction time) with clicks. The next question is whether clicks could be used to *reduce* performance in a memory task. To further explore the effect of clicks on memory and recognition rate, the present study presented participants with an image which, after a delay (of either 3, 5 or 8 seconds) of either clicks or no-clicks, had to be compared to the image directly after the delay. Specifically, they were asked to report whether the second image (presented after the variable delay) was the same as the first or not. Since previous findings have shown that clicks increase subjective experience of duration, it was expected that there would be a greater memory decay (poorer image recognition) after clicks compared to no-clicks since the delay would appear subjectively longer resulting in more ‘time’ for the image representation to deteriorate.

10.1.1 Method

Participants

Forty undergraduate participants took part for course credit which were not contingent on performance.

Apparatus

See Apparatus for Experiment 1a. All responses were made on the computer keyboard. The visual stimuli consisted of 72 images (400 x 400 pixels) of 3D cubes arranged in various formations inside a circle (Shepard & Metzler, 1971).

Procedure

Each participant completed a total of 72 trials divided into 6 different conditions: the delay period was filled with clicks for 3 seconds, 5 seconds or 8 seconds (click condition), or silence for 3 seconds, 5 seconds or 8 seconds (no-click condition). There were 12 trials in each condition and they were presented in a random order. The number of correct responses for each condition was recorded.

Participants were asked to read the instructions on the computer screen before pressing the space bar to begin the first trial. In the click condition, participants viewed an image presented on the computer screen for 200ms. This was followed by a tone (frequency of 700Hz) played for 20ms before a 3, 5 or 8 second delay period filled with clicks (at a frequency of 5Hz). At the end of the delay period there was another tone (frequency of 700Hz) played for 20ms. Then an image appeared on the screen (in 50% of trials this was the same image as the one seen at the beginning of the trial and on the other 50% of trials this was a different image). Beneath the image there was the question; “Is this picture the same as the previous one?” Participants responded by pressing Y (for yes) or N (for no) on the keyboard. They were prompted on the screen to press any key to start the next trial. For the silent condition the procedure was exactly the same, except the 3, 5 and 8 second delay period was silent.

10.1.2 Results

The number of correct responses for each of the 6 conditions for the 40 participants is shown in Figure 38. Descriptive statistics showed that the overall mean number of correct responses for the no-clicks and clicks conditions were 10.67 (SE = .14) and 10.23 (SE= .19), respectively. The mean number of correct responses for the no-clicks conditions on each delay duration of 3, 5 and 8 seconds were 11.5 (SE = .14), 10.7 (SE = .2) and 10.15 (SE = .2), respectively. For the click condition on the same delay durations, the mean number of correct responses were 10.33 (SE = .2), 10.05 (SE = .27) and 10.33 (SE = .24). Inspection of Figure 38 shows that clicks appear to decrease the number of correct responses, at least for the decay durations of 3 and 5 seconds.

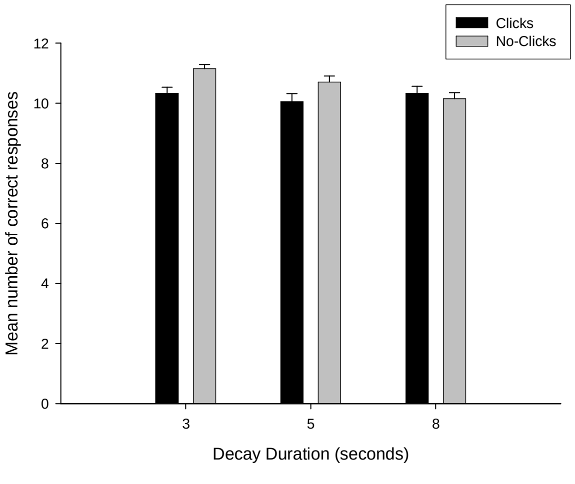


Figure 38: Mean number of correct responses plotted against the decay duration (3, 5 or 8 seconds) for both the clicks and no-clicks conditions of Experiment 6.

A repeated measures ANOVA was used with one factor being the delay type (clicks or no-clicks) and delay duration (3, 5 or 8 seconds) on the number of correct recognition responses. There was a significant main effect of delay type, $F(1,39) = 4.35$, $p < .05$, $\eta_p^2 = .1$. MSE = 2.59 and delay duration, $F(2,78) = 4.01$, $p < .05$, $\eta_p^2 = .09$. MSE = 1.33. There was also a significant two-way interaction between delay type and delay duration, $F(2,78) = 6.33$, $p < .05$, $\eta_p^2 = .14$. MSE = .9.

Paired samples correlations were then carried out and showed significant correlations between the no-clicks and clicks for the 3 second delay duration, $p < .001$. However, there was no significant correlation between the no-clicks and clicks for the 5 and 8 second delay duration, $p = .32$ and $p = .28$, respectively. Paired-samples *t* tests were then carried out between the two conditions (delay type and delay duration) which found significant differences between the following pairs: clicks and no-clicks at the 3 second duration, $t(39) = 3.96$, $p < .001$ and for clicks and no-clicks at the 5 second duration, $t(39) = 2.1$, $p <.05$. However, there was no significant effect between the two conditions (delay type and delay duration) for clicks and no-clicks at the 8 second duration, $t(39) = -.62$, $p = .54$.

10.1.3 Discussion

The present study investigated whether the delay type (clicks or no-clicks) and the delay duration (3, 5 or 8 seconds) had an effect on recognition (number of correct responses). It was predicted that correct recognition for the image would decrease when the delay period was filled with clicks compared to no-clicks. In addition, it was predicted that as the delay period increased, correct recognition would decrease. Findings showed that, in general, it appears that clicks also increase the rate of memory decay. Clicks increase the rate of memory decay, compared to no-clicks, for both the 3 and 5 second delay duration. However, no effect of clicks on memory decay is found at the 8 second delay duration.

There are two potential explanations for these effects. First, clicks lengthen subjective experience of duration (speed-up the internal clock), which subsequently allows the participants more time in which to process the information given to them. This suggests that psychological processes take place in subjective as opposed to real ‘clock’ time. Second, is the notion that clicks directly increase the rate of information processing which then goes on to distort subjective duration of time. In sum, the question of how the clicks work is one of directionality. Either the clicks ‘speed up’ the internal clock and subsequently ‘speed up’ information processing, or changes in information processing cause a change in subjective time. Further investigating whether information processing takes place in subjective time rather than real time, the present study showed that information processing (in this case, the psychological process of memory) does indeed appear to take place in subjective time. This is indicated by the finding that clicks, which lengthen subjective duration, resulted in an increase in memory decay. If on the other hand, information processing occurs in real time, then we would expect no effect of clicks on memory decay. This conclusion is consistent with previous findings (i.e., Jones et al., 2010) which found improved recall performance with clicks. It is important to point out the differences between the present study and the previous ones (Jones et al., 2010). In the present study, clicks were presented after the presentation of the first image to be remembered while, in the previous studies, the clicks preceded the display (i.e., the matrix). Despite, these differences, findings remained consistent.

A potential flaw with the present study is that although decay was greater with clicks, it could be that just having any noise in the retention interval (the delay of either 3, 5 or 8 seconds) would have the same effect. To investigate this potential confound in the present experiment, in the temporal lab at The University of Manchester, the experiment was repeated with an additional white noise condition and findings revealed no difference between white noise and clicks. However, both white noise and clicks increased the rate of memory decay more than silence. This suggests then, that the fact we have any noise in the retention interval may be causing the increase in memory decay and it is not specific to the repetitive nature of the clicks and any effect this may be having on the internal clock. However, both the present experiment and the improved design conducted in the temporal lab are somewhat flawed and on reflection in order to properly investigate this, a potential future experiment could instead modify the order of events in the experiment. In the original study the sequence of events were as follows: 1) participants given the image to encode, 2) the presentation of a delay of either 3, 5 or 8 seconds filled with either clicks or no-clicks and lastly, 3) the presentation of the recognition task. The future experiment could improve on this by modifying the structure so that the noise given is not presented during the retention interval and thus causing any potential interference effects during this delay/retention interval. So the experiment would be structured as follows: 1) participants given the image to encode, 2) the presentation of five seconds of either no-clicks, clicks or white noise, 3) then the retention interval of either 3, 5 or 8 seconds and lastly, 4) the presentation of the recognition task. Although not perfect, this potential experiment attempts to separate the retention interval from the noise manipulation (silence, clicks and white noise). Having a white noise condition as well as the clicks would also address the critique of masking as being the possible mechanism by which the clicks could have interfered with storage resulting in the findings of the present study. If there is an effect of clicks and not white noise in this modified experiment, then it would suggest that the observed effects are due to something other than simple masking effects.

In conclusion, the findings from the present study showed that clicks, compared to no-clicks, increase the rate of memory decay at delay durations of 3 and 5 seconds. However, this effect disappears at delay durations of 8 seconds. These findings suggest that the click trains, despite being played after the presentation of the ‘to be remembered’ shape, interfered with the stored representation. The current study shows that lengthening subjective time through the use of clicks did indeed result in greater memory decay, suggesting that information processing takes place in subjective time. Thus suggesting that information processing is mediated in some direction by the speed of the internal clock.

Chapter 11

The Effect of Clicks and Emotionally Arousing Auditory and Visual Stimuli on Verbal Estimation

11.1 Experiment 7a - Verbal Estimation of Tones after Five Second Presentation of Emotionally Arousing Visual Stimuli and Clicks

As discussed in Chapter 1, it is well known that in situations of high danger or fear (e.g., such as in a car crash) people report that ‘time slows down’, an effect simulated (but to a lesser extent) in the laboratory through the use of ‘click trains’ (i.e., Penton-Voak et al., 1996). Previous studies have found that repetitive stimulation (in the form of flashes or clicks) can create a subjective lengthening of the experience of time (Treisman et al., 1990). Since it is argued by Treisman et al. (1990) that this effect is due to the periodic stimulation producing an increase in “arousal” (leading to a higher pacemaker rate), it seems that the next logical step in exploring this issue would be to investigate the stimuli that we know to be arousing and examine their effect on individual’s timing estimations. In other words, if the clicks are indeed arousing in some way (as argued by, for example, Treisman et al., 1990), then will any clearly arousing stimuli produce the same effect?

The research question that the present experiment addressed was what are the effects of emotionally arousing visual stimuli on verbal estimation of tones? To this aim, using a task of verbal estimation of tones, the present experiment used pictures which were either high or low in arousal as well as including click train stimuli and silence as two other conditions. The high and low arousing picture stimuli were all taken from the International Affective Picture System (IAPS) database (See Appendix A). Some examples of the low arousing pictures include a rabbit and a butterfly. The high arousing pictures include, for example, a mangled hand and an electric chair. This study examined specifically whether stimuli which are known to be arousing cause overestimation of duration in the same way that clicks appear to do. If they failed to show an effect, this would show that there is something intrinsic about the clicks themselves. Suggesting that it is the repetitive nature of the clicks which is important. On the other hand, if the high arousing pictures did indeed produce overestimation, this would lend support to the idea that there may be some internal clock which is being manipulated resulting in the subjective time distortions. Importantly, it would suggest that the clicks may produce their effect, not because of their repetitive nature, but because they are somehow arousing.

11.1.1 Method

Participants

Thirty-five undergraduate psychology students took part for course credits which were not contingent on performance.

Apparatus

See apparatus for Experiment 1a.

Procedure

At the beginning of each session, instructions appeared on the computer screen, participants were requested to press the space bar to commence the first trial when ready. There were four trial conditions (click, no-click, low and high arousing pictures taken from the IAPS). Ten low arousing pictures and ten high arousing pictures were selected from the IAPS database (see Appendix B for ratings on dimensions of valence and arousal). In the click condition, participants were instructed to look at a fixation cross in the centre of the screen and to begin the trial by pressing the spacebar. In condition A, a 700Hz tone was then presented for 25ms. After which there was five seconds of clicks (5Hz), followed by another 700Hz tone presented for 25ms. After this, there was a random delay between 300 and 1,200ms. Then a tone (500Hz) was presented through headphones. The tone was selected randomly from a selection of ten different tones. The tones differed only in duration (300, 478, 567, 656, 745, 834, 923, 1,012, 1,101 and 1,300ms). After the tone, a screen was presented with the following instruction: ‘Type in your estimate of the tone. Press enter for next trial’. The participant then typed their response and pressed enter and an instruction to ‘Press spacebar for next trial’ appeared. Condition B was the same as condition A except that instead of five seconds of clicks, there were five seconds of silence. Condition C was the same, except with the presentation of a low arousing picture for five seconds and condition D, a high arousing picture for five seconds. Participants were given a minimum and maximum value to limit their estimates, between 250ms and 1,350ms. Each of the four conditions were randomised across participants. There were 40 trials in each, giving a total of 160 trials. Since there were ten different tones to be verbally estimated, each condition randomly presented each of the ten tones four times. The picture stimuli were also presented with equal frequencies. Each of the ten high and low arousing picture stimuli was presented four times.

11.1.2 Results

The data from three participants were removed from the analysis as their estimates indicated that they had not attended to the task. One participant who was removed had a block in which they rated all the stimuli as lasting 1,350ms with a few rated as 1,200ms. Also, they did not keep within the range provided to select their estimates (range between 250 and 1,350ms) as some of the responses were as low as 50ms. The other two participants who were removed also gave estimates that were outside of the range (i.e., 50 and 100ms). The remaining thirty-two participants' data was analysed. The data were analysed in two different ways: initially using verbal estimates, then using slope and intercept values derived from regression analysis on each individual participants' data.

Verbal Estimates

The verbal estimates from thirty-two participants were analysed. Figure 39 shows the mean verbal estimates (in milliseconds) plotted against stimulus duration for all four conditions (clicks, no-click, low and high arousing visual stimuli). Inspection of Figure 39 suggests that mean estimates increased as an approximately linear function of actual stimulus duration in all four conditions.

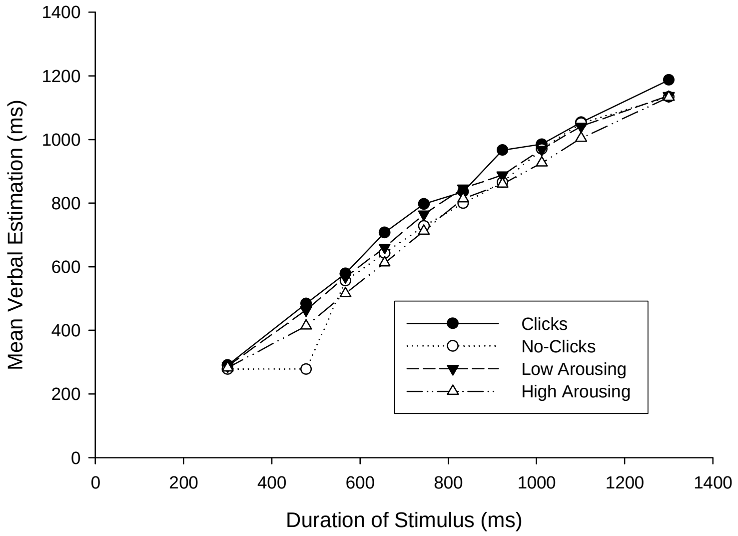


Figure 39: Mean verbal estimates for each of the ten duration types plotted for all conditions (clicks, no-click, low and high arousing visual stimuli) of Experiment 7a.

A repeated measures ANOVA was then used with one factor being condition (clicks, no-clicks, low and high arousing stimuli) and the other being stimulus duration (one for each of the ten durations). There was a significant main effect of condition, *F*(3,93) = 4.33, $p < .05$, $\eta_p^2 = .12$, MSE = 50272.73 and a significant main effect of stimulus duration, *F*(9,279) = 441.39, $p < .001$, $\eta_p^2 = .93$, MSE = 21480.1. However, there was no condition x stimulus duration interaction, *F*(27,837) = 1.11, $p = .32$, $\eta_p^2 = .04$, MSE = 8874.7.

The results for the click and no-clicks conditions and the low and high arousing conditions were then analysed separately. Figure 40 shows the mean verbal estimates (in milliseconds) plotted against stimulus duration for both the click and no-click conditions. Descriptive analysis showed that the mean verbal estimates of duration for the click and no-click conditions were 788.48ms (SE = 21.67) and 745.51ms (SE = 21.31), respectively. Inspection of Figure 40 suggests that mean estimates increased as an approximately linear function of actual stimulus duration in both conditions (clicks and no-clicks). Furthermore estimates of stimulus duration appear to be consistently longer for the stimuli preceded by clicks than for those preceded by silence.

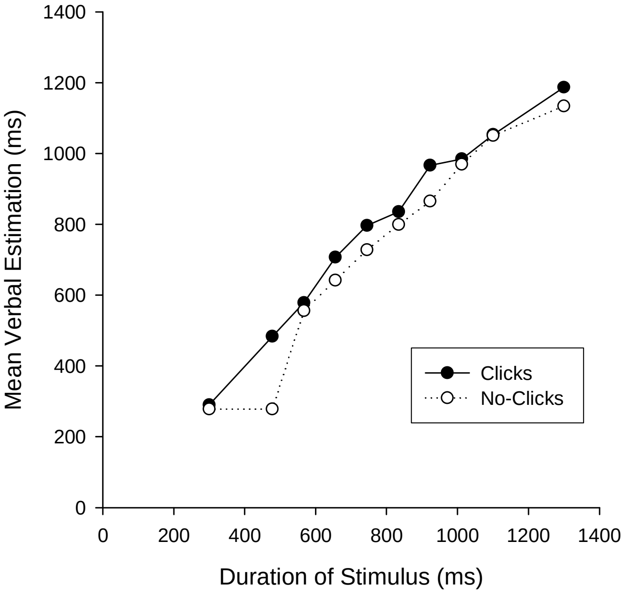


Figure 40: Mean verbal estimates for each of the ten duration types plotted for both click and no-click conditions of Experiment 7a.

Figure 41 shows the mean verbal estimates (in milliseconds) plotted against stimulus duration for both the low and high arousing visual stimuli conditions. The mean verbal estimates of duration for the low and high arousing visual stimuli were 762.5ms (SE = 27) and 727.13ms (SE = 25.5), respectively. Inspection of Figure 41 suggests that the mean estimates increased as an approximately linear function of actual stimulus duration in both conditions (low and high arousing picture stimuli). Furthermore estimates of stimulus duration appear to be consistently longer for the stimuli preceded by low arousing picture stimuli than for those preceded by high arousing picture stimuli.

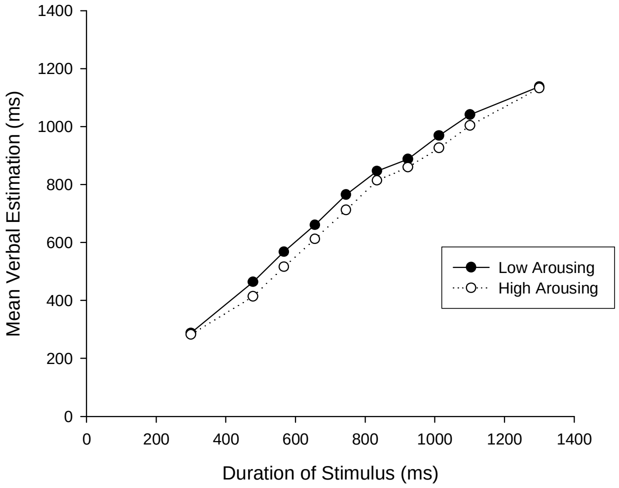


Figure 41: Mean verbal estimates for each of the ten duration types plotted for both low and high arousing picture stimuli conditions of Experiment 7a.

A repeated measures ANOVA was used with one factor being presence or absence of clicks (clicks and no-clicks) and the other being stimulus duration (one for each of the ten durations). There was a main effect of clicks on estimates, $F(1,31) = 7.87$, $p < 0.01$, $\eta_p^2 = .20$, MSE = 37558.67 and a significant main effect of stimulus duration, $F(9,279) = 361.37$, $p < .001$, $\eta_p^2 = .92$, MSE = 13425.58. However, there was no significant clicks/no-clicks x stimulus duration interaction, $F(9,279) = 1.47$, $p = .16$, $\eta_p^2 = .05$, MSE = 10324.23.

Similarly, a repeated measure ANOVA was used with one factor being arousal condition (low versus high arousing stimuli) and the other being stimulus duration (one for each of the ten durations). There was a borderline significant main effect of arousal condition on estimates, $F(1,31) = 3.72$, $p = .06$, $\eta_p^2 = .11$, MSE = 53838.19 and a significant main effect of stimulus duration, $F(9,279) = 282.8$, $p < .001$, $\eta_p^2 = .9$, MSE = 16402.89. However, there was a non-significant arousal condition x stimulus duration interaction, $F(9,279) = .66$, $p = .75$, $\eta_p^2 = .02$. MSE = 7951.52.

Linear Regression Analysis

Slope Values

Linear regressions for each individual participant for each condition were then calculated and the slope values were analysed. Figure 42 shows the mean slope values for all four conditions (clicks, no-clicks, low arousing and high arousing). The mean overall slope value was 0.9 for the click condition and 0.89 for the no-click condition. The mean overall slope values were 0.87 for the low arousing picture stimuli and 0.88 for the high arousing picture stimuli. Inspection of Figure 42 suggested that the mean gradients do not differ greatly across all conditions, clicks, no-clicks, low and high arousing picture stimuli.

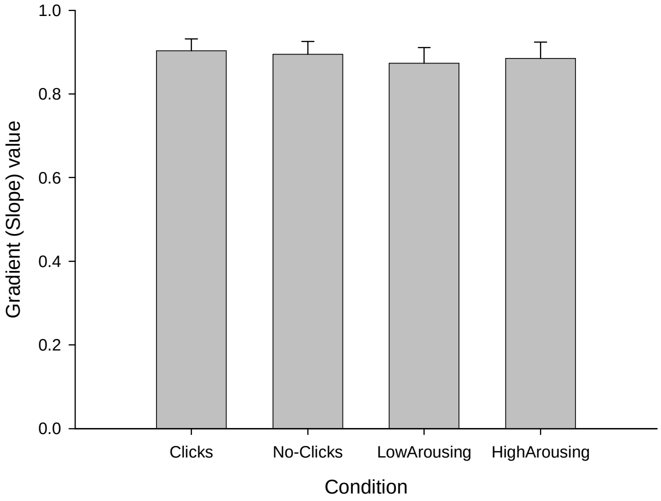


Figure 42: Mean slope values for all four conditions (clicks, no-clicks, low arousing and high arousing stimuli) of Experiment 7a.

A repeated measures ANOVA with one factor; condition (clicks, no-clicks, low and high arousing visual stimuli) was conducted on the mean slope values. There was no significant main effect of condition, $F(3,93) = .31$, $p = .82$, $\eta_p^2 = .01$, MSE = .02.

Paired-samples *t* tests on the slope values derived from regression of data from individual participants found no significant difference between the clicks slope and no-clicks slope values, $t(31) = .29$, $p = .77$ and for the difference between the low arousing slope and high arousing slope values, $t(31)= -.39$, $p = .7$.

Intercept Values

Linear regressions for each individual participant for each condition were then calculated and the intercept values were analysed. Figure 43 shows the mean intercepts values for all four conditions (clicks, no-clicks, low and high arousing). The overall mean intercept values were 74.14 and 37.49 for the click and no-click conditions respectively. The mean overall intercept values were 71.6 and 26.42 for the low and high arousing picture stimuli respectively. Inspection of Figure 43 suggested that mean intercept values are greater for the clicks and low arousing stimuli conditions compared to the no-clicks and high arousing conditions.

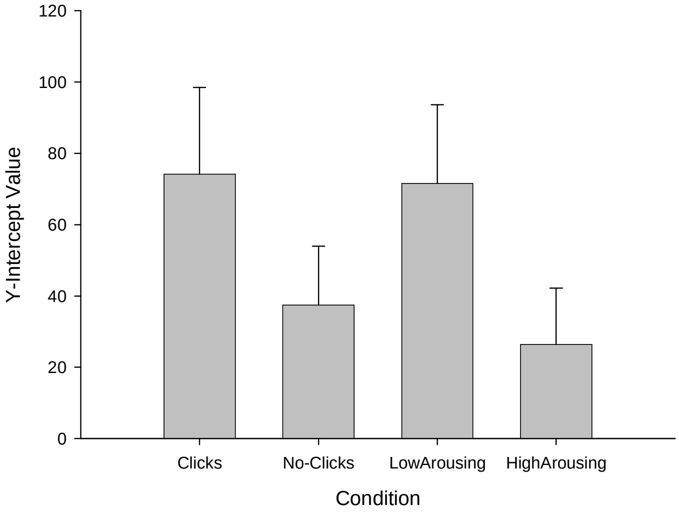


Figure 43: Mean intercept values for all four conditions (clicks, no-clicks, low arousing and high arousing stimuli) of Experiment 7a.

A repeated measures ANOVA with one factor; condition (clicks, no-clicks, low and high arousing visual stimuli) was conducted on the mean intercept values. There was no significant main effect of condition, $F(3,93) = 2.18$, $p = .1$, $\eta_p^2 = .07$, MSE = 8524.23.

Paired-samples *t* tests on the intercept values derived from regression of data from individual participants found a borderline significant effect of the difference between the clicks intercepts and no-clicks intercepts, $t(31) = 1.76$, $p = .09$ and for the difference between the low arousing stimuli intercept and high arousing intercept values, $t(31)= 1.86$, $p = .07$.

11.1.3 Discussion

The main results of the current study confirmed previous findings (Jones et al., 2010), that verbal estimates of tones are perceived by the participant as greater when preceded by clicks compared to when they are preceded by no-clicks. However, there was no significant difference in the slope values of the clicks and no-clicks conditions. The research question that this experiment addressed was whether emotionally arousing visual stimuli has an effect on the verbal estimation of tones. Findings showed that tones were perceived as lasting subjectively longer when preceded by low arousing stimuli compared to high arousing stimuli, although this reached only borderline significance. Additionally, slope anaylsis revealed no significant difference between the low arousing and high arousing stimuli. If the effect of clicks was due to their arousing capabilities on the speed of the internal clock, then surely we would expect that the high arousing pictures would result in an increase in the subjective length of the tonal durations. It appears then, that arousal may not necessarily be what underlies participants' overestimation of tonal duration and the effect of clicks. However, the findings from this study do not rule out entirely the possibility that the clicks have an arousing effect on the speed of the internal clock. In order to further establish this, Experiment 9 of this thesis will explore electrophysiological response during the clicks to see whether there are any indications of arousal induced by them.

A potential limitation with the present study is the inclusion of a click condition. This is potentially problematic since we know that clicks have an effect on participants' internal clock and one of the explanations for how this occurs is that the clicks are somehow arousing and this in turn speeds up the internal clock. Therefore it is possible that the high arousing stimuli condition, compared to the click condition, is somehow not as relatively as arousing. Put another way, it is possible that without the click condition, the high arousing stimuli may have had a significant effect on participants' estimates of duration. A future experiment could explore this by repeating the experiment with the omission of the click condition. Instead, the click condition could be replaced with a neutral picture condition.

The use of a mixture of high arousing emotions may also be problematic. There were ten different high arousing picture stimuli used in the present design (snake; spider; pit bull;

shark; angry face; injury; electric chair; aimed gun; roaches on pizza and sliced hand). They were selected for the condition of high arousal because they were rated in the IAPS as being highly arousing. However, what is not considered or included is the type of discrete emotion of the pictures. There are generally three types of high arousal emotions represented in the ten pictures, namely, anger (angry face), fear (snake, pit bull, shark, injury, electric chair and aimed gun) and disgust (spider, roaches on pizza and sliced hand). Pictures with the discrete emotion type of fear are predominant. Studies have revealed that the type of discrete emotions employed is crucial in timing judgments. For instance, Tipples (2007) found that angry facial expression produced a greater overestimation of time (relative to neutral facial expressions) compared to both fearful and happy expressions. Although previous studies (i.e., Droit-Volet et al., 2004) have found that the duration of angry facial expressions is generally overestimated compared to neutral and other facial expressions, they failed to compare the effects of angry expressions with other types of negative highly arousing facial expressions. Tipples (2007) also found that the perceived arousal of the sender is not the only factor at play in the emotional responses and the subsequent effects on time estimation. Typically, fearful faces are rated as being more arousing than angry faces. If the effects of facial expressions on time perception vary only as a function of the aroused state or facial expression of the sender then fearful and angry expressions should have produced the same degree of overestimation. However, overestimation was significantly greater for angry expressions which may be evidence of a fear-specific response system.

Additionally, Droit-Volet and her colleagues, using facial expressions of both disgust and anger (both rated as arousing) found that disgust induced no timing distortions (Droit-Volet & Meck, 2007; Droit-Volet & Gil, 2009; Gil & Droit-Volet, 2009). Indeed, only the angry face resulted in an overestimation compared to neutral faces. Since the basic function of disgust is to avoid the ingestion of foods that may make us ill (Darwin, 1872/1998) a disgusted face may not be relevantly strong enough a cue to affect time processing. Angry faces, on the other hand, depict a social signal of potential aggression (Marsh, Ambady, & Keck, 2005) and, in order to survive, the perceiving organism must quickly prepare to respond (fight or flight).

The importance of the type of emotional stimuli selected for study is further highlighted in a study Gil and Droit-Volet (in press) which explored time perception in response to ashamed faces in children and adults and found that from the age of 8 years, participants who recognised the facial expressions of shame underestimated their presentation time compared to that of neutral faces. However, no time distortion was found in the children who did not recognise the ashamed faces or in those younger children who did. This suggests that shame is a self-conscious emotion which develops to involve an attentional mechanism as indicated by underestimation.

All these findings are important for the present findings since three of the ten high arousing pictures were disgust. This may have reduced the effect (if any) of the fear and anger emotional stimuli. A future study could repeat the same experiment with separate conditions for fear, anger and disgust. This would enable the investigation of specific discrete emotions. Grommet, Droit-Volet, Gil, Hemmes, Baker and Brown (2011) explored time estimation of fear cues in human observers using images from the IAPS. Findings revealed that judgments were longer for fear cues than for neutral images and that the mechanism underlying this difference in temporal judgments produced by fear versus neutral cues was additive rather than multiplicative implying mediation by the switch mechanism rather than any clock speed manipulation.

In sum, the present experiment suggests that the effect of clicks may not be mediated by arousal because when we replaced the clicks with stimuli which we know to be highly arousing, there was no effect on verbal estimates compared to low arousing stimuli. However, it is possible that we have found no effect of high arousing stimuli on verbal estimates because of the type of modality employed in the present experiment. Perhaps if we used stimuli in the *auditory* modality an effect may be found. In order to establish whether this is case, Experiment 7b explored the effect of emotionally arousing *auditory* stimuli on verbal estimation of tones.

11.2 Experiment 7b - Verbal Estimation of Tones after Presentation of Emotionally Arousing Auditory Stimuli

Experiment 7a found no effect of emotionally arousing visual stimuli but perhaps this was due to the nature of the modality used. The research question that Experiment 7b addressed was what are the effects of emotionally arousing *auditory* stimuli on verbal estimation of duration? No previous study had replaced clicks with emotional stimuli. To our knowledge, only one other study had used emotional sounds as stimuli to be timed. This study, carried out by Noulhiane, Mella, Samson, Ragot and Pouthas (2007), asked participants to estimate the duration of a variety of emotional sound stimuli (2, 3, 4, 5 or 6 seconds in duration). Their main finding included high arousing stimuli being perceived as shorter than low arousing stimuli. In addition, they found that negative sounds were perceived as longer than positive ones. These findings are interesting with respect to the effects of emotional sounds on human timing abilities. The findings suggest that emotional stimuli, at least the auditory domain, result in an increase in the rate of the pacemaker. However, there are some limitations to the study carried out by Noulhiane et al. (2007) which prompted us to carry out the experiment which is addressed in Experiment 8.

As in experiment 7a, we used auditory stimuli that we definitely know to be emotionally arousing. The same sound categories as Noulhiane et al. (2007) were adopted. However, many of the sound stimuli were changed in order to more accurately reflect the emotional categories (see Rating Experiment, section 11.2.2). Emotional sounds were presented for five seconds followed by the classic tonal durations to be estimated (300, 478, 567, 656, 745, 834, 923, 1,012, 1,101 and 1,300ms). The Self-Assessment Manikin (SAM) (Bradley & Lang, 2007) was also used for participants to rate each sound on two dimensions, namely, arousal and valence. This particular measure was used because it was the same one used by Noulhiane et al. (2007) as well as being the measure used to determine the ratings of the sounds in the International Affective Digitalized Sounds Database (from which the sounds for the study were taken). The importance of carrying out this further experimental rating task was crucial. It demonstrated that the participants who took part in the main experiment of the present study, overall, perceived the sounds to be similar on dimensions of pleasure and arousal to that of IADS. This effectively allowed the confirmation that the sound stimuli contained in each of the emotional sound categories, accurately reflected that category in the current study.

If there is an effect of the emotionally arousing auditory stimuli on participant’s estimates of duration, then it would support the idea that arousal mediates the effect of clicks. If on the other hand, no effect of emotionally arousing auditory stimuli is found, then this would support the idea that the effect of clicks is due to their repetitive nature rather than any arousing or attentional properties it may be exerting. Additionally, it would support the idea that the effect of clicks is due to some effect it may have on the internal clock.

11.2.1 Method

Participants

Thirty-four undergraduate participants took part and were compensated with four course credits which were not contingent on performance.

Apparatus

See apparatus for Experiment 1a. In this study the Self-Assessment Manikin (SAM) (Bradley & Lang, 2007) was employed.

Procedure

The same five sound categories as Noulhiane et al. (2007) were used. Namely, (a) pleasant high-arousal sounds (e.g., erotic sounds), (b) pleasant low-arousal sounds (e.g., brook), (c) unpleasant low-arousal sounds (e.g., clock), (d) unpleasant high-arousal sounds (e.g., female scream), (e) one group of 6 neutral low-arousal sounds (e.g., rain). (See Appendix C for sounds used in each condition). (See 'Rating Experiment' in section 11.2.2 for detail on the ratings of these sounds and why they were chosen). There were two additional conditions which acted as controls, namely, silence and a 500Hz tone.

The present study, therefore, had seven conditions. Each category contained six different sounds. Each participant received three randomly from each category during the entire experiment. This enabled each sound stimuli to be coupled randomly (with equal frequency) with each of the subsequently presented 500Hz tonal durations to be estimated (300, 478, 567, 656, 745, 834, 923, 1,012, 1,101 and 1,300ms). Participants received five seconds of the emotional sound, silence or the 500Hz control tone followed by the 500Hz tone to be estimated. There were 210 trials in total, split into seven groups of thirty.

At the beginning of each session, the following instructions appeared on the computer screen: "Press the space bar to commence the first trial when ready". A 700Hz tone was then presented for 25ms. After which there was five seconds of one of the conditions: pleasant high-arousing; pleasant low-arousing; unpleasant low-arousing; unpleasant high-arousing; neutral sound; control sound (silence) or the control sound (500Hz tone), followed by another 700Hz tone presented for 25ms. After which there was a random delay between 300 and 1,200ms. Following the random delay, a 500Hz tone was presented through headphones. The tone was selected randomly from a selection of ten different tones. The tones differed only in duration (300, 478, 567, 656, 745, 834, 923, 1,012, 1,101 and 1,300ms). After the tone was presented, a screen was shown with the following instruction: ‘Type in your estimate of the tone. Press enter for next trial’. When the participant had entered their response and pressed enter, another screen appeared with the instruction to ‘Press spacebar for next trial’. The participants were given a range from which they could select their estimates of duration. This was from 250 through to 1,350ms. The experiment was programmed not to accept estimates not contained within this range. The participant was unable to continue until they rectified the error by making a correct entry.

After the participants had taken part in the verbal estimation experiment, they were then given a rating task. This involved presenting the participants with all of the 30 sounds (half of which they had heard during the experiment). After they had heard each sound, they were then asked to rate each of the sounds according to two dimensions of valence (pleasure) and arousal, using the Self-Assessment Manikin (SAM). SAM is an affective rating system devised by Lang (1980) and also used by Bradley and Lang (1994). The rating system uses graphic figures which depict values along each of the two dimensions on a continuously varying scale representing emotional reactions. SAM ranges from a smiling, happy figure to a frowning, unhappy figure when representing the affective valence dimension. For the arousal dimension, SAM ranges from an excited, wide-eyed figure to a relaxed, sleepy figure. The scale for each of the two dimensions goes from 1 – 9. Participants were told they could indicate how they felt while listening to the sound by typing in the number which corresponded to the feeling that the figure represented on the scale. For the arousing scale, participants were told that the nine figures were arranged along a continuum. For this scale, they were told that 1 represented one extreme on the scale, namely, a feeling of being completely relaxed, calm, sluggish, dull, sleepy and un-aroused. The scale gradually became less relaxing with the other extreme of the scale (9) being very stimulated, excited, frenzied, jittery, wide-awake, aroused (See Appendix D for this scale).

Similarly, for the valence scale, participants were told that the nine figures were arranged along a continuum. For this scale, they were told that 1 represented one extreme on the scale, namely, a feeling of being completely unhappy, annoyed, unsatisfied, melancholic, despaired and bored. The scale gradually became less unhappy as it progressed towards 9 with 9 being the other end of the extreme representing feelings of being very happy, pleased, satisfied, contented and hopeful (See Appendix D for this scale).

11.2.2 Results

Verbal Estimation: Internal Clock Speed

Figure 44 shows all the mean verbal estimates plotted against stimulus duration for all seven sound conditions. Descriptive analysis showed that the mean verbal estimates of the tones for the seven sound conditions (pleasant high-arousing; pleasant low-arousing; unpleasant low-arousing; unpleasant high-arousing; neutral sound; control sound of silence and control sound of a 500Hz tone) were as follows: 702.04ms (SE = 27.79); 694.44ms (SE = 24.85); 689.93ms (SE = 22.21); 711.34ms (SE = 26.65); 690.39ms (SE = 24.12); 635.13ms (SE = 27.07) and 736.38ms (SE = 29.04). Inspection of Figure 44 suggests that mean estimates increased as an approximately linear function of actual stimulus duration across all seven conditions. From the graph, the largest difference appears to be between the control sound silence and control sound (500Hz tone). This can be seen more clearly in Figure 45. Figure 45 also seems to demonstrate the classic empty versus filled duration illusion which has been investigated by Wearden, Norton, Martin and Montford-Bebb (2007). Wearden et al. (2007) found that the subjective durations of tones were significantly greater than those of unfilled intervals (represented either by clicks or gaps). Specifically, Wearden et al. (2007) found that the unfilled intervals were judged as being approximately 55%–65% of the duration of the filled ones despite the duration being the same. With respect to Figure 45, participants appear to give significantly higher estimates of the duration of the tones when they were preceded by a filled interval (500Hz tone) compared to when they were preceded simply by silence.

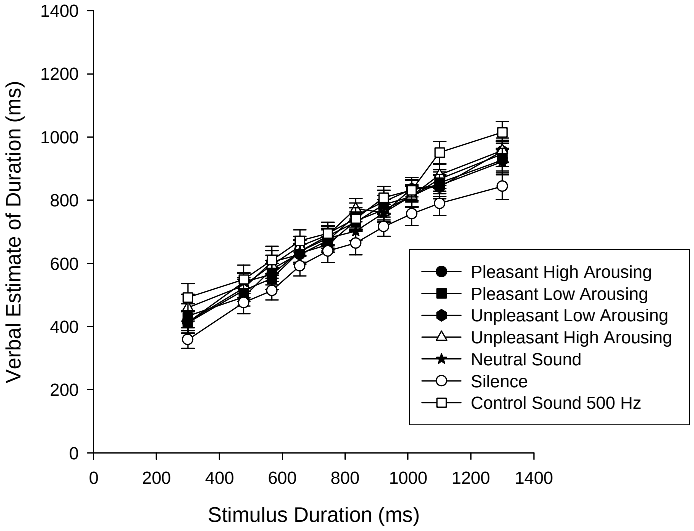


Figure 44: Mean verbal estimates plotted against stimulus duration for all seven conditions of Experiment 7b.

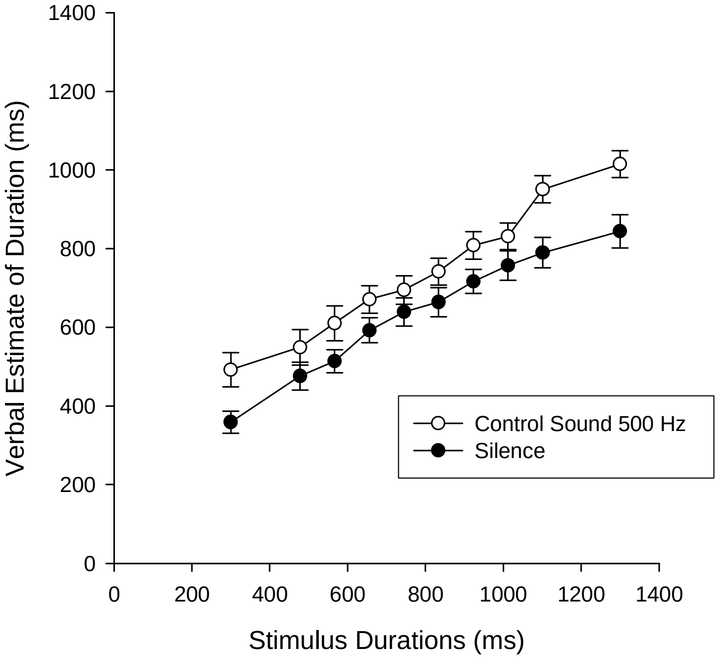


Figure 45: Mean verbal estimates plotted against stimulus duration for control sound silence and control sound 500Hz tone conditions of Experiment 7b.

The data were analysed in two ways, firstly the mean estimate data was analysed. Secondly linear regression for each individual participant for each condition was calculated and the intercept values were analysed. No linear regressions were performed on the slope values for each individual participant on all conditions because there was no significant two-way interaction between stimulus duration and arousal condition. However, because of the trend found in Figure 45, a separate analysis (both repeated measures and slope analysis) on the control sound (500Hz tone) versus silence was performed.

Mean Verbal Estimates Analysis

A repeated measures ANOVA was used with one factor being the arousal condition (pleasant high-arousing; pleasant low-arousing; unpleasant low-arousing; unpleasant high-arousing; neutral sound; control sound, silence and control sound, 500Hz tone) and the other being stimulus duration (one for each of the ten durations). There was a significant main effect of arousal condition on estimates, $F(6, 198) = 6.22$, $p < .001$, $\eta_p^2 = .16$, MSE = 51498.39. There was also a significant main effect of stimulus duration, $F(9, 297) = 86.6$, $p < .001$, $\eta_p^2 = .72$. MSE = 70117.84. However, there was no significant arousal condition x stimulus duration interaction, $F(54, 1782) = 1.09$, $p = .3$, $\eta_p^2 = .03$, MSE = 1782.

However, it could be that only one or two conditions were driving this significant effect of condition, namely, the control sound of 500Hz and silence. In order to establish whether this was the case, a second repeated measures ANOVA was carried out with the condition of control sound (500Hz) and control sound (silence) removed from analysis. Indeed, it showed that the control sounds were driving the significant effect found before, since no main effect of arousal condition was found, $F(4, 132) = 1.57$, $p = .19$, $\eta_p^2 = .05$, MSE = 17823.5. There was still a main effect of stimulus duration, $F(9, 297) = 80.71$, $p < .001$, $\eta_p^2 = .71$, MSE = 54024.53 and no stimulus duration x arousal condition interaction, $F(36, 1188) = .87$, $p = .69$, $\eta_p^2 = .03$, MSE = 9729.35.

In order to explore whether the filled duration illusion was taking place, a repeated measure ANOVA was carried out with one factor being condition (control sound of a 500Hz tone and silence) and the other factor being stimulus duration. There was a significant main effect of condition, $F(1,33) = 12.92$, $p < .05$, $\eta_p^2 = .28$, MSE = 134833.93. There was also a significant main effect of stimulus duration, $F(9,297) = 60.74$, $p < .001$, $\eta_p^2 = .65$, MSE = 28329.17. Lastly, there was a significant condition x stimulus duration interaction, $F(9,297) = 2.2$, $p < .05$, $\eta_p^2 = .06$, MSE = 12165.96.

Linear Regression Analysis

Intercept Values

Figure 46 shows the mean intercept values for each of the seven conditions. The mean overall intercept value for the seven conditions: pleasant high-arousing; pleasant low-arousing; unpleasant low-arousing; unpleasant high-arousing; neutral sound; control sound (silence) and control sound (500Hz tone) were, 277.64ms (SE = 47.91); 261.04ms (SE = 51.05); 279.42ms (SE = 49.6); 308.09ms (SE = 56.43); 284.89ms (SE = 49.75); 225.53ms (SE = 41.53) and 302.48ms (57.24), respectively. Inspection of Figure 46 suggests that that there may be some significant difference between the intercept values for some of the conditions, for example, control sound (silence) compared to unpleasant high-arousing. Subsequent statistical analysis was carried out to determine whether this is indeed significant and also if any others are statistically significant.

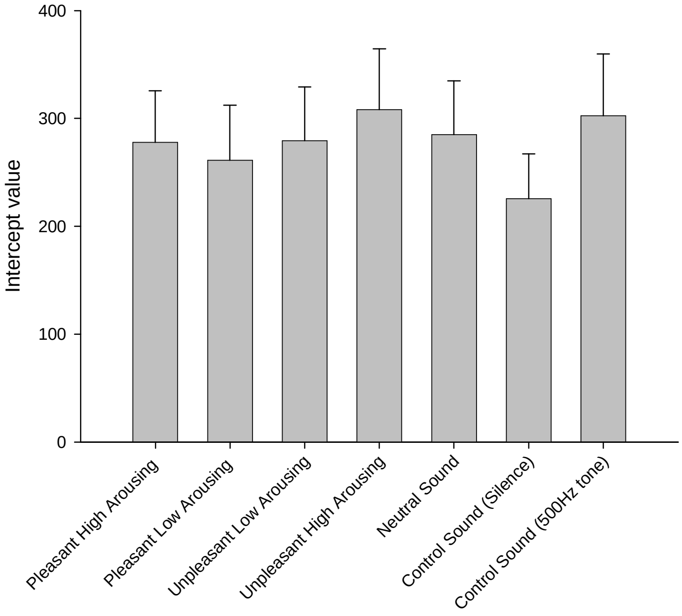


Figure 46: Mean intercept values (ms) plotted against all seven arousal conditions of Experiment 7b.

A repeated measures ANOVA with one factor; arousal condition (pleasant high-arousing; pleasant low-arousing; unpleasant low-arousing; unpleasant high-arousing; neutral sound; control sound (silence) and control sound (500Hz tone)) was conducted on the mean intercept values. There was no significant main effect of arousal condition, $F(6, 198) = 1.76$, $p = .11$, $\eta_p^2 = .05$, MSE = 14792.19. So we can conclude that there is no evidence to suggest a significant effect of arousal on participants' verbal estimations of tones.

Slope Values for the Control Sound (500Hz tone) and Silence

The mean slope values for the silence and control condition (500Hz tone) was .49 (SD = .05) and .55 (SD = .05), respectively.

A repeated measures ANOVA with one factor; condition (control sound of a 500Hz tone and silence) was conducted on the mean slope values. There was a significant main effect of condition, $F(1,33) = 4.17$, $p < .05$, $\eta_p^2 = .11$, MSE = .01. Therefore, when the interval is filled (in this case with a 500Hz tone), participants judged the subsequent tone as being longer than when it was preceded by the unfilled interval (silence). This supports the findings by Wearden et al. (2007) with respect to the filled duration illusion.

Rating Experiment

In addition to the main experiment, each participant took part in a further experiment which obtained each participant's own ratings of arousal and valence on all thirty emotional sounds. These scores were then analysed to see if they were consistent with the scores in the IADS (See Appendix E for stimuli used in the present study versus IADS for both arousal and pleasure). As discussed in the introduction, the present study used the same emotional categories as those used by Noulhiane et al. (2007) but improved on the stimuli used in each category. The stimuli used in each category by Noulhiane et al. (2007) were in many instances not appropriate (or best) for the categories that they were put into. Due to the complex nature of emotional stimuli, it was impossible to have discrete categories. There was some degree of overlap as a result of this in the ratings. For instance, it is very difficult to get a sound which is both unpleasant and low in arousal. Despite this, the study does improve on the one carried out by Noulhiane et al. (2007). As an example, one of the sounds they selected for the pleasant high arousing category was IADS 810 (Beethoven). The ratings for the valence dimension was appropriate (Mean = 7.51, SD = 1.66), however, the rating for the arousal dimension was not in the correct range (Mean = 4.18, SD = 1.66). What is highlighted in bold, under sound conditions, is what was removed and changed for the present study (See Appendix F for the stimuli used by Noulhiane et al., 2007). Additionally, the neutral condition was reduced to six different sounds to be consistent with the other sound conditions. Noulhiane et al. (2007) included twelve different neutral stimuli, despite having six in all other sound categories.

Pearson's product moment correlation coefficients (Pearson's *r*) were then performed. The correlation between subjective valence rating scores from the participants of the present study and those of the IADS were significant ($p < .001$, $r = .97$), which shows that the subjective valence ratings were consistent with those of the IADS. Correlations between subjective arousal rating scores from the participants of the present study and those of the IADS were significant ($p < .001$, $r = .93$), which shows that the subjective valence ratings were consistent with those of the IADS (See Appendix G for differences between present and IADS on ratings for mean arousal and pleasure/valence). For the valence dimension, the ratings for the selected unpleasant stimuli on the IADS ranged from 1.63 to 4.86. On the neutral rating, stimuli ranged from 5.31 to 5.99. On the pleasant rating, stimuli ranged from 6.2 to 7.9. For the arousal dimension, the rating for the selected low arousing stimuli on the IADS ranged from 3.36 to 4.93. On the neutral rating, stimuli ranged from 3.71 to 4.6. On the high arousing, stimuli ranged from 5.51 to 8.14. Appendix H shows the range (including mean, maximum and minimum values) for each sound condition for both the arousal and valence dimensions.

11.2.3 Discussion

Inconsistent with the findings by Noulhiane et al. (2007), the present study did not find any significant effect of emotionally arousing auditory stimuli on participants' verbal estimation of tones. When both control sounds (silence and a 500Hz tone) were removed from the analysis, there was no significant effect of arousal on participant's verbal estimates of the duration of the tones. Both these control conditions were driving the significant main effect of arousal in the initial analysis. This confirms the findings from Experiment 7a which replaced clicks with emotionally arousing stimuli in the visual modality in the same task of verbal estimation of tones. This indicates that the lack of findings in Experiment 7a cannot simply be explained by the fact that we were using stimuli in the visual modality because the present study also found no significant effect when using emotionally arousing *auditory* stimuli.

In sum, the findings from both Experiment 7a and b casts doubt on the notion that the effect of clicks on verbal estimation of tones is due to arousal or any attention properties since, when we replaced the clicks with stimuli that we know to be emotionally arousing (in both the visual and auditory modality), there were no effects on the verbal estimation of tones. The findings support then, the argument that it is the repetitive nature of the clicks which is important in driving the effect previously found on verbal estimation of tonal durations (i.e., Jones et al., 2010). The research question that Experiment 7a and b addressed was, what are the effects of emotionally arousing visual and auditory stimuli on verbal estimation of tones? Experiment 7a and b showed that presenting emotionally arousing stimuli in both the auditory and visual modality for five seconds, had no effect on participant’s verbal estimation of subsequent tones.

Chapter 12 Verbal Estimation of Emotionally Arousing Auditory Stimuli

12.1 Experiment 8 - Verbal Estimation of Emotionally Arousing Auditory Stimuli

The previous experiment discussed in this thesis (Experiment 7b) explored whether replacing clicks with emotionally arousing auditory stimuli differing on dimensions of arousal and valence (pleasure) affected our subsequent estimation of durations of tones. Findings revealed that arousal and valence had no significant effect on estimations of the duration of tones. This was inconsistent with those of Noulhiane et al. (2007) who showed that high-arousing emotional sounds were judged as being of shorter duration than the low-arousing emotional sounds. Additionally, Angrilli et al. (1997) using emotional visual stimuli (for durations of 2, 4 and 6 seconds) found that for low arousal stimuli, participants judged the duration of negative images as being relatively shorter than the positive images. For high arousal stimuli, participants judged the duration of negative images as being longer than the duration of positive images. Specifically, in the high arousing stimuli condition it was found that participants overestimated the duration of the stimuli in the first two seconds, irrespective of valence, then switched to underestimation of the duration of the high arousing images at six seconds. They argued that this was due to a double mechanism, in which high arousing stimuli triggers an initial emotionally-driven mechanism which is faster than the second, attention-driven, mechanism. For the low arousing stimuli, participants underestimated the duration across all levels which suggests that this type of stimuli is governed by an attentional mechanism (as proposed by Angrilli et al., 1997). However, it must be pointed out that this underestimation becomes less strong with increasing duration.

These findings by Angrilli et al. (1997) are overall inconsistent with those of Noulhiane et al. (2007). In sum, Noulhiane et al. (2007) found that high-arousing stimuli were underestimated, while low-arousing stimuli were overestimated, relatively. However, Angrilli et al. (1997) found the opposite. Difficulty in making any conclusions is even more complicated with the findings from Experiment 7b which found no effect of emotional stimuli at all on the estimates of the durations of tones. Experiment 7b suggests that the previous effect of clicks we have seen on the estimation of the duration of tones, may not be due to any arousing properties it may have. It seems then that some other mechanism is at play besides arousal itself that manipulates our internal clock speed.

Noulhiane et al. (2007) failed to demonstrate a slope effect indicating a change in clock speed, since emotional arousal or valence of a sound did not vary as a function of duration. Angrilli et al. (1997) also found significant effects of valence and arousal using visual stimuli on durations judgments. However, they also found an interaction between the two which was inconsistent with the findings from Noulhiane et al. (2007). Instead, Noulhiane et al. (2007) found significant effects of both valence and arousal on duration judgments. However, Angrilli et al. (1997) did not find any main effect of these variables (only an interaction between the two). So it appears that the effect of both valence and arousal are independent in the auditory modality, while interacting in the visual modality. The question is what could have given rise to these differences? As we have already seen in Chapter 1, section 1.2.3, studies have revealed that auditory stimuli are judged as longer than visual stimuli of the same duration (i.e.,Wearden et al., 1998; Treisman et al., 1990). Perhaps the different modalities used to deliver the emotional stimulus between the studies by Angrilli et al. (1997) and Noulhiane et al. (2007) may have resulted in the differences in findings between the studies.

The discrepancies in the findings of these studies may also have arisen due to the potential problems with the stimulus durations employed by Noulhiane et al. (2007) in their verbal estimation task. The present experiment improved on the existing study by Noulhiane et al. (2007). The design of their verbal estimation study comprised of five standard durations to be estimated, namely, 2, 3, 4, 5 and 6 s. Three series of 36 different sounds were employed in which each sound appeared twice. Specifically, the following sound categories (pleasant high-arousal, pleasant low-arousal, unpleasant high-arousal and unpleasant low-arousal) each contained 6 sounds which were all presented twice. The fifth sound category, neutral sound, contained 12 different sounds which were also presented twice. All the sounds were randomly assigned to the durations (2, 3, 4, 5 and 6 s). Therefore, each series was made up of 72 stimuli trials. That Noulhiane et al. (2007) used durations of this nature is potentially problematic. The present study used two durations in between each of these values in order to eliminate the possibility that participants could simply learn the 6 different durations presented to them (2, 3, 4, 5 and 6 s). Thus making it far more difficult for any categorical learning to take place.

Additionally, Noulhiane et al. (2007) did not give their participants a range from which they could select their verbal estimates. Instead, they initially presented their participants with the shorter (2 s) and the longer (6 s) durations of the neutral sound to give them an idea as to the range of the durations used in the experiment. This means that participants could give estimates much further from the range they used which may confound their findings. However, from the presented data in the paper by Noulhiane et al. (2007), this does not appear to have occurred. Noulhiane et al. (2007) does not discuss this issue and whether they had to omit data because of unusually large or small estimates. So we can only assume that not having a range was irrelevant in this instance.

In light of the problems with the study by Noulhiane et al. (2007), the present experiment was designed as an improvement to this existing study by using less problematic durations (2,000, 2,250, 2,750, 3,000, 3,250, 3,750, 4,000, 4,250, 4,750, 5,000, 5,250, 5,750 and 6,000ms) as well as carrying out the appropriate analysis to determine the involvement, if any, of the internal clock via slope effects. Specifically, by exploring whether underestimation or overestimation of stimulus durations becomes greater with increasing stimulus duration in addition to investigating the mean slope values for each condition to see whether there were any significant differences. Participants were asked to estimate the duration of emotional auditory stimuli and to rate all the emotional sound stimuli on dimensional scales of arousal and valence in a separate rating study. The emotional auditory stimuli were taken from the internationally recognised database known as the ‘International affective digitized sounds (IADS)’ database (Bradley & Lang, 1999).

In sum, Experiments 7a and b fail to support the notion that the effect of clicks is mediated by arousal. In order to rule out the possibility that arousal has an effect on verbal estimation, the present study required participants to estimate the duration of emotionally arousing auditory stimuli. This is contrast to Experiment 7a and 7b in which the emotion visual and auditory stimuli were presented for five seconds followed by a tone which they had to estimate the duration of. The research question that Experiment 8 addressed was whether emotionally arousing auditory stimuli can have an effect on human timing abilities.

12.1.1 Method

Participants

Thirty-five undergraduate participants took part and were compensated with 4 course credits for their time and effort. These credits were not contingent on performance.

Apparatus

See apparatus for Experiment 1a. In this present study the Self-Assessment Manikin (SAM) (Bradley & Lang, 2007) was used (see procedure section).

Procedure

The same five sound categories as Noulhiane et al. (2007) and Experiment 7b were used. Namely, (a) pleasant high-arousal sounds (e.g., erotic sounds), (b) pleasant low-arousal sounds (e.g., a babbling brook), (c) unpleasant low-arousal sounds (e.g., a ticking clock), (d) unpleasant high-arousal sounds (e.g., a woman screaming), (e) one group of 6 neutral low-arousal sounds (e.g., rain). However, the present study also included a control sound condition, (f) 500Hz tone. Thus, giving the study 6 sound conditions (see Appendix C for the sound stimuli used in each category). As in Experiment 7b, each category contained 6 different sounds. Each participant received three randomly from each category during the entire experiment. This enabled each sound stimuli to be presented randomly (with equal frequency) for each of the 13 durations that the sound stimuli can be presented. So, all the sound stimuli were presented randomly (with equal frequency) for a duration selected from a range of 13 durations (2,000, 2,250, 2,750, 3,000, 3,250, 3,750, 4,000, 4,250, 4,750, 5,000, 5,250, 5,750, 6,000ms). The 500Hz tones (f) were simply presented for each of the 10 different durations 3 times. There were 234 trials in total, split into 6 groups of 39. So, the participant had five breaks during the experiment.

The experiment began with an instruction to participants to “When ready, press space bar to begin”. The participants then pressed the spacebar and were presented with an emotional sound from one of the 5 conditions ((a) » (e)) or the 500Hz tone (condition (f)). After the sound, a screen was presented with the following instruction: ‘Type in your estimate of the duration of the sound. Press enter for next trial’. After the participant pressed enter, there was a 2,000ms delay. After the delay the participant was presented with the next trial. The participants were given a range from which they could select their estimates of duration. They were given the following instruction: “Select your estimates from anywhere between

1,000 and 7,000ms (1,000ms = 1 second)”. If they entered say, 8,000, a screen appeared reiterating the estimate range. Participants were not able to continue until they rectified the error by a correct entry. Participants were also told not to use any counting strategies throughout the experiment. After the participants had taken part in the verbal estimation experiment, they were then given the Self-Assessment Manikin (SAM) (See procedure section for Experiment 7b).

12.1.2 Results

Verbal Estimation: Internal clock speed

Figure 47 shows the mean verbal estimates plotted against stimulus duration for all six sound conditions. Descriptive analysis showed that the mean verbal estimates for the six sound conditions (neutral; pleasant high-arousing; pleasant low-arousing; unpleasant high-arousing; unpleasant low-arousing and control sound (500Hz) were as following: 3491.5ms (SE = 103.78); 3661.5ms (SE = 103.04); 3546.33ms (SE = 109.42); 3758.03ms (SE = 121.84); 3610.13ms (SE = 106.14) and 4353.79ms (SE = 124.57). Inspection of Figure 47 suggests that mean estimates increased as an approximately linear function of actual stimulus duration in across all six conditions. From the figure it appears that the control sound of 500Hz is the only condition that differs significantly from the others.

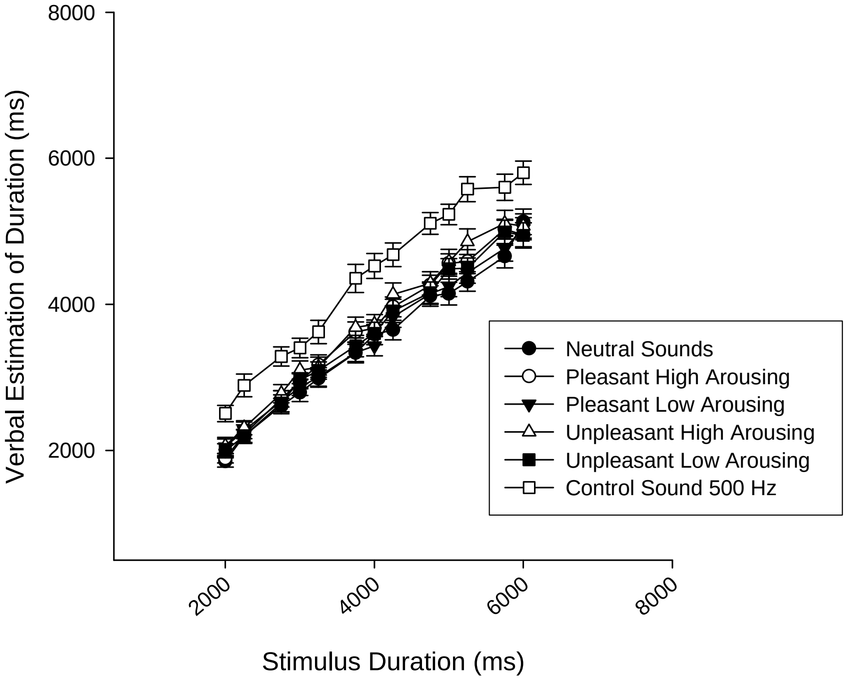


Figure 47: Mean verbal estimates plotted against stimulus duration for all six conditions of Experiment 8.

Figure 48 shows a plot of pleasant high-arousing, pleasant low-arousing, unpleasant high-arousing and unpleasant low-arousing.

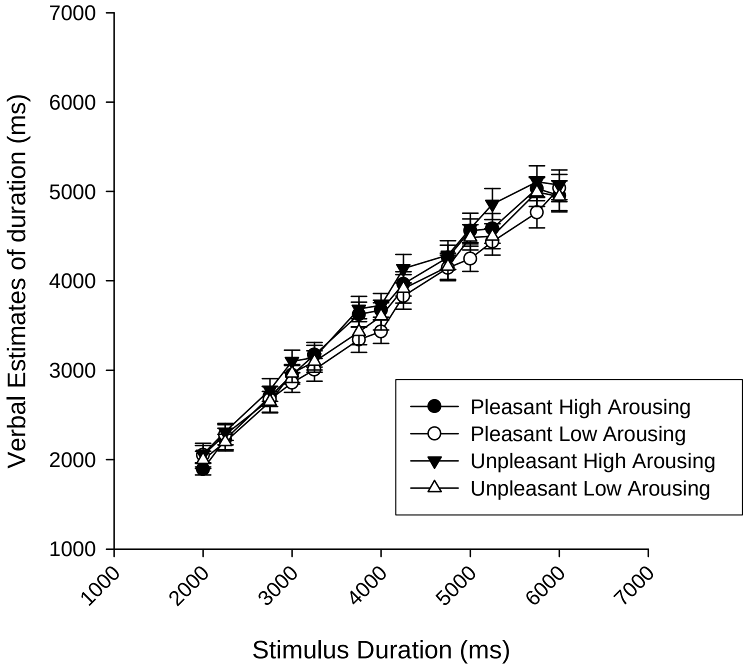


Figure 48: Mean verbal estimates plotted against stimulus duration for all arousal conditions of Experiment 8.

The data were analysed in two ways, firstly the mean estimate data was analysed. Secondly linear regression for each individual participant for each condition were calculated and the slope and intercept values were analysed.

Mean Verbal Estimates Analysis

A repeated measures ANOVA was used with one factor being the arousal condition (pleasant high-arousal sounds; pleasant low-arousal sounds; unpleasant low-arousal sounds; unpleasant high-arousal sounds; one group of five neutral low-arousal sounds; control sound of 500Hz) and the other being the stimulus duration (one for each of the thirteen durations), which showed a significant main effect of arousal condition on estimates, $F(5, 170) = 32.82$, $p < .001$, $\eta_p^2 = .49$. MSE = 1384425.41. There was also a significant main effect of stimulus duration, $F(12, 408) = 473.83$, $p < .001$, $\eta_p^2 = .93$. MSE = 452182.93. Moreover, there was a significant arousal condition x stimulus duration interaction, $F(60, 2040) = 1.71$, $p < .001$, $\eta_p^2 = .05$. MSE = 234484.47.

Linear Regression Analysis

Slope Values

Individual linear regressions for each participant for each condition were then calculated. The mean overall slope values for the six conditions (neutral sound; pleasant high-arousing; pleasant low-arousing; unpleasant high-arousing; unpleasant low-arousing and control sound, 500Hz tone) were, .74 (SE = .03); .78 (SE = .03); .73 (SE = .04); .78 (SE = .03); .76 (SE = .03) and .84 (SE = .03), respectively. Figure 49 shows the mean slope values (gradient) for each condition. Inspection of Figure 49 suggests that there was no significant difference between the slope values of any of the conditions. Subsequent statistical analysis was carried out to determine whether any of these were statistically significant.

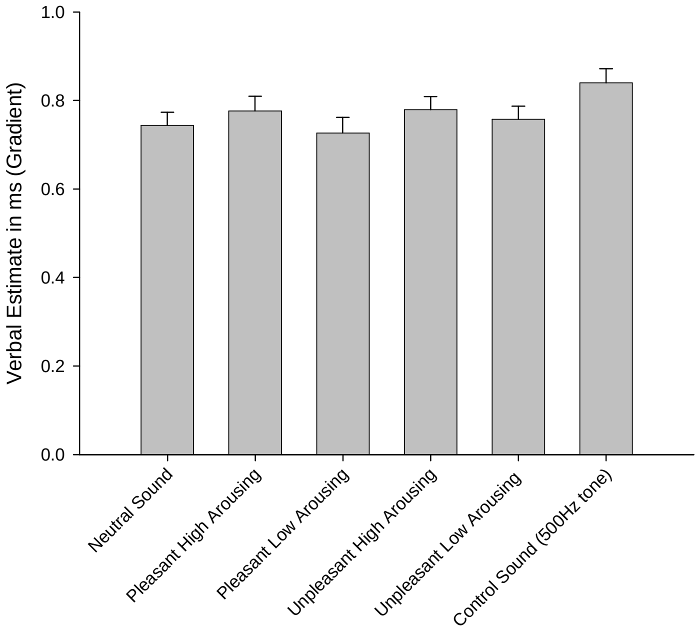


Figure 49: Mean slope values plotted against all arousal conditions of Experiment 8.

A repeated measures ANOVA with one factor; arousal condition (pleasant high-arousal sounds; pleasant low-arousal sounds; unpleasant low-arousal sounds; unpleasant high-arousal sounds; neutral low-arousal sounds and a control sound of 500Hz) was conducted on the mean slope values. There was a significant main effect of arousal condition, $F(5, 170) = 4$, $p < .05$, $\eta_p^2 = .11$, MSE = 2.29.

However, it could be that one condition is driving this significant effect of condition, namely, the control sound of 500Hz. In order to establish whether this was the case a second repeated measures ANOVA was carried out with the condition of control sound (500Hz) removed from analysis. Indeed, it appears that the control sound of 500Hz was driving the significant main effect found before, since no effect of arousal condition was found with 500Hz removed from the analysis, $F(4, 136) = 1.29$, $p = .28$, $\eta_p^2 = .04$, MSE = .01.

Intercept Values

Figure 50 shows the mean intercept values for each of the six conditions. The mean overall intercept values for the six conditions (neutral sound; pleasant high-arousing; pleasant low-arousing; unpleasant high-arousing; unpleasant low-arousing and control sound, 500Hz tone) were, 511.98ms (SE = 104.53); 559.45ms (SE = 133.16); 638.9ms (SE = 156.67); 638.81ms (SE = 107.86); 577.5ms (SE = 100.31) and 992.84ms (SE = 151.51), respectively. Inspection of Figure 50 suggests that that there is a significant difference between the intercept values for the control sound condition compared to the others. Subsequent statistical analysis was carried out to determine whether this was indeed significant and also if any others were statistically significant.

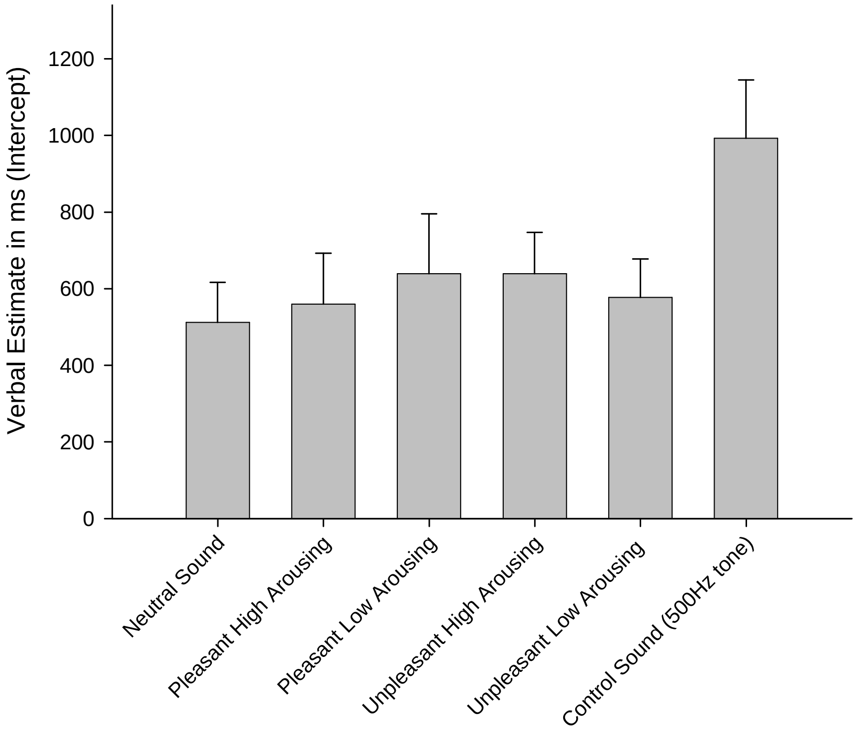


Figure 50: Mean intercept values (ms) plotted against all arousal conditions of Experiment 8.

A repeated measures ANOVA with one factor; arousal condition (pleasant high-arousal sounds; pleasant low-arousal sounds; unpleasant low-arousal sounds; unpleasant high-arousal sounds; one group of 6 neutral low-arousal sounds, control sound of 500Hz) was conducted on the mean intercept values. There was a significant main effect of arousal condition, $F(5, 170) = 4.23$, $p < .001$, $\eta_p^2 = .11$, MSE = 248663.52.

Again, it could be that one condition was driving this significant effect of condition, namely, the control sound of 500Hz. In order to establish whether this was the case a second repeated measures ANOVA was carried out with the condition of control sound (500Hz) removed from analysis. Indeed, it appears that the control sound of 500Hz was driving the significant effect found before, since no effect of arousal condition was found with the 500Hz condition removed from analysis, $F(4, 136) = .49$, $p = .74$, $\eta_p^2 = .01$, MSE = 211261.36.

Rating Experiment

In addition to the main experiment, each participant took part in a further experiment which obtained each participant's own ratings of arousal and valence on all thirty emotional sounds. These scores were then analysed to see if they were consistent with the scores in the IADS. The present study used the same emotional categories as the study by Noulhiane et al. (2007) (i.e., pleasant high-arousing). However, as discussed in the rating section of Experiment 7b, the present study improved on the stimuli (See Appendix E for stimuli used in the present study versus IADS for both arousal and pleasure) used by Noulhiane et al. (2007). What is highlighted in bold, under sound conditions, is what was removed and changed for the present study (See Appendix F for the stimuli used by Noulhiane et al., 2007). Correlations between subjective valence rating scores from the participants of the present study and those of the IADS were significant ($p < .001$, $r = .93$), which shows that the subjective valence ratings were consistent with those of the IADS. Correlations between subjective arousal rating scores from the participants of the present study and those of the IADS were significant ($p < .001$, $r = .93$), which shows that the subjective valence ratings were consistent with those of the IADS (See Appendix I for differences between present and IADS on ratings for mean arousal and pleasure/valence). For the valence dimension, the ratings for the selected unpleasant stimuli on the IADS ranged from 1.63 to 4.86. On the neutral rating, stimuli ranged from 5.31 to 5.99. On the pleasant rating, stimuli ranged from 6.2 to 7.9. For the arousal dimension, the rating for the selected low arousing stimuli on the IADS ranged from 3.36 to 4.93. On the neutral rating, stimuli ranged from 3.71 to 4.6. On the high arousing, stimuli ranged from 5.51 to 8.14. Appendix J shows the range (including mean, maximum and minimum values) for each sound condition for both the arousal and pleasure dimensions.

12.1.3 Discussion

Findings showed that any difference between conditions was driven largely by one condition, namely, control sound (500Hz tone). When this was removed from analysis, there were no significant differences between any of the different types of emotional sound conditions. Therefore, the current study provided no evidence to support the idea that arousal or pleasure/valence influences subjective duration of time. This is inconsistent with the findings from the study by Noulhiane et al. (2007) which did show that high-arousing sound stimuli were judged as shorter than low-arousing sound stimuli. Further, that unpleasant sounds were judged as lasting subjectively longer than pleasant sounds. However, the conclusions drawn from the study carried out by Noulhiane et al. (2007) have to be viewed tentatively since the study was fraught with both methodological and statistical problems (see introduction and results section for details).

However, there are two potential limitations of the present study. First, is the use of different emotional auditory stimuli. For instance, low versus high arousing stimuli are characterised by different tempo, such that any effect (if at all) on the perception of time of the high arousing auditory stimuli may be due to its relatively faster tempo. Second, there is also a strong possibility that, as for music, all the natural occurring sounds may have captured attention more than the 500Hz tone and resulted in a temporal underestimation. In order to investigate whether this was the case, the same study could be repeated with the control sound of a 500Hz tone removed.

In sum, the current findings indicate that the verbal estimation of emotionally arousing auditory stimuli *themselves* has no effect on participant's timing judgments and ultimately their internal clock. Therefore, arousal by itself cannot account for the effect of clicks on verbal estimation of duration, again highlighting the important of the clicks repetitive nature. If we are to believe that the effect of clicks in increasing timing judgments *are* due to its arousing properties, then we would expect that stimuli which are highly arousing would cause a similar if not greater effect. This was not the case. Therefore, the present findings support the findings from Experiment 7a and b which found that when clicks are replaced with stimuli which we know to be emotionally arousing (auditory and visual stimuli), there is no effect on subsequent verbal estimations of tonal durations. It can be argued then that the clicks must mediate their effect through some process other than arousal. A strong candidate for this process may be the repetitive nature of the clicks which has some kind of effect on brain synchronicity and/or alpha rhythm (see Chapter 2).

Chapter 13

An Electrophysiological and Behavioural Investigation into the Effect of Clicks on Verbal Estimation

13.1 Experiment 9 - The Effect of Clicks on Verbal Estimation: An Electrophysiological and Behavioural Study

It is well known that in situations of high danger or fear (e.g. such as in a car crash) people report that ‘time slows down’, an effect simulated (but to a lesser extent) in the laboratory through the use of ‘click trains’ (i.e., Treisman, Faulkner, Naish & Brogan, 1990; Burle & Casini, 2001; Wearden, Norton, Martin & Montford-Bebb, 2007). Penton-Voak, Edwards, Percival, & Wearden, (1996) suggested that changes in time perception may be due to increases in levels of arousal, which in turn causes an increase in pacemaker speed. They showed that preceding an auditory or visual stimulus by five seconds of periodic clicks made the stimulus seem to last longer (see also Wearden et al., 1998; Wearden, Philpott & Win, 1999, for replications) whereas when people were required to produce time intervals of specific durations, preceding the production with clicks made the productions shorter. The mathematics of pacemaker-accumulator clocks (discussed in Wearden et al., 1998 and below) predict that if click trains speed up the pacemaker, they will have a more marked effect at longer stimulus durations and this result has been found in a number of studies (e.g., Penton-Voak et al., 1996; Wearden et al., 1998).

As well as speeding up the internal clock, it has recently been shown that click trains can also speed up information processing rate in both reaction time tasks and in memory encoding (Jones et al., 2010). This has made the investigation of how click trains cause their effect imperative. In order to assess the role that arousal plays in this effect of repetitive stimulation, the present experiment investigated electrophysiological (as well as behavioral) measures in a task of verbal estimation of tones when preceded with either clicks or silence.

To our knowledge, there has been no investigation into whether the effects of clicks, for example, is mediated by “arousal”. A train of clicks is obviously not very arousing in the everyday sense of the word - but it may induce “specific arousal” of the internal clock. Previous studies have suggested that emotional stimuli can influence our perception of time in a variety of timing tasks (i.e., Droit-Volet & Meck, 2007; Droit-Volet, Brunot & Niedenthal, 2004; Ward & Cox, 2004; Angrilli et al., 1997). Overall, the main findings suggest that emotional stimuli are systematically overestimated compared to neutral stimuli. Since it is clear that the emotional stimuli used in these studies are arousing, the question is whether clicks (repetitive stimulation) are also perceived as arousing and it is this component which is giving rise to the effects on time abilities. Surprising, this has not yet been investigated and it crucial to furthering our understanding of time processing. However, if clicks were arousing, then the next question would be why? The initial answer would seem to be because they are arousing. Clearly, this is a rather circular argument and the only way to address this circularity problem would be to try and measure arousal itself; which is the aim of the current study. The experiments presented in Chapter 11 (Experiments 7a and b) and in Chapter 12 (Experiment 8) have explored the effect of emotionally arousing visual *and* auditory stimuli on verbal estimation. However, no effect was found with high emotionally arousing visual *or* auditory stimuli on verbal estimates. So, the research question that Experiment 9 addressed was what is the involvement of autonomic arousal in the operation of repetitive stimulation?

The current study involved a verbal estimation task in which participants were asked to estimate the duration of auditory tones that were either preceded by clicks or no-clicks. Since it has previously been shown that click trains increase internal clock speed and therefore slow down subjective time, what will be the main focus of investigation is the autonomic physiological response to the clicks, specifically using Electrocardiogram (ECG or EKG), Galvanic skin response (GSR) and Electromyography (EMG). If participants demonstrate an increase in electrophysiological response during the clicks compared to no-click trials (resulting in the previously found timing effects) then we come closer to understanding the role of arousal and external factors on internal clock functions. This will be the first investigation into whether the clicks have an arousing effect on the human body and may be the first investigation to pose limitations on the arousal argument if no such effects are found. If arousal is not found to have an effect, then it would provide further support to the idea that it is the repetitive nature of the clicks which is important in mediating their effect on both time estimation and information processing. This would be consistent with the non-specific sympathetic frequency and specific frequency arguments discussed in Chapter 2.

13.1.1 Method

Participants

Fifty participants took part in the experiment and were compensated with £7 for their time which was not contingent on performance.

Materials

Behavioural Measures

A Dell PC computer controlled all experimental events. The computer speaker produced the auditory stimuli and instructions were displayed on the computer screen. The experiment was created using an E-Prime program (Psychology Software Tools Inc.). All responses were made on the computer keyboard. Electrophysiological measures were recorded using PsyLab 7 software program from Contact Precision Instruments running on two interfaced Dell-compatible PCs; one recorded the behavioral data, presenting the stimuli and recording the verbal estimates. The other recorded the electrophysiological measurements.

Electrophysiological Measures

A variety of electrophysiological measures were taken. Electrophysiological measures were simultaneously recorded during the behavioural experiment. A finger transducer was used to obtain peripheral pulse by detecting changes in infra-red and visible light with blood flow. Skin conductance (SC) was measured with 8mm diameter silver/silver chloride electrodes positioned on the medial phalanx of the middle fingers held in position by double sided sticky electrode collars. A non-saline gel was used in order to gain contact with the skin, essentially filling the gap between the skin and the electrode within its casing. Electromyography (EMG) was recorded from the following sites: A) Medial frontalis (eye region), B) Lateral frontalis (eye region), C) Levator labii superioris (mouth region) and D) Zygomaticus major (mouth region). More simply, silver chloride electrode pairs were positioned 1cm apart across each muscle to be measured. Specifically, two above the eye and two on the side of the mouth.

Procedure

The behavioral task

At the beginning of each session, instructions appeared on the computer screen. Participants were requested to press the space bar to commence the first trial. There were two trial conditions (clicks and no-click). In the clicks condition, participants were instructed to look at a fixation cross in the centre of the screen and to begin the trial by pressing the spacebar. Participants were then presented with a 25ms tone (700Hz), followed by a 5 second period of clicks at 5Hz (each click was 10ms long). A further 25ms tone (700Hz) terminated the clicks. The tone (500Hz) to be estimated was then presented. The duration of the tone was selected from 10 different stimulus durations (300, 478, 567, 656, 745, 834, 923, 1,012, 1,101 and 1,300ms) presented randomly across trials. After presentation of the test tone, participants were asked to type their estimate of the duration of the tone on the keyboard. Participants were also given a range from which they could select their estimates. This ranged from 250 to 1350ms. This range was derived from the minimum actual presented duration and the maximum, 300 and 1,300ms, respectively. So the range started from the smallest actual presentation duration minus 50ms and the largest plus 50ms. Participants were told the importance of selecting their estimates only from within this range. The fixation cross remained on screen throughout this process. The no-click trials were identical except that 5 seconds of silence replaced the clicks. Once a response had been made the participants began the next trial after a prompt to press enter when ready to continue. There was a 500ms delay between the pressing of the enter key and the presentation of the next trial.

There were four experimental blocks, each with 20 trials (40 no-clicks and 40 clicks) thus 80 trials in total. Each of the ten possible durations of tones occurred once in each block for both 'click' and 'no-click' trials in a random order in each block. The participants were given a break after the first 27 trials, then after 54 trials. They were allowed as much time as they wanted during these official breaks. The participants were also given the option to pause during the trials if necessary.

Electrophysiological Measures

In order to match the electrophysiological response to the trial type, unique triggers were sent from the behavioural computer to the electrophysiological one. For the purposes of consistency across all conditions, the trial length examined each time was 6,800ms. This was taken from the onset of the tone beginning the 5 seconds of clicks or no-clicks and ending 6,800ms later. The value 6,800ms was used since this is the longest possible trial duration (5 seconds + 500ms + 1,300ms = 6,800ms).

13.1.2 Results

Behavioural Analysis

The data from the fifty participants' was analyzed in two different ways: initially using mean verbal estimates and then using slope and intercept values derived from linear regression analysis on each participant's data.

Verbal Estimates

Figure 51 shows mean verbal estimates (in milliseconds) plotted against stimulus duration for both the 'click' and 'no-click' conditions. Descriptive analysis showed that the mean verbal estimates for the no-clicks and click condition were 756.76ms (SE = 18.32) and 802.47ms (SE = 18.8), respectively. Inspection of Figure 51 suggests that mean estimates increased as an approximately linear function of actual stimulus duration in both conditions (clicks and no-clicks). Furthermore, estimates of stimulus duration appear to be consistently longer for the stimuli preceded by clicks than for those preceded by silence (no-clicks).

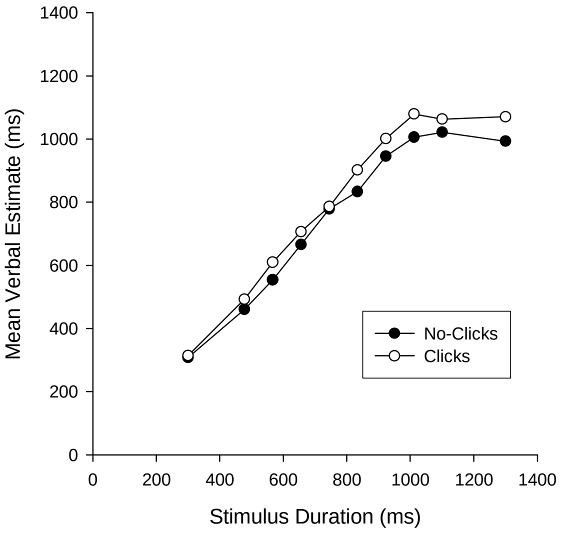


Figure 51: Mean verbal estimates for each of the ten duration types plotted for both click and no-click conditions of Experiment 9.

Across all ten stimulus durations, the verbal estimates for the no-clicks conditions were subtracted from the clicks condition (See Figure 52.). Figure 52 clearly shows that the tones preceded by clicks are reported as being subjectively longer and that there appears to be a trend for this difference to be greater with increasing stimulus duration. These suggestions were supported by subsequent statistical analysis.

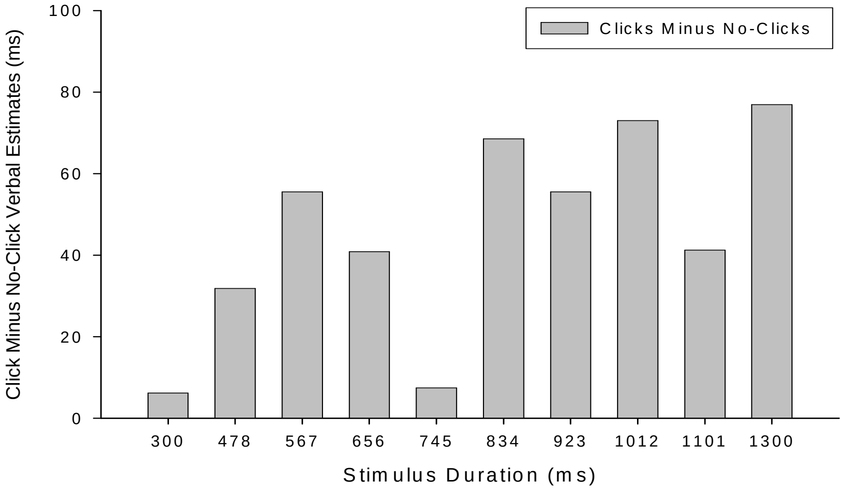


Figure 52: The verbal estimates for the no-click condition are subtracted from the estimates for the click condition across all ten stimulus durations of Experiment 9.

A repeated-measures ANOVA was used with one factor being the presence or absence of clicks (clicks and no-clicks) and the other being the stimulus duration (one for each of the ten durations). There was a significant main effect of the presence or absence of clicks on verbal estimates, $F(1,49) = 40.98$, $p < .0001$, $\eta_p^2 = .46$. MSE = 12745.20. There was also a significant main effect of stimulus duration, $F(9,441) = 489.45$, $p < .0001$, $\eta_p^2 = .91$. MSE = 13738.16. Moreover, there was a significant presence or absence of clicks x stimulus duration interaction, $F(9,441) = 3.17$, $p < .01$, $\eta_p^2 = .06$. MSE = 4985.20.

As there was a significant main effect of presence or absence of clicks as well as an interaction of presence or absence of clicks x stimulus duration, we conducted individual linear regressions for each participant’s data to obtain slope and intercept values for each condition, these were then subjected to statistical analysis.

Slope and Intercept

Figure 53 (Top-Left Panel) shows the mean slope values derived from the individual linear regressions for each condition. A paired samples t-test was then carried out on the slope values from the click (.84) and no-click (.79) conditions. Results indicated a significant difference between these two conditions, $t(49) = -3.46$, $p < .01$.

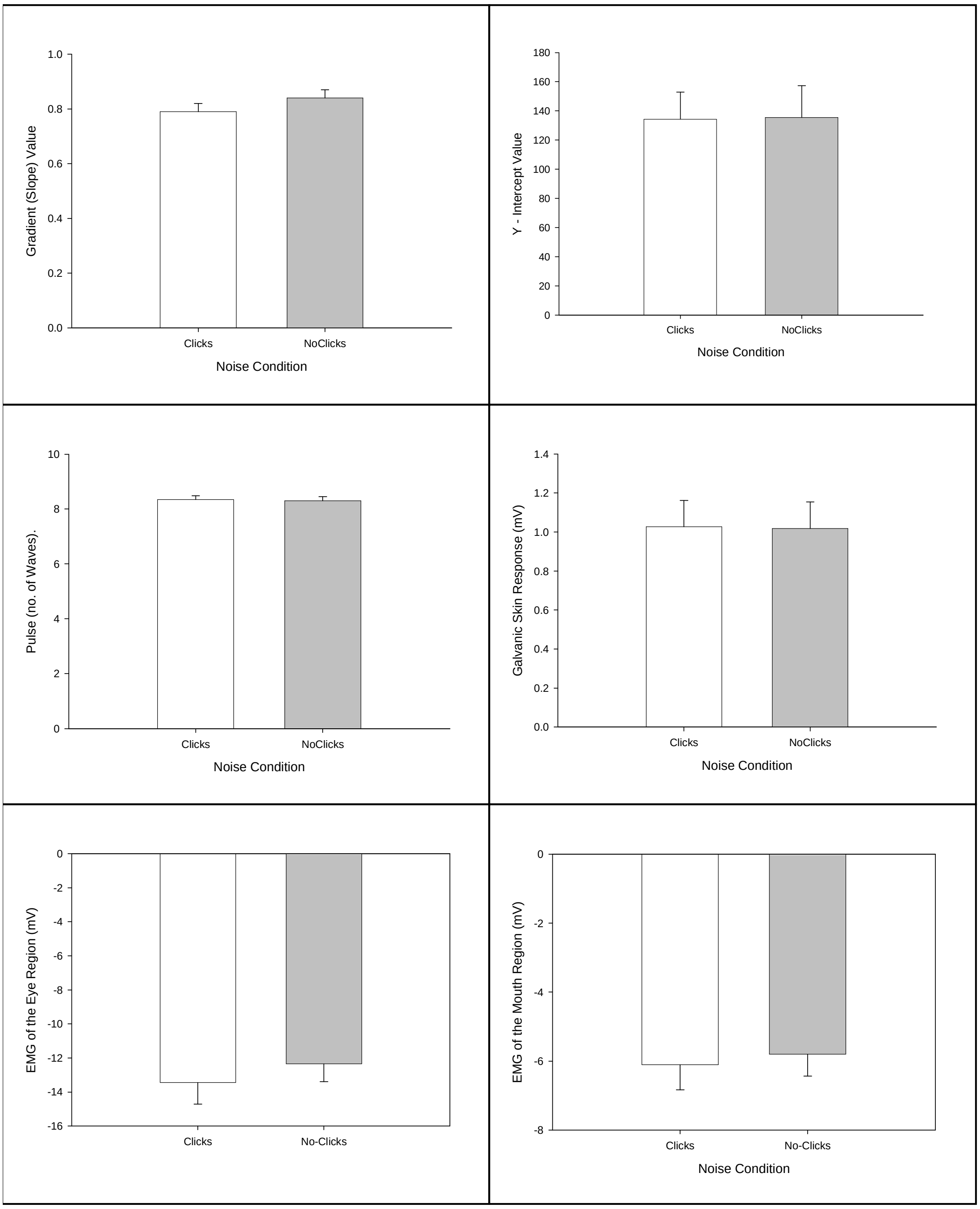


Figure 53. *Top-Left Panel:* Mean slope values for the click and no-click conditions; *Top-Right Panel:* Mean intercept values for the click and no-click conditions; *Middle-Left Panel:* Mean number of pulses (measured in waves) for the click and no-click conditions; *Middle-Right Panel*: Measure of galvanic skin response (GSR), measured in mV, for the two conditions (clicks and no-clicks); *Bottom-Left Panel:* Electromyography (EMG) of the eye region muscle activity measured in mV, for the two conditions (clicks and no-clicks); *Bottom-Right Panel:* Electromyography (EMG) of the mouth region muscle activity measured in mV, for the two conditions (clicks and no-clicks). All for Experiment 9.

Figure 53 (Top-Right Panel) shows the mean intercept values derived from the individual linear regressions for each condition. A paired samples t –test was then carried out on the intercept values from the click (135.46ms) and no-click (134.24ms) conditions. Results indicated no significant difference between these two conditions, *t*(49) = -.10, *p* = .92. Further, there was no difference between the standard error estimate between the click and no-click conditions, *t*(49) = -1.02, *p* = .31.

Electrophysiological Measures

The electrophysiological data from forty-nine participants was analysed as one participant's data file became corrupted.

Pulse (number of waves)

In order to investigate whether the clicks had an effect on the pulse rate, the numbers of waves from peak to trough were calculated for each trial and the mean of these was taken. For the purposes of consistency across all conditions, the trial length examined each time was 6,800ms. This was taken from the onset of the tone beginning the 5 seconds of clicks or no-clicks and ending 6,800ms later. Figure 53 (Middle-Left Panel) shows the mean number of waves (pulse) for click and no-click conditions. A paired samples t-test was carried out on the mean wave values from the click (8.34 mV, SD = 1.00) and no-click (8.30 mV, SD = 1.03) conditions. Results indicated no significant difference between these two conditions, *t*(48) = -1.69, *p* = .10, two-tailed.

Galvanic Skin Response

Figure 53 (Middle-Right Panel) shows the mean galvanic skin response (GSR) for the click and no-click conditions. A paired samples t-test was carried out on the mean GSR values from the click (1.03 mV, SD = .95) and no-click (1.02 mV, SD = .95) conditions. Results indicated no significant difference between these two conditions, *t*(48) = -1.64, *p* = .11, two-tailed.

Electromyography (EMG): Eyes Region

Figure 53 (Bottom-Left Panel) shows the mean EMG activity of the eye region for the click and no-click conditions. A paired samples t-test was carried out on the mean EMG values from the click (-13.45 mV, SD = 8.81) and no-click (-12.35 mV, SD = 7.35) conditions. Results indicated no significant difference between these two conditions, *t*(48) = .94, *p* = .35, two-tailed.

Electromyography (EMG): Mouth Region

Figure 53 (Bottom-Right Panel) shows the mean EMG activity of the mouth region for the click and no-click conditions. A paired samples t-test was carried on the mean EMG values from the click (-6.1 mV, SD = 5.13) and no-click (-5.8 mV, SD = 4.45) conditions. Results indicated no significant difference between these two conditions, *t*(48) = .72, *p* = .48, two-tailed.

13.1.3 Discussion

The main results of the current study confirmed previous findings (Jones et al., 2010), that verbal estimates of tones are longer when preceded by clicks compared to when they are preceded by no-clicks. The behavioural findings were strong and demonstrated a slope effect consistent with the notion that we have sped something up. The current study took the investigation of clicks further, by measuring participant's physiological parameters during the click and no-click conditions which has never previously been explored. The research question that the present experiment addressed was what is the involvement of autonomic arousal in the operation of repetitive stimulation? The results revealed there was no significant difference in any of the electrophysiological measures (pulse rate, GSR, EMG of eye muscles and EMG of mouth muscles) between click and no-click conditions. This would lead us to propose that the robust effect of the clicks on participant's verbal estimates of tones found in this study and many others cannot be explained by any autonomic arousing effect they may have on the body. One could of course argue that the measures we have used here are not sensitive enough or are too peripheral to detect any arousing effects that the clicks may have on the body, but this seems unlikely. However to fully exhaust this possibility one could explore this using parasympathetic measures, for example, a pupillometer which measures pupil dilation.

Given this finding, there remain three other potential candidates for the method of action of the clicks on temporal and non-temporal processing. Firstly, it could be argued that although the clicks do not cause autonomic arousal, they are still 'psychologically arousing' in some way. If this arousal is not independently measurable in some way then this argument leads to a tautology. However, Experiment 7a and b found that when we replaced the clicks with stimuli that we know to be emotionally arousing (both visual and auditory), there was no behavioural effect on the internal clock.

This lends support to the second potential candidate which is the idea that it is the repetitive nature of the click trains that is key, specifically that the frequency of the clicks is of some multiple of the pacemaker of the internal clock itself. This is the 'specific arousal' idea proposed by Treisman (1963) in his version of the internal clock model and has found some support in studies which have manipulated click frequency (see Burle, Macar & Bonnet, 2003). However two potential flaws with this idea are that firstly the behavioural effect of the clicks is very reliable across participants, but in order to work it would require that the internal pacemaker frequency of all participants is the same as (or a multiple of) the click frequency. Secondly, it is not clear why repetitive stimulation at the same (or multiple) frequency of the pacemaker would actually cause a 'speeding up' rather than just an increase in amplitude or strength of the pacemaker.

A third explanation which has gained recent attention is the idea that the frequency is of little import, instead, that the stimulation only need be repetitive. It is known that repetitive stimulation can induce non-specific sympathetic synchronisation of neural activity (Will & Berg, 2007). If the click stimuli typically used in studies such as ours also induce such activity (which is at the current time unknown) then this may reduce signal to noise ratio, or synchronise the transmission of upstream neurons and the receptivity of downstream neurons (for a full discussion see Burle et al., 2003 and Jones et al. in press). This would potentially explain the clicks' effect on reaction time and memory encoding, but it is more difficult to envisage the consequences for the pacemaker of the internal clock.

In conclusion, this experiment provides important evidence for informing the debate of the mechanism of action of repetitive stimulation on temporal and non-temporal processing. The lack of physiological findings with clicks strengthens the findings of Experiments 7a and b which found no effect of emotionally arousing visual or auditory stimuli on verbal estimations of tones. Additionally, it supports the findings from Experiment 8 which found no effect on verbal estimations of emotionally arousing auditory stimuli *themselves.* The findings from these experiments forces us to reconsider the mechanism by which the clicks operate and brings into question a simple arousal explanation to account for the effect of clicks on information processing and the internal clock.

Chapter 14

General Discussion

14.1 Review of the Main Theoretical Questions

The primary aim of this thesis was determining the relationship (if any) between information processing and the internal clock. The research strategy employed throughout consisted primarily of tasks of verbal estimation and reaction time. The main factor across many of the studies contained in this thesis is the effect of a repetitive stimulation (click train) on these different tasks.

The secondary aim of this thesis was exploring the mechanisms underlying the effect of clicks on information processing and internal clock speed. There were four possible explanations put forward in Chapter 2. First, the possible role of alpha rhythms and its relation to cognitive functions, such as intelligence, memory, information processing speed (as evidenced by reaction time) and sense of time. Second, the specific frequency argument which suggests that what is of importance in driving the effect of clicks is the *particular frequency* in which they are delivered. The main proponents behind this notion are Burle and Bonnet (1999) who explored the effect of variation in click train frequency in a choice RT task. They found increases in RTs with 20.5Hz frequency clicks, while decreased RT were found for frequencies of 21 and 21.5Hz. These findings demonstrated the importance of certain frequencies in driving the effects of clicks on information processing. Third, and probably the strongest argument based on the findings in this thesis, is the non-specific sympathetic entrainment argument which postulates that repetitive stimulation produces synchronization of brain waves (Will & Berg, 2007). This theory of the underlying nature of clicks argues that frequency is irrelevant in direct contradiction to the specific frequency argument which favours the idea of the importance of frequency. Next was the long-term potentiation argument (Bliss & Lomo, 1973). Here, it is argued that rapid or repetitive visual stimulation increases the speed at which brain cells communicate to each other (Teyler et al., 2005). Lastly, arousal was also investigated as another potential explanation as to how clicks affect time perception.

14.2 The Possible Mechanisms by which Clicks Affect Time Perception and Information Processing

14.2.1 Alpha Rhythms

Experiment 1a and b, (Chapter 5) explored the effect of repetitive stimulation (specifically the parameters of the effect), in the form of a click train, on a 1, 2 and 4 choice reaction time task. Consistent with previous findings by Jones et al. (2010), there was a significant effect of clicks, with click trains in general reducing reaction time response. Specifically, Experiment 1a found that six of the nine conditions demonstrated this reduced reaction time with clicks. Important, though, was the finding of no significant effect of gap duration (500, 2,000 and 5,000ms). Therefore, the effect of clicks was not reduced over time in the present study. Only with a gap duration of 500ms was there no evidence of a reduced reaction time on trials preceded by clicks. Using the same design as Experiment 1a, Experiment 1b investigated the parametrics of the clicks further using even longer durations of 5,000, 7,500 and 10,000ms. Supporting the findings from Experiment 1a, there was no significant main effect of gap duration with the clicks having an effect on reaction time after a delay as long as 10 seconds. Further experiments are required to explore the sustainability of the click effect, in effect, at what point it ‘wears off’. So far, overall findings have shown that on trials preceded by clicks, reaction times were reduced compared to trials preceded by no-clicks. However, one limitation with the design of Experiment 1a and b was the potential presence of expectancy effects. Controlling for expectancy effects, Experiment 1c found the effect of clicks was not as strong as in Experiment 1a and b. However, the present study still supports the findings from Experiment 1a and b, since there was no significant effect of gap which suggests that the effect of clicks has not been reduced over time.

In sum, the effect of clicks on a variety of reaction time tasks is well established. It appears that clicks increase our information processing rate as evidenced by the decrease in reaction time after clicks. Experiments in this thesis and previous findings (i.e., Jones et al., 2010; Penton-Voak et al., 1996) have demonstrated that clicks also affect the internal clock. The fact that clicks have an effect on both information processing and the internal clock is suggestive of a relationship between the two. We can begin to understand what these findings tell us about the possible underlying mechanisms of the clicks by exploring the literature associating alpha rhythms with reaction time performance. According to Surwillo (1961; 1962; 1964), participants with high alpha frequency show faster reactions times, whereas individuals with low alpha rhythms display much slower reaction times. This suggests a strong link between alpha rhythms and information processing rate and can perhaps explain the effect of clicks as being an external stimulus which induces a higher alpha frequency resulting in faster reaction times. The alpha frequency argument seems the most relevant here to explain the underlying effect of clicks since a vast amount of the literature links alpha rhythms to reaction time (in particular, Klimesch et al., 1996; Surwillo, 1961; Woodruff, 1975). However, despite this support for the alpha argument, it still does not provide a strong case against the remaining arguments. Namely, that of long-term potentiation, the non-specific sympathetic entrainment argument,the specific frequency argument and the notion that the effect of clicks is mediated by arousal.

14.2.2 Specific Frequency Argument

Previous studies have suggested the importance of click frequency on reaction time (i.e., Burle & Bonnet, 1999; Treisman et al., 1990; Burle & Casini, 2001) and time perception (Treisman et al., 1990). The aim of Experiment 4a and b was to *systematically* investigate whether there is any effect of the frequency and duration of the repetitive auditory stimuli on the internal clock speed and information processing. Experiment 4a and b (Chapter 8) manipulated the clicks in terms of frequency and stimulus number/duration (click ‘peaks’) in tasks of reaction time and verbal estimation, respectively. Essentially, would varying the duration and specifically frequency of the clicks have any differential effect on the internal clock and resultant estimates of duration or is there something unique to 5Hz?

Findings from Experiment 4a revealed no significant effect of sound condition on reaction time. These findings suggest that the frequency of the clicks is irrelevant and that it is perhaps simply the presence of *any* repetitive stimulation that is driving the effect of clicks. This is inconsistent with findings by Treisman et al. (1990) and Burle and Casini (2001). However, it supports the findings by Jones et al. (2010) who found no difference on reaction time using clicks of a frequency of 5Hz and 25Hz. However, it is important to point out here that 25Hz is a multiple of 5Hz, so if click frequency is driving the effect of clicks, you may not expect a difference only using a multiple of the typically used 5Hz.

However, Experiment 4a and b did employ frequencies which were non-multiples of 5Hz, yet no effect of *frequency* was found.

The findings from the verbal estimation task of Experiment 4b revealed that the mean verbal estimates increased linearly with the duration of the presented stimulus.
Overall, the findings show that there is a significant effect of click type condition. The main findings showed that there was no difference between the conditions in which the duration of the presented clicks is constant for a duration of five seconds. However, there was a difference between the conditions in which the number of stimulations presented by the clicks was controlled for across the four different frequencies (2, 5, 7 and 12Hz). The longer the clicks were presented for, the stronger the effect on verbal estimates. While Experiment 4a demonstrated no significant effect of noise type, the findings from Experiment 4b suggest that what is of importance is the *duration* not the frequency of the clicks. This finding is consistent with the non-specific sympathetic entrainment explanation for the effect of clicks and runs counter to the idea presented by the specific frequency argument. The non-specific sympathetic entrainment argument can also be applied to the findings of Experiment 4a since no difference in reaction times were found with the varying frequencies. However, a potential problem with Experiments 4a and b is the absence of a control sound condition. Future studies could repeat the same experiments (perhaps using different frequencies) and use a control condition of silence.

14.2.3 Non-Specific Sympathetic Entrainment Argument

As argued by Will and Berg (2007), it is the *repetitive* nature of the clicks which drive the effect of clicks (in synchronizing brain waves), not frequency. Based on Experiment 4a and b discussed in the previous section, it appears that the longer the clicks are presented for, the stronger the effect supporting the idea of entrainment. So the question is whether the facilitatory effect on information processing and on the internal clock speed is specific only to repetitive auditory stimulation and any entrainment effects it may have. Perhaps, any sound replacing the clicks would have the same beneficial effect on participants' reaction time. In order to answer these questions, we first replaced clicks with white noise to see whether it had any affect on internal clock speed. Experiment 2a (Chapter 6) showed that the presence or absence of white noise had no effect on participant's verbal estimates of stimulus duration. This indicates that white noise has no effect on internal clock speed and therefore provides a good control for replacing clicks in a 1, 2 and 4 choice reaction time to see whether it has any effect on information processing. This is exactly what we did in Experiment 2b (Chapter 6). Presentation of white noise failed to affect participants' reaction times. Therefore, white noise has no effect on information processing suggesting that there is something special about the repetitive nature of the clicks. It is not simply any pre-stimulus event that produces the effect. If white noise *had* demonstrated an effect on information processing, then it would suggest it is not mediated by the internal clock (since it was previously found not to affect internal clock speed, Experiment 2a). The implication of Experiment 2a is that the clicks are speeding up our internal clock resulting in more pulses being accumulated and subsequently increasing our subjective duration of time giving the participant longer time in which to react. Experiment 2c (Chapter 6) explored the effect of white noise on a more complex reaction time task involving mental arithmetic. Findings revealed no effects on information processing with white noise. However, clicks have previously been found to reduce information processing on the same task (Jones et al., 2010).

In sum, Experiment 2a demonstrated that white noise has no effect on internal clock speed. Experiment 2b and c showed that white noise has no effect on information processing. These findings rule our the idea that the effect of clicks on both information processing and internal clock speed is merely a coincidence since if white noise had demonstrated an effect on information processing, then it would suggest it is not mediated by the internal clock (since it was previously found not to affect internal clock speed). This would also indicate that the effect of clicks is independent from the internal clock. However, the opposite was found, namely, white noise does not have an effect on information processing, suggesting that there is something special about the clicks. It is not simply any pre-stimulus event that produces the effect. Instead, these experiments specifically highlight the importance of the repetitive nature of the clicks in producing their effects. Furthermore, by showing that the effect of clicks cannot simply be explained by any arousing or attentional aspects of a pre-stimulus event, it provides further evidence that clicks are possibly speeding up a hypothetical internal clock mechanism and that this change leads to an increase in information processing. If the common idea that clicks are arousing and/or attention 'grabbing', then surely any pre-stimulus noise would produce the same effect? Since this was not the case, it seems as if the repetitive nature of the stimulus is important in driving the effect which would be consistent with the non-specific sympathetic entrainment.

14.2.4 Long Term Potentiation Argument

The findings from the experiments contained in this thesis cannot rule out the explanation of the effect of clicks being due to long term potentiation, namely, an increased efficacy between communicating neurons. Further studies are required to explore the idea that clicks are increasing the efficacy of communication speed between neurons resulting in faster information processing speed.

14.2.5 Arousal

Since it is well known that in situations of high arousal (such as a car crash) time seem to slow down, could this be a potential explanation for the way in which clicks work? It is argued that during arousal, the rate of the internal clock increases which results in a greater accumulation of clicks and a subsequent overestimation of subjective duration of time. Could clicks be arousing? Indeed, the common explanation for how the clicks operate is that they *are* in some way arousing and this arousal then affects the speed of the internal clock (Treisman et al., 1992). In order to explore this explanation, Experiment 7a (Chapter 11) investigated the effect of clicks, no-clicks and low and high arousing visual picture stimuli on a task of verbal estimation of tonal durations (same as previously used). Tones were perceived as lasting subjectively longer when preceded by low arousing stimuli compared to high arousing stimuli. However, this effect was found to be a bias (or intercept) effect since there was no significant difference between the slopes of each condition. If the effect of clicks was due to their arousing capabilities on the speed of the internal clock, then surely we would expect that the high arousing pictures would result in an increase in the subjective length of the tonal durations.

In order to rule out the possibility that no effect of arousing visual on verbal estimates was due to the fact that it was presented in the visual modality, Experiment 7b (Chapter 11) instead used *auditory* stimuli varying along two dimensions (valence and arousal) presented for five seconds followed by a tone which participants had to estimate the duration of (same task as used in Experiment 7a). However, no clear findings were demonstrated as in previous studies like Noulhiane et al. (2007) who found that high-arousing stimuli are judged to be shorter than low-arousing stimuli. The present study suggests, then, that the effect on time we have seen with clicks may not be due to any arousal capabilities we expect it may have.The lack of findings in Experiment 7a could not be explained by modality, since no findings were demonstrated when we used auditory stimuli. These findings cast doubt on the idea that the clicks mediate their effect through arousal because when we replaced the clicks with stimuli that we definitely know to be arousing, there was no effect on verbal estimation (the internal clock).

The rationale for Experiment 8 was to further explore whether emotional stimuli has an effect on timing abilities. Compared to Experiment 7a and b, this time the duration of the emotional sounds *themselves* was being estimated. Overall findings revealed no relationship between arousal and time estimation, consistent with Experiment 7a and b. Experiment 8, strongly argues against the possibility that arousal mediates the effect of clicks on internal clock speed.

Experiment 7a and b explored whether replacing clicks with emotionally arousing visual and auditory stimuli had any effect on subsequent judgments of the duration of tones in order to see whether the previous found effect of clicks on subsequenting timing judgement is due to any arousal effect produced by the clicks. However, here we are only exploring whether the clicks mediate their effect through psychological arousal not physiological arousal. Experiment 9 adopted an electrophysiological and behavioural approach to investigating the effect of clicks on both verbal estimation and autonomic arousal. While the robust effect of clicks was found in the behavioural measurement, there was no evidence of a physiological arousal during the click conditions, compared to no-clicks conditions. These findings (including those of Experiment 7a, b and, in particular, Experiment 8) have major implications for the notion that arousal underlies the effect on human timing and reaction time abilities and forces us to reconsider the mechanism by which clicks mediate their effect. Therefore, the idea that the internal clock is mediated by arousal is not supported. One could of course argue that the measures we have used here are not sensitive enough or are too peripheral to detect any arousing effects that the clicks may have on the body, but this seems unlikely. However to fully exhaust this possibility one could explore this using parasympathetic measures, for example, a pupillometer which measures pupil dilation.

The lack of findings demonstrating a link between arousal and internal clock speed lends support to the second potential candidate which is the idea that it is the repetitive nature of the click trains that is key.This is consistent with the findings from the Experiments 2a, b and c which replaced clicks with white noise and found no effect on reaction time or verbal estimation with this stimulus. Therefore, it is not simply any arousing or attention grabbing pre-stimulus event which produces the effect of clicks. So it is possible that the frequency of the clicks is of some multiple of the pacemaker of the internal clock itself. This is the ‘specific arousal’ idea proposed by Treisman (1963) in his version of the internal clock model and has found some support in studies which have manipulated click frequency (see Burle, Macar & Bonnet, 2003). However one potential flaw with this idea is that the behavioural effect of the clicks is very reliable across participants but in order to work, it would require that the internal pacemaker of all participants is the same (or a multiple) of the click frequency which seems unlikely. Indeed, Experiments 4a and b explored the effect of frequency and duration of clicks and found frequency was not relevant. This also supports the idea that the effect of clicks may not be mediated by arousal, since you would expect that a higher frequency would induce a greater arousal and a faster internal clock.

These findings support the third explanation, that the frequency is of little import and that the stimulation needs only to be repetitive, therefore, supporting the non-specific sympathetic entrainment argument (see Chapter 2, section 2.10). It is known that repetitive stimulation can induce synchronisation of neural activity (Will & Berg, 2007). If the click stimuli typically used in studies (i.e., Jones et al., 2010) also induce such activity (which is at the current time unknown) then this may reduce signal to noise ratio, or synchronise the transmission of upstream neurons and the receptivity of downstream neurons (for a full discussion see Burle et al., 2003 and Jones et al., 2010). This would potentially explain the clicks effect on reaction time and memory encoding but it is more difficult to envisage the consequences for the pacemaker of the internal clock (Jones et al., 2010). It is possible that clicks have a particular effect on theta activity which operates between 4-8Hz (von Stein & Sarnthein, 2000), a range which encompasses the 5Hz click frequency across all the experiments in this thesis. Perhaps the clicks reduce theta activity since a study carried out by Hermens, Soei, Clarke, Kohn, Gordon and Williams (2005) noted that in individuals with attention-deficit hyperactivity disorder, there is an abnormally increased theta band activity during resting conditions. Since, it is known that timing deficits do exist in individuals with this disorder (Gilden & Marusich, 2009) it seems to suggest a possible link between theta activity and timing. Moreover, the study by Hermens et al. (2005) investigated whether cognitive performance (as measured on an auditory oddball task and a visual continuous performance test) was specifically linked to increased theta in individuals with attention-deficit hyperactivity disorder. Indeed, they found that compared to controls, individuals with the disorder demonstrated a clear increase in (primary left) frontal theta coupled with a significantly delayed reaction time as well as poorer accuracy during both of the tasks. Therefore, the effect we found in our previous experiments which demonstrated a reduced reaction time on trials preceded by clicks, may have been due to a reduce theta activity, since theta appears to have a detrimental effect on such tasks.

14.3 Evidence of a Link between Information Processing and Internal Clock Speed

Experimental Chapter 4 of this thesis was a novel investigation of the literature to explore the behavioural parallels between time perception and information processing. Previously, MacDonald and Meck (2004) have emphasised the “behavioural parallels between RT and interval-timing experiments” arguing that “interval timing and RT processes are in fact two sides of the same coin”. Jones et al. (2010) have already shown that there appears to be a link between information processing and internal clock speed. However, Chapter 4 in a meta-review explored various factors to see what effect they had on both the internal clock and information processing, including what it suggested about the relationship between the two processes.

It began by exploring the effect of attention on both time perception and information processing. Zakay and Block (1996) argue that when more attention is given to an event, less attention is then given to the processing of time, producing an underestimation of duration. Attention is also found to reduce reaction time (i.e., Stuss et al., 1989). This suggests a link between both the internal clock and information processing, since attention affects both processes. It then looked at the effect of intensity on both time perception and information processing. Kraemer et al. (1995) have clearly shown that higher intensities in the visual modality result in longer judgments of duration. Eisler and Eisler (1992) have also found that with increasing sound intensity, there were shorter reproductions of duration. Thus, intensity clearly has an effect on the internal clock. With respect to information generally, studies have shown that RT decreases with greater intensities (i.e., Ulrich & Mattes, 1996; Faber & Spence, 1956). That higher intensity causes a lengthening of subjective duration is consistent with the fact that it has been shown to also produce faster reaction times. The next factor investigated was that of arousal. Treisman et al. (1992) investigated the link between click rate and reaction time and found some evidence which suggests congruence with the response time results and time estimation data. Therefore, the study by Treisman et al. (1992) supports the notion of a link between information processing and the internal clock.

The investigation of modality showed that it can have a differential effect on the internal clock. For instance, findings revealed that auditory stimuli are judged as being longer than visual stimuli (Wearden et al., 1998). Wearden et al. (1998) argued that this may be due to a faster pacemaker with auditory compared to visual stimuli. Findings also showed that there is a modality difference with respect to information processing, with Jaskowski et al. (1990) finding that auditory stimuli are processed faster than visual stimuli. This advantage of auditory stimuli over visual stimuli has also been found in other variants of reaction time (i.e., Bertelson & Tisseyre, 1969; Dufft & Ulrich, 1999). What is demonstrated by these studies is that there are strong parallels in the effect of modality on both time perception and information processing.

Studies investigating the effect of anxiety and mood on time perception showed that there does appear to be a link in that depressive individuals experience a lengthening of subjective duration (Gil et al., 2009). This slowing down of passing time was also shown in anxious individuals (i.e., Deffenbacher, 1986; Watts & Sharrock, 1984). A possible interpretation here is that fear/anxiety causes the internal clock to run faster. These timing findings are inconsistent with reaction time studies. Studies seem to suggest that individuals with depression display longer reaction times compared to controls (i.e., Bonin-Guillaume et al., 2004; Martin & Rees, 1966). This slowing down of information processing is inconsistent with the fact that their internal clock is running faster as argued by Gil et al. (2009). However, it is possible that the longer reaction times displayed by individuals with depression may be due to response selection impairments rather than anything to do with the internal clock *per se* (Azorin et al., 2009). Because of this, a relationship between the internal clock and information processing cannot be ruled out here. With respect to age as a factor, despite some contradictory findings a substantial amount of evidence indicates that the rate of the internal clock slows down as we age, making subjective time appear to run at a faster rate (Wearden, 2005b). Consistent with this, studies looking at the effect of age on RT demonstrate increased reaction times with age (i.e., Fozard et al., 1994; Philip et al., 1999). The fact that reaction time appears to be reduced in elderly adults is consistent with this slower rate of internal clock. If time is perceived as going faster, they will have less time to react and less information processing time. These findings are indicative of a relationship between the internal clock and information processing.

Drugs have also been found to have an effect on both the internal clock (Meck, 1986; Matell et al., 2004) and reaction time in PD patients. Some studies have found a slowness in reaction time of individuals with PD (Jahanshahi et al., 1993; Stelmach, Worringham & Strand, 1986), while others have found no exaggerated slowness with increasing reaction time complexity (i.e., Russ & Seger, 1995; Pullman et al., 1990; Evarts et al., 1981). Pascual-Leone et al. (1994a) found that PD patients are sometimes, but not always, slower than controls in choice RT tasks. Therefore for both processes (information processing and the internal clock), the findings are conflicting and no clear relationship is apparent. The effect of caffeine on both time perception and information processing was then reviewed. The effect of caffeine on the speed of the internal clock is conflicting. There is some evidence which suggests that caffeine slows down the rate of the internal clock (i.e., Gruber & Block, 2003), while other studies show that it speeds up the internal clock (i.e., Hogervorst et al., 1998). Stine et al. (2002) found no effect of caffeine on perception of duration, which further complicates determining the relationship between caffeine and the internal clock. The findings of the effects on caffeine on reaction time performance (information processing) are more clear cut. Studies demonstrate that caffeine reduces reaction time (i.e., Clubley et al., 1979; Franks et al., 1975; Lieberman et al., 1987). Interestingly, Swift and Tiplady (1988) even found reduced reaction time as well as a significant increase in tapping rate. In sum, the effects of caffeine on information processing definitely point towards the idea that the arousal effects of caffeine are speeding up the internal clock (going with the study by Hogervorst et al., 1998) and enabling participants to react faster (indicative of a speeding up of information processing).

Lastly, the effect of exercise on time perception and information processing was explored. Evidence that exercise effects human timing functions comes from Vercruyssen et al. (1989) who found that participants demonstrated greater variability in their time estimates and decreased estimates of time intervals during exercise. This suggests that the internal clock is being slowed down during exercise. Exercise is generally considered to be arousing (LeDuc, Caldwell Jr & Ruyak, 2000), so this suggests an effect going in the opposite direction to that suggested by Treisman et al. (1992). Findings from studies looking at the effect of exercise on information processing show that simple cognitive performance can be improved during exercise (i.e., Collardeua et al., 2001, Davranche & Audiffren, 2004). Exercise is argued to increase arousal. If this is indeed the case, then the findings on timing are inconsistent with the notion that the exercise caused the rate of the internal clock to speed up which led to an increase in information processing as evidenced by reduced reaction times while exercising.

In conclusion, many factors have an effect on information processing and time perception which indicates a relationship between the two. Behavioural parallels on both time perception and reaction time were found with the following factors: attention, stimulus intensity, arousal, stimulus modality, age, caffeine and exercise. Overall, the factors explored support the idea of some form of relationship between the internal clock and information processing.

14.3.1 Evidence Supporting a Link between Information Processing and the Internal Clock

Clicks were shown to increase information processing as evidenced by faster reaction times in a 1, 2 and 4 choice reaction time task (Experiments 1a, b, c) and Experiment 1b showed that the reduction of reaction time due to clicks can last as long as 10,000ms. Clicks were also shown to increase the speed of the internal clock, producing overestimation of duration, consistent with previous studies (i.e., Jones et al., 2010; Penton-Voak et al., 1996). The fact that clicks have been shown to have an effect on both information processing and internal clock suggests a link between these two processes and this link is strengthened by the findings from the following three experiments that investigated whether any pre-stimulus event can produce the effects that clicks have shown. Experiment 2a replaced the clicks with white noise in a task of verbal estimation and found no effect. No effect of white noise was found in Experiment 2b which used a 1, 2 and 4 choice reaction time task and Experiment 2c which employed a more complex reaction time task involving mental arithmetic. Experiments 4a and b manipulated frequency and duration of clicks in a task of reaction time and verbal estimation, respectively and found no differential effect. These findings suggest that the frequency of the clicks is irrelevant and that it is perhaps simply the presence of repetitive stimulation that is driving the effect of clicks. This is inconsistent with previous findings (Treisman et al., 1990; Burle & Casini, 2001) while supporting those of Jones et al. (2010). That these click manipulations had no affect on both information processing and the internal clock support the idea of a link between them.

The next study explored whether clicks affect the rate of memory decay. In Experiment 6 (Chapter 10) we reviewed the findings of a task in which clicks were used to improve performance in a recognition/recall task. The next question was whether clicks could be used to *reduce* performance in a memory task. To investigate this, Experiment 6 (Chapter 10) was designed to explore the effect of clicks on the rate of memory decay. In particular, the clicks were used to attempt to change the rate of memory decay using a 3, 5 and 8 second delay. It is hypothesised that compared to the no-click condition, the click condition would *increase* the rate of memory decay. Further, that this effect would become greater the longer the duration of the delay filled with the clicks. The rationale for this would be that the clicks make duration seem subjectively longer, therefore the participants have more time in which the image can decay from memory since it is well known that memory decays the longer the duration. Indeed, clicks were found to increase the rate of memory decay for the 3 and 5 second delay duration. Additionally, the difference of recognition between the clicks and no-clicks condition decreased as the delay duration increased. Experiment 6 indicates that information processing takes place in subjective time. Since subjective time is directly linked to the speed of the internal clock, these findings strengthen the relationship between information processing and the internal clock.

However, a potential limitation with this study is that the clicks may not actually have manipulated the speed of the internal clock. It may be that clicks presented as *interference* and it was the interference of the clicks which produced the effect seen at the 3 and 5 second delay duration, rather than some internal clock speed manipulation *per se*. The condition in which silence was presented as opposed to clicks would not have caused any interference, resulting in improved retention of the image (less memory decay). In order to control for this, a future study could include a third condition in which the pre-stimulus was also a noise, for instance, white noise. White noise would prove a strong control because previous experiments (Chapter 6, Experiments 2a, b and c) have shown that white noise has no apparent effect on both information processing and the internal clock. So if any effects are shown with memory decay in this white noise condition, then it would strongly indicate that the effect is due to interference and therefore would bring into question whether the effect seen with clicks is due to a change in the internal clock or information processing. The findings from the present study do not rule out the notion of a link between information processing and the internal clock.

However, what is of interest is whether when people report a lengthening of subjective duration do they also have an increase in the rate of information processing. In other words, is clock speed related to brain speed? Jones et al. (2010) investigated the effect of clicks on memory recall using an adapted version of the Sperling's (1960) memory task. They found that the typically reported subjective lengthening of duration caused by the click trains (i.e., Penton-Voak et al., 1996) enabled participants to extract more letters from the matrix compared to trials without clicks. However, the question is whether the participants in this experiment by Jones et al. (2010) not only experienced an increase in information processing, but whether this was coupled *simultaneously* with an experience of subjective lengthening of duration as a result of clicks. In order to determine whether participants demonstrate both effects as a result of clicks, Experiment 5 (Chapter 9) replicated the same task as used by Jones et al. (2010), only this time exploring the effect of clicks on memory recall and time estimation *simultaneously* using a dual task procedure. In the time estimation condition, participants were requested to estimate the duration of the presented matrix (array of letters). As previously shown, clicks (compared to no-clicks) generally enabled participants to process more information as shown by an increase in correctly recalled letters. More interestingly, for the first time it was shown that participants also overestimated the durations of the array when they were preceded by clicks compared to no-clicks (silence). This is indicative of an increase in the pace of the internal clock with clicks. The fact that both information processing and the internal clock were affected simultaneously by the clicks provides us with further evidence that a link between the two may exist. However, there was no evidence of a correlation between the number of letters correctly recalled and the verbal estimates of duration of the array emphasising the complexity of disentangling the relationship between the internal clock and information processing. Additionally, whether the internal clock rate caused the increased rate of information processing or vice versa cannot be concluded from this study alone and therefore more research is needed to explore the directionality (if any) of this relationship. It is possible that information processing rate and the speed of the internal clock may even operate independently of each other.

14.3.2 Evidence Weakening the Suggestion of a Link between Information Processing and the Internal Clock

Experiment 3a and b in tasks of both a 1, 2 and 4 choice reaction time and verbal estimation, respectively, found that having to process the clicks had an effect on information processing while having no effect on verbal estimation. Having to process the clicks actually increased reaction time, in not only the click-change condition but also in the click and no-click condition of the Ask group. The Ask group had significantly greater reaction time compared with the Don’t Ask group. The fact that this change to the clicks impacted on information processing and not the internal clock gives rise to the possibility that the two are not strongly linked. Further evidence for this was found in Experiment 5 which investigated whether clicks could speed up the internal clock while *simultaneously* increasing information processing in a memory recall and verbal estimation task. Indeed, clicks were found to produce overestimation of duration as well as increasing the number of letters recalled. Although this initially suggests a relationship, the fact that there was no correlation shows that they are not directly related.

So the next question is whether one needs to postulate the existence of a specific ‘internal clock’ located in the brain or whether it is equivalent to information processing. Information processing includes a variety of processes such as reaction time, attention and executive functions (See Chapter 1, section 1.4.4). In Chapter 2, evidence against the idea that clicks (or repetitive stimulation) affect an underlying mechanism specific only to time (i.e., the putative pacemaker) was discussed. The study demonstrating this was carried out by Droit-Volet (2010) who discovered that the click train can affect not only the perception of time but also the perception of other quantities such as number and length, quantities which did not require a pacemaker (See Chapter 2, section 2.3). An effect of the click train appeared for number and length only when these types of quantity were presented sequentially, and did so to a greater extent for length – which is a continuous quantity – than for number which is a discontinuous quantity. This provides evidence for an effect of clicks on information processing without the inclusion of an internal clock. Jones et al. (2010) also showed that clicks can affect information processing as indicated by the reduced reaction time on trials preceded by clicks. Again, this may be further evidence of an effect of clicks on information processing, independent of an internal clock if one even exists. So here we have evidence to suggest clicks may be having a direct effect on information processing, rather than any effect on a specific internal clock. This also supports the findings by Burle and Bonnet (2000) who demonstrated that the clicks also affect reaction times consistent with more recent studies (i.e., Jones et al., 2010). These findings of a link between information processing (as measured by reaction time as well as the processing of other quantities such as number and length) and clicks, suggest that other factors may also be involved in timing and information processes, for instance, attention (Block & Zackay, 1996). In sum, the study by Droit-Volet (2010) clearly demonstrates that the clicks “acted primarily on the mechanisms underlying the processing of periodic information, in other words, on the temporal flow of information to be captured and aggregated and that they did so whatever the modality” (p. 7). Thus, suggesting that the internal clock may be equivalent to information processing.

14.4 Evidence that Different Timing Mechanisms Operate at Different Time Scales

As we have seen, the way in which time is perceived, represented and estimated has been understood using the pacemaker–accumulator model that can explain the patterns of both behavioural and biological data. Despite the relative success of the information processing model in explaining a large set of behavioural and physiological results, its relevance to the brain mechanisms that are involved in interval timing remain unclear (Buhusi & Meck, 2005). The next step is to identify the neural mechanisms of interval timing by integrating information from numerous approaches.

Currently, evidence supports the idea that there are two timing circuits which can be dissociated. The first timing circuit being an automatic timing system that works in the millisecond range, which is used in discrete-event (discontinuous) timing and involves the cerebellum. The second timing circuit being a continuous-event, cognitively controlled timing system that requires attention and involves the basal ganglia and related cortical structures. The findings from the experiments in this thesis only apply to timing at the shorter time scale, in the range of milliseconds. Buhusi and Meck (2005) argue that since these two timing systems work in parallel, appropriate experimental controls are necessary to engage (and reveal) each system independently of the other (Fraisse, 1984; Lewis & Miall, 2003) which is exactly what Rammsayer (1999) did. Rammsayer (1999) found that temporal processing of intervals in the range of seconds or more is cognitively mediated, whereas processing of brief durations below 500 msec appears to be based on brain mechanisms independent of cognitive control. In order to determine the role of a variety of neurotransmitters in timing processes in humans, the effects of 3 mg of haloperidol, a dopamine receptor antagonist, 11 mg of the benzodiazepine midazolam, and 1 mg of scopolamine, a cholinergic receptor antagonist, were compared in a placebo-controlled double-blind experiment. Rammsayer (1999) also explored changes in cortical arousal, semantic memory and cognitive and motor skill acquisition. Findings revealed that temporal processing of long durations was significantly impaired by haloperiodol and midazolam, whereas processing of extremely brief intervals was only affected by haloperidol. Overall the findings are consistent with the idea that temporal processing of longer intervals is mediated by working-memory functions. Therefore any pharmacological treatment, regardless of the neurotransmitter system involved, that results in a deterioration of working memory may interfere with temporal processing of longer intervals (Rammsayer, 1999). On the other hand, experiments have shown that temporal processing of extremely brief intervals is unrelated to the effective level of cortical arousal (Rammsayer, 1992). Instead it appears to depend on *sensory* rather than cognitive processes (Rammsayer & Lima, 1991). The notion of a sensory timing mechanism is also supported by the findings that LSD and mescaline, which both strongly affect processing of longer intervals, failed to change temporal processing of intervals in the range of milliseconds (Mitrani, Shekerdjiiski & Gourevitch, 1977). These findings led Mitrani et al. (1977) to conclude that brief time intervals are processed almost automatically at a lower level of the central nervous system and beyond cognitive control. In sum, the theory is that short intervals in the millisecond range are directly perceived, whereas longer intervals in the seconds range are “cognitively” processed which indicate voluntary and conscious activity.

Lastly, information from lesion studies has indicated the areas which may be involved in processing short and longer intervals (Buhusi & Meck, 2005). Since interval timing depends on the intact striatum (Malapani, Dubois, Rancurel & Gibbon, 1998) but not on the intact cerebellum (Malapani et al., 1998; Harrington, Lee, Boyd, Rapcsak & Knight,

2004) the cerebellum is argued to be the proponent of millisecond timing (Ivry & Spencer, 2004) and the basal ganglia with interval timing (Matell & Meck, 2000; Matell & Meck, 2004; Meck & Benson, 2002). However, findings in the literature regarding the neurobiological mechanism underlying different time scales of perception (for a review, see Grondin, 2001). For instance, inconsistent with the findings from Matell and Meck (2000; 2004), Rammsayer (1999) does suggest that the temporal processing of intervals in the range of milliseconds depends on the effective level of dopaminergic activity in the basal ganglia.

14.5 Potential Practical Applications and Future Directions

14.5.1 Alzheimer's Disease and Clicks

Jones, Sahakian, Levyl, Warburton and Gray (1992) explored the effects of nicotine on patients with Alzheimers Disease (AD). Findings showed no change in memory, however perceptual and visual attention deficits were improved in Alzheimer patients (AD) after nicotine (Jones et al., 1992). With respect to time, Nichelli, Venneri, Molinari, Tavani and Grafman (1993) investigated whether AD affects subjective time durations using prospective time estimation tasks. Participants were asked to repeatedly reproduce standard intervals of 1 second, the short-time durations. For longer time durations, a verbal estimation procedure was used in which participants had to read either 5, 10, 20, or 40 digits presented one at a time, while simultaneously maintaining the rhythm of 1 key press per second. After each sequence, participants were asked to judge the elapsed time from the beginning of the trial. AD patients showed increased variability on repeated reproduction of 1-s intervals and were inaccurate in the verbal estimations for longer durations, compared to the performance of the matched young normal control group and the elderly subject control group. Nichelli et al. (1993), based on the SET model, argue that AD patients display a variety of deficits indicative of involvement of the clock, memory, as well as decisional mechanisms (Nichelli, Venneri, Molinari, Tavani & Grafman, 1993). In addition, Papagno, Allegra and Cardaci, (2004) also explored prospective time verbal estimation in individuals with Alzheimer’s and found that the performance of AD patients was much poorer than that of controls (Papagno et al., 2004). Furthermore, Carrasco, Guillem and Redolat (2000) also found time perceptions deficits in individuals with Alzheimer’s using production tasks which required participants to make estimates of short temporal intervals. Participants had to produce three short empty intervals (5, 10 and 25 s). In all three intervals, Carrasco et al. (2000) found that AD patients showed deficits both in the accuracy of time judgments as well as displaying more variability in time judgments compared to controls (Carrasco et al., 2000). Clearly, AD patients have deficits on a variety of different timing tasks. It would be interesting to investigate further the timing abilities of individuals with AD using click trains to determine whether the effect of clicks on the 1, 2 and 4 choice reaction time task is as significant in individuals with AD as it is in controls (the population used for the experiment discussed in this thesis).

Previous studies focus primarily on the reproduction of time intervals in individuals with AD. Another experiment could involve reproduction of intervals in which the standards are preceded either by 5 seconds of clicks or 5 seconds of silence. An interesting question would be whether the trials with clicks cause shorter productions in AD patients to the same extent as controls. Information processing could also be explored using clicks in a 1, 2 and 4 choice reaction time task. If AD patients demonstrate impaired performance on the timing tasks using clicks but have intact performance on the reaction time task, then it would again weaken the idea of a relationship between information processing and the internal clock.

14.5.2 Parkinson's Disease and Reaction Times

Pastor, Artieda, Jahnshahi and Obeso (1992) found that patients with Parkinson's disease (PD) underestimated the duration of a time interval on a task of verbal estimation. They also overproduced short time intervals, supporting the notion that in PD the internal pacemaker is slowed down. Malapani, Rakitin, Levy, Meck, Deweer, Dubois and Gibbon, (1998) argue that timing deficits in PD are due to a dopamine-related dysfunction since normal performance on timing tasks can be seen after administration of levodopa-apomorphine. Others, however, argue that PD patients can demonstrate similar abilities and characteristics as controls on timing tasks regardless of dopamine levels (Wearden, Smith-Spark, Cousins, Edelstyn, Cody & O'Boyle, 2008). Instead, Wearden et al. (2008) draw attention to the fact that many timing tasks on individuals with PD involve a motor component which they are known to have difficulties with. Therefore, deficits in timing may not necessarily be due to a central timing impairment, rather an impaired motor timing ability. Animal studies argue that dopamine deficiency causes an increase in neural "noise" in the basal ganglia. Therefore, in individuals with PD, they may be performing tasks as if they were doing two simultaneously (Bloxham, Dick & Moore, 1987). If the notion that the clicks works because they reduce the neural "noise", then perhaps clicks would improve the performance of individuals with PD on timing tasks.

14.5.3 Repetitive Movements and Time Judgments

Here the idea would be that some repetitive movement made by the participant (e.g., foot-tapping or hand clenching) might influence subjective time judgments. So, estimates of the duration of auditory or visual stimuli would be preceded by 5 seconds of inactivity, or 5 seconds of repetitive movement. One factor of interest might be the hand used. So, for example, we could contrast left- and right-side hand or foot movements in right handed participants. There would be three conditions: no movement, right-side and left-side. The main idea of this study is to explore which stimuli might have the same effect as clicks. Considering the absence of effect of white noise as reported in this thesis, it is argued that it is repetitive stimuli which causes arousal, thus speeding up the internal clock. If the same effect as clicks occurs in this study, it would further support this idea. The control would be non-repetitive movement. The repetitive movement manipulations could also be used in a reaction time task. If an effect of repetitive movement is found in both the verbal estimation and reaction time task, then it would provide further evidence of a link between information processing and the internal clock.

14.5.4 Effect of Valid and Invalid Cueing in the 1, 2 and 4 Choice Reaction Time Task Using Clicks and No-Clicks

A potential problem with the 1, 2 and 4 choice reaction time task used in Chapter 6 in this thesis, is that when the participant is waiting for the presentation of the cross in one of the four boxes, they are sweeping across all four boxes and this could present potential latency problems. Take the following scenario. A participant is waiting for the cross to appear in one of the four boxes. When the participant is fixated temporarily on box one, the cross appears in box four. The participant then has to disengage their attention away from the current box to locate the cross in the other box in order to make the correct response. This may take more time than if the participant was actually fixating on the same box that the cross happens to appear in. Such an effect may even exist if the participants were asked to fixate at a cross in the middle of the four boxes (between box two and three). In this scenario, the presentation of a cross in either of the outer boxes (box one and four) may be at a disadvantage, since they are more in the peripheral vision of the participant. A way to reduce this problem could be the introduction of a cueing type 1, 2 and 4 choice reaction time paradigm. So, when the participants are waiting for the cross to appear in one of the four boxes they could receive a valid or invalid cue as to what box the cross will appear in. However, a much simpler way to reduce this problem of fixation would be to make the boxes smaller, so they can always be seen in one fixation.

14.6 Conclusion

The primary aim of this thesis was to explore the relationship between information processing and the internal clock. Many of the findings strongly indicated a link between the two while others weakened the suggestion. The inconsistency of the findings emphasise the complexity of disentangling this relationship while highlighting the need for further study. Additionally, despite some strong evidence of a link, the *directional* nature of the relationship is uncertain and further studies as suggested are required to ascertain this.

References

Adrian, E. D., & Matthews, B. H. C. (1934). The Berger rhythm: potential changes from the occipital lobes in man. *Brain, 57,* 355 384.

Alexander, J.E., O'Boyle, M.W., & Benbow, C.P. (1996). Developmentally advanced EEG alpha power in gifted male and female adolescents. *International Journal of Psychophysiology, 23,* 25-31.

Allan, L.G. (1998). The influence of the scalar timing model on human timing research. *Behavioural Processes, 44,* 101-117.

Amalric, M., & Koob, G.F. (1987). Depletion of dopamine in the caudate nucleus but not in nucleus accumbens impairs reaction-time performance in rats. *The Journal of Neuroscience, 7,* 2129-2134.

Angelakis, E., Lubar, J.F., Stathopoulou, S., & Kounios, J. (2004). Peak alpha frequency: an electroencephalographic measure of cognitive preparedness. *Clinical Neurophysiology, 115,* 887-897.

Angelakis, E., Stathopoulou, S., Frymiare, J.L., Green, D.L., Lubar, J.F., & Kounios, J. (2007). EEG neurofeedbeck: a brief overview and an example of peak alpha frequency training for cognitive enhancement in the elderly. *The Clinical Neuropsychologist, 21,* 110-129.

Angrilli, A., Cherubini, P., Pavese, A., & Manfredini, S. (1997). The influence of affective factors on time perception. *Perception and Psychophysics, 59*, 972-982.

Anokhin, A., & Vogel, F. (1996). EEG alpha rhythm frequency and intelligence in normal adults. *Intelligence, 23,* 1–14.

Antelman, S.M., Eichler, A.J., Black, C.A., & Kocan, D. (1980). Interchangeability of stress and amphetamine in sensitization. *Science, 2007,* 329-331.

Ashcraft, M.H. (2002). *Cognition*. 3rd Edition. Prentice Hall International Inc.

Atkinson, A.P., & Adolphs, R. (2005). Visual emotion perception: Mechanisms and processes. In: *Emotion and Consciousness,* Feldman-Barrett, L., Niedenthal, P.M. and Winkielman, P. Guilford Press.

Audiffren, M., Tomporowski, P.D. & Zagrodnik, J. (2008). Acute aerobic exercise and information processing: energizing motor processes during a choice reaction time task. *Acta Psychologica (Amst), 129,* 410-419.

Auerbach, S. M. (1974). Anxiety and Time Estimation: A Failure to Replicate Felix. *Journal of Genetic Psychology, 124,* 187-196.

Azorin, J.M., Benhaïm, P., Hasbroucq, T., & Possamaï, C.A. (1995). Stimulus preprocessing and response selection in depression: a reaction time study. *Acta Psychologica (Amst),* 89, 95-100.

Baddeley, A.D. (1966). Time-estimation at reduced body-temperature. *The American Journal of Psychology, 79,* 475-479.

Basar, E., & Schurmann, M. (1996). Alpha rhythms in the brain: functional correlates. *News in Physiological Sciences, 11,* 90-96.

Basar, E., Schurmann, M., Basar-Eroglu, C., & Karakas, S. (1997). Alpha oscillations in brain functioning: an integrative theory. *International Journal of Psychophysiology, 26*, 5-29.

Başar, E., Başar-Eroglu, C., Karakaş, S., & Schürmann, M. (2001). Gamma, alpha, delta, and theta oscillations govern cognitive processes. *International Journal of Psychophysiology, 39,* 241-248.

Bates T, Mangan G, Stough C., & Corballis P. (1995). Smoking, processing speed and attention in a choice reaction time task. *Psychopharmacology (Berl), 120*, 209-212.

Baudouin, A., Vanneste, S., & Isingrini, M. (2004). Age-related cognitive slowing: the role of spontaneous tempo and processing speed. *Experimental Aging Research, 30*, 225-239.

Baunez, C., Nieoullon, A., & Amalric, M. (1995). Dopamine and complex sensorimotor integration: further studies in a conditioned motor task in the rat. *Neuroscience, 65,* 375-384.

Baum, S.K., Boxley, R.L., & Sokolowski, M. (1984). Time perception and psychological well-being in the elderly. *The Psychiatric Quarterly, 56,* 54-61.

Behar, I., & Adams, C. (1966). Some properties of the reaction time ready-signal. *American Journal of Psychology, 79*, 419-426.

Bell, C.R., & Provins, K.A. (1967). Relation between physiological responses to environmental heat and time judgments. *Journal of Experimental Psychology, 66,* 572-579.

Bell, C.R. (1975). Effects of lowered temperature on time estimation. *Quarterly Journal of Experimental Psychology, 27*, 531-538.

Bell, C.R. (1977). Time and temperature: A reply to Green and Simpson. *Quarterly Journal of Experimental Psychology, 29,* 341-344.

Bennett, J. (2004). Time in human experience. *Philosophy, 79*, 165 – 183.

Benton, A.L., Jentsche, R., & Wahler, H.J. (1960). Effects of motivating instructions on reaction time in schizophrenia. *Journal of Nervous and Mental Disease, 130*, 26-29.

Ben-Simon, E., Podlipsky, I., Arieli, A., Zhdanov, A., & Hendler, T. (2008). Never resting brain: Simultaneous representation of two alpha related processes in humans. *PLoS ONE, 3,* 1-9.

Bernstein, I., Chu, P., Briggs, P., & Schurman, D. (1973). Stimulus intensity and foreperiod effects in intersensory facilitation. *Quarterly Journal of Experimental Psychology, 25*, 171-181.

Berry, E., Nicolson, R.I., Foster, J.K., Behrmann, M., & H. J. Sagar, H.J. (1999). Slowing of reaction time in Parkinsons disease: the involvement of the frontal lobes. *Neuropsychologia, 37,* 787-795.

Bertelson, P., & Boons, J-P. (1960). Time uncertainty and choice reaction time. *Nature, 187,* 531–532.

Bertelson, P., & Tisseyre, F. (1969). Time-course of preparation: Confirmatory results with visual and auditory warning signals. *Acta Psychologica, 30*, 145-154.

Bilang-Bleuel, A., Revah, F., Colin, P., Locquet, I., Robert, J.J., Mallet, J., & Horellou, P. (1997). Intrastriatal injection of an adenoviral vector expressing glial-cell-line-derived neurotrophic factor prevents dopaminergic neuron degeneration and behavioral impairment in a rat model of Parkinson disease. *Proceedings of the National Academy of Sciences of the United States of America, 94*, 8818-8823.

Binkofski, F., & Block, R.A. (1996). Accelerated time experience after left frontal cortex lesion. *Neurocase, 2,* 485-493.

Bishop, G.H. (1933). Cyclic change in the excitability of the optic pathway of the rabbit. *American Journal of Physiology, 103*, 211–224.

Bizo, L.A., & White, G. (1999). Pacemaker rate in the behavioural theory of timing. *Journal of Experimental Psychology: Animal Behaviour Processes, 20,* 308-321.

Blanchard, J., & Sawers, S.J. (1983). Comparative pharmacokinetics of caffeine in young and elderly men. *Journal of Pharmacokinetics and Biopharmaceutics, 11*, 109-126.

Bliss, T.V.P., & Lomo, T. (1973). Long-lasting potentiation of synaptic transmission in the dentate area of the anaesthetized rabbit following stimulation of the perforant path. *Journal of Physiology, 232,* 331-356.

Bliss, T.V.P., & Collingridge, G.L. (1993) A synaptic model of memory: long term potentiation in the hippocampus. *Nature, 361,* 31–39.

Block, R. (1990). Models of psychological time. In: Block, R. (ed.), *Cognitive models of psychological time.* Hillsdale, NJ: Lawrence Erlbaum, 1–36.

Block, R. A., & Zakay, D. (1996). Models of psychological time revisited. In H. Helfrich (Ed.), *Time and mind* (pp. 171–195). Gottingen, Germany: Hogrefe and Huber.

Block, R.A., Zakay, D., & Hancock, P.A. (1998). Human aging and duration judgments: a meta-analytic review. *Psychology and Aging, 13,* 584-596.

Block, R.A., Zakay, D., & Hancock, P.A. (1999). Developmental Changes in Human Duration Judgments: A Meta-Analytic Review. *Developmental Review, 19,* 183-211.

Block, R. A., Hancock, P. A., & Zakay, D. (2000). Sex differences in duration judgments: A meta-analytic review. *Memory and Cognition, 28,* 1333–1346.

Bloxham, C.A., Dick, D.J., & Moore, M. (1987). Reaction times and attention in Parkinson's disease. *Journal of Neurology, Neurosurgery and Psychiatry, 50,* 1178-1183.

Bonin-Guillaume, S., Blin, O., & Hasbroucq, T. (2004). An additive factor analysis of the effect of depression on the reaction time of old patients. *Acta Psychologica, 117,* 1-11.

Botella, P., Bosch, F., Romero, F.J., & Parra, A. (2001). Sex differences in estimation of time intervals and in reaction times are removed by moderate but not high doses of caffeine in coffee. *Human Psychopharmacology: Clinical and Experimental, 16,* 533-540.

Botwinick, J. (1971). Sensory-set-factors in age differences in reaction time. *Journal of Genetic Psychology, 119,* 241-249.

Bradley, M.M., & Lang, P.J. (1999). *International affective digitalized sounds (IADS): Stimuli, instruction manual and affective ratings* (Tech. Rep. No. B-2). Gainsville, FL,: University of Florida, Center for Research in Psychophysiology.

Brazier, M. A. B. (1960). Long-persisting electrical traces in the brain of man and their possible relationship to higher nervous activity. *Electroencephalography and Clinical Neurophysiology, Supplement, 13,* 347-358.

Brisswalter, J., Arcelin, R., Audiffren, M., & Delignières, D. (1997). Influence of physical exercise on simple reaction time: effect of physical fitness. *Perceptual and Motor Skills, 85,* 1019-1027.

Brisswalter, J., Collardeau, M., & Arcelin, R. (2002). Effects of acute physical exercise on cognitive performance. *Sports Medicine, 32,* 555–566.

Brown, R.G., Marsden, C.D., Quinn, N., & Wyke, M.A. (1985). Alterations in cognitive performance and affect arousal state during fluctuations in motor functions in Parkinson's disease. *Journal of Neurology, Neurosurgery and Psychiatry, 47,* 454-465.

Brown, R.G., & Marsden, C.D. (1988). Internal versus external cues and the control of attention in Parkinson's disease. *Brain, 111,* 323-345.

Brown, V.J., & Robbins, T.W. (1991). Simple and choice reaction time performance following unilateral striatal dopamine depletion in the rat. Impaired motor readiness but preserved response preparation. *Brain, 114,* 513-525.

Brown, V.J., Brasted, P.J., & Bowman, E.M. (1996). The effect of systematic d-amphetamine on motor versus motivational processes in the rat. *Psychopharmacology, 128,* 171-180.

Brown, S. W. (1997). Attentional resources in timing: Interference effects in concurrent temporal and nontemporal working memory tasks. *Perception and Psychophysics, 59,* 1118–1140.

Brown, G.D.A., Preece, T., & Hulme, C. (2000). Oscillator-based memory for serial order. *Psychological Review 107,* 127–181.

Brunner, D., Fairhurst, S., Stolovitsky, G., & Gibbon, J. (1997). Mnemonics for variability: Remembering food delay. *Journal of Experimental Psychology: Animal Behavior Processes, 23,* 68–83.

Bryan, J., Luszcz, M.A., & Crawford, J.R. (2005). Verbal knowledge and speed of information processing as mediators of age differences in verbal fluency performance among older adults. *Psychology and Aging, 12,* 473-478.

Buhusi, C. V., & Meck, W. H. (2002). Differential effects of methamphetamine and haloperidol on the control of an internal clock. *Behavioural Neuroscience, 116,* 291–297.

Buhusi, C.V., & Meck, W.H. (2005). What makes us tick? Functional and neural mechanisms of interval timing. *Nature Reviews, 6,* 755-765.

Burdick, A. (2006). The future of time. The Mind in Overdrive. Can we increase productivity by revving up the neural pacemakers in the brain? Discover, 27 (4). Website accessed on 27/01/08. http://multiplex.integralinstitute.org/Public/cs/forums/thread/10867.aspx

Burle, B., & Bonnet M. (1997). Further argument for the existence of a pacemaker in the human information processing system. *Acta Psychologica (Amst), 97,* 129-143.

Burle, B., & Bonnet, M. (1999). What’s an internal clock for? From temporal information processing to temporal processing of information. *Behavioural Processes, 45,* 59-72.

Burle, B., & Bonnet, M. (2000). High-speed memory scanning: a behavioral argument for a serial oscillatory model. *Cognitive Brain Research 9,* 327–337.

Burle, B., & Casini, L. (2001). Dissociation between activation and attentional effects in time estimation: implications for internal clock models. *Journal of Experimental Psychology: Human Perception and Performance, 27,* 195-205.

Callaway, E., & Yaeger, C. (1960). Relationships between reaction time and EEG alpha phase. *Science, 132,* 1765-1766.

Campbell, L.A., & Bryant, R.A. (2007). How time flies: a study of novice skydivers. Shorter communication. *Behaviour Research and Therapy, 45,* 1389 – 1392.

Carrasco, C., Redolat, R., & Simon, V.M. (1998). Time estimation in minimally abstinent smokers. *Human Psychopharmacology: Clinical and Experimental, 13,* 543-549.

Carrasco, M.C., Guillem, M.J., & Redolat, R. (2000). Estimation of short temporal intervals in Alzheimer's disease. *Experimental Aging Research, 26,* 139-51.

Carrasco, M.C., Bernal, M.C., & Redolat, R. (2001). Time estimation and aging: a comparison between young and elderly adults. *International Journal of Aging and Human Development, 52,* 91-101.

Cattell, J. McK (1886). The influence of the intensity of the stimulus on the length of the reaction time. *Brain, 8,* 512-515.

Celebi, G.A. (1978). Simple apparatus for generating reaction time histograms. Brief communication. *Physiology and Behavior, 20,* 355-356.

Cevik, M.O. (2003). Effects of Methamphetamine on duration discrimination. *Behavioral Neuroscience, 117,* 774-784.

Chapman, P., Cox, G., & Kirwan, C. (2005). Chapter 16. Distortions of drivers’ speed and time estimates in dangerous situations. In *Behavioural Research in Road Safety: Fifteeth Seminar*. Department of Transport, London.

Chen, W.R., Lee, S., Kato, K., Spenser, D.D., Shepherd, G.M., & Williamson, A. (1996) Long-term modifications of synaptic efficacy in the human inferior and middle temporal cortex. *Proceedings of the National Academy of Sciences (PNAS), 23,* 8011–8015.

Church, R.M. (1984). Properties of the internal clock. Annals of the New York Academy of Sciences, 423, Issue, *Timing and time perception,* 566-582.

Clapp, W.C., Kirk, I.J., Hamm, J.P., Shepherd, D., & Teyler, T.J. (2005). Induction of LTP in the human auditory cortex by sensory stimulation. *European Journal of Neuroscience, 22,* 1135-1140.

Clapp, W.C., Muthukumaraswamy, S.D., Hamm, J.P., Teyler, T.J., & Kirk, I.J. (2006). *Neuroscience Letters, 398,* 220-223.

Clubley, M., Bye, C.E., Henson, T.A., Peck, A.W., & Riddington, C.J. (1979). Effects of caffeine and cyclizine alone and in combination on human performance, subjective effects and EEG activity. *British Journal of Clinical Pharmacology, 7,* 157-163.

Colcombe, S., & Kramer, A.F. (2003). Fitness effects on the cognitive function of older adults: a meta-analytical study. *Psychological Science, 14,* 125–130.

Cooper, C.J. (1973). Anatomical and physiological mechanisms of arousal, with special reference to the effects of exercise. *Ergonomics, 16,* 601-609.

Cooper, J.A., Sagar, H.J., Tidswell, P., & Jordan, N. (1994). Slowed central processing in simple and go/no-go reaction time tasks in Parkinson’s disease. *Brain, 117,* 517–529.

Collardeau, M., Brisswalter, J., & Audiffren, M. (2001). Effects of a prolonged run on simple reaction time of well trained runners. *Perceptual and Motor Skills, 93,* 679-689.

Colman, A.M. (2001). *Dictionary of psychology*. Oxford University Press.

Csikszentmihalyi. M. (1990). *Flow: The psychology of optimal experience.* New York: Harper & Row.

Darwin, C. (1998). *The expression of the emotions in man and animals*. England: Oxford University Press. (Original work published 1872).

Davey, C.P. (1973). Physical exertion and mental performance. *Ergonomics, 16,* 595-599.

Davis, H., & Davis, P. (1936). Action potentials of the brain in normal persons and in normal states of cerebral activity. *Archives of Neurology and Psychiatry, (Chic.), 36,* 1214-1224.

Davranche, K., & Audiffren, M. (2004). Facilitating effects of exercise on information processing. *Journal of Sports Sciences, 22,* 419-428.

Davranche, K., Burle, B., Audiffren, M., & Hasbroucq, T. (2005). Information processing during physical exercise: a chronometric and electromyographic study. *Experimental Brain Research, 165,* 532-540.

Davranche, K., Burle, B., Audiffren, M., & Hasbroucq, T. (2006). Physical exercise facilitates motor processes in simple reaction time performance: an electromyographic analysis. *Neuroscience Letters, 396,* 54-66.

Dehaene, S. (1993). Temporal oscillations in human perception. *Psychological Science, 4,* 264 – 270.

Deffenbacher, J.L. (1986). Cognitive and physiological components of test anxiety in real-life exams. *Cognitive Therapy and Research, 10,* 635 – 644.

Delay, E.R., & Mathey, M.E. (1985). Effects of ambient noise on time estimation by humans. *Perceptual and Motor Skills, 61,* 415-419.

Delignie`res, D., Brisswalter, J., & Legros, P. (1994). Influence of physical exercise on choice reaction time in sports experts: the mediating role of resource allocation. *Journal of Human Movement Studies, 27,* 173–188.

Dempsey, E.W., & Morison, R.S. (1943). The electrical activity of a thalamocortical relay system. *American Journal of Physiology, 138*, 283-296.

Derbyshire, A. J., & Bohn, S. S. (1938). Electroencephalography: Introduction and present status. *Journal - Michigan Medical Society, 37*, 985-990.

Dews, P.B. (1970). The theory of fixed-interval responding. In W.N., Schoenfeld (Ed). *The Theory of reinforcement Schedules.* New York: Appleton-Century-Crofts, 43-61.

Di Lollo, V. (1977). Temporal characteristics of iconic memory. *Nature, 267,* 241-243.

Dietrich, A., & Sparling, P.B. (2004). Endurance exercise selectively impairs prefrontal-dependent cognition. *Brain and Cognition, 55*, 516–524.

Dietrich, A. (2006). Transient hypofrontality as a mechanism for the psychological effects of exercise. *Psychiatry Research, 145,* 79-83.

Dobrossy, M.D., & Dunnett, S.B. (1997). Unilateral striatal lesions impair response execution on a lateralized choice reaction time task. *Behavioural Brain Research, 87,* 159-171.

Donders, F.C. (1969). Over de snelheid van psychische processen [Speed of Mental Processes]. Onderzoekingen gedann in het Psysiologish Laboratorium der Utrechtsche Hoogeschool (W.G. Koster, Trans.). In W.G. Koster (Ed.), Attention and performance II. Acta Psychologica, 30, 412-431. (Original work published 1868).

Dongier, M., McCallum, W.C., Torres, F., & Vogel, W. (1976). Psychological and Psychophysiological States. In: E. Chatrian and G.C. Lairy (Eds.), *Handbook of Electroencephalography*. Clinical Neurophysiology, Section III. Elsevaier, Amsterdam, pp. 6A-195, 6A-256.

Drew, M.R. Fairhurst, S., Malapani, C., Horvitz, J.C., & Balsam, P.D. (2003). Effects of dopamine antagonists on the timing of two intervals. *Pharmacology, Biochemistry and Behavior, 75,* 9-15.

Droit-Volet, S., & Wearden, J. (2002). Speeding up an internal clock in children? Effects of visual flicker on subjective duration. *The Quarterly Journal of Experimental Psychology, 55B,* 193-211.

Droit-Volet, S. (2003). Alerting attention and time perception in children. *Journal of Experimental Child Psychology, 85*, 372-384.

Droit-Volet, S., Tourret, S., & Wearden, J. (2004). Perception of the duration of auditory and visual stimuli in children and adults. *The Quarterly Journal of Experimental Psychology, 57A*, 797-818.

Droit-Volet, S., Brunot, S., & Niedenthal, P.M. (2004). Perception of the duration of emotional events. *Cognition and Emotion, 18,* 849-858.

Droit-Volet, S., & Meck, W.H. (2007). How emotions colour our perception of time. *Trends in Cognitive Sciences, 11*, 504-513.

Droit-Volet, S., & Gil, S. (2009). The time-emotion paradox. *Philosophical Transactions of The Royal Society, 364,* 1943-1953.

Droit-Volet, S., & Gil, S. (2009). Emotion and time perception. *Journal of Philosophical Transactions of the Royal Society (Biological Sciences), 364*, 1943–1953.

Droit-Volet, S. (2010). Speeding up a master clock common to time, number and length? Behavioural Processes, xxxx.

Dubois, B., Danze, F., Pillon, B., Cusimano, G., Lhermitte, F., & Agid, Y. (1987). Cholinergic-dependent cognitive deficits in Parkinson’s Disease. *Annals of Neurology, 22,* 26-30.

Dubois, B., & Pillon, B. (1996). Cognitive deficits in Parkinson’s disease. *Journal of Neurology, 244,* 1432-1459.

Dufft, C.C., & Ulrich, R. (1999). Intersensory facilitation: also concomitant visual stimuli can decrease reaction time. (Article in German). *Zeitschrift für experimentelle Psychologie : Organ der Deutschen Gesellschaft für Psychologie, 46*, 16-27.

Duffy, F. H., Iyer, V. G., & Surwillo, W. W. (1989). *Clinical electroencephalography and topographic brain mapping: Technology and practice.* New York: Springer-Verlag.

Dusser de Barenne, J.G., & McCulloch, W.S. (1941). Functional interdependence of sensory cortex and thalamus. *Journal of Neurophysiology, 4,* 304-310.

Dustman, R.E., & Beck, E.C. (1965). Phase of alpha brain waves, reaction time and visually evoked potentials. *Electroencephalography and Clinical Neurophysiology, 18,* 433–440.

Dustman , R.E., Emmerson, R.Y., Ruhling, R., Shearer, D.E., Steinhaus, L.A., Johnson, S., Bonekat, H., & Shigeoka, J. (1990). Age and fitness effects on EEG, ERPs, visual sensitivity and cognition. *Neurobiology of Aging, 11,* 193-200.

Dustman, R.E., LaMarche, J.A., Cohn, N.B., Shearer, D.E., & Talone, J.M. (1985). Power spectral analysis and cortical coupling of EEG for young and old normal adults. *Neurobiology of Aging, 6,* 193-198.

Dustman, R.E., Ruhling, R., Russell, E., Shearer, D.E., Bonekat, H., Shigeoka, J., Wood, J., & Bradford, D. (1984). Aerobic exercise training and improved neuropsychological function of older individuals. *Neurobiology of Aging, 11*, 193-330.

Dustman, R.E, Shearer, D.E., & Emmerson, R.Y. (1993). EEG and event-related potentials in normal aging. *Progress in Neurobiology, 41*, 369-401.

Eagleman, D.M. (2004). The where and when of intention. *Neuroscience, 303*, 1144-1146.

Eagleman, D.M., Tse, P.U., Buonomano, D., Janssen, P., Nobre, A.C., & Holcombe, A.O. (2005). Time and the brain: how subjective time relates to neural time. Mini-symposium. *The Journal of Neuroscience, 25,* 10369-10371.

Eagleman, D.M. (2007). Does our perception of time slow during a crisis? http://machineslikeus.com/does-our-perception-of-time-slow-during-a-crisis.html. Website accessed on 7th of June 2010.

Effron, R., & Lee, D.N. (1971). The visual persistence of a moving stroboscopically illuminated object. *American Journal of Psychology, 84,* 365-375.

Effron, D.A., Niedenthal, P.M., Gil, S., & Droit-Volet, S. (2006). Embodied temporal perception of emotion. *Emotion, 6,* 1-9.

Eggermont, J.J. (1994). Neural interaction in cat primary auditory cortex 11. Effects of sound stimulation. *Journal of Neurophysiology, 71,* 246-270.

Egner, T., & Gruzelier, J. (2004). EEG Biofeedback of low beta band components: Frequencyspecific effects on variables of attention and event-related brain potentials. *Clinical Neurophysiology, 115*, 131–139.

Eisler, H., & Eisler, A.D. (1992). Time perception: effects of sex and sound intensity on scales of subjective duration. *Scandinavian Journal of Psychology, 33,* 339-358.

Eimer, M. (1998). The lateralized readiness potential as an on-line measure of central response activation processes. *Behavior Research Methods Instruments and Computers, 30*, 146-156.

Engle, R. W., Tuholski, S. W., Laughlin, J. E., & Conway, A. R. (1999). Working memory, short-term memory and general fluid intelligence: A latent-variable approach. *Journal of Experimental Psychology, General, 128,* 309–331.

Espinosa-Fernandez, L., Miro, E., Cano, M., & Buela-Casal, G. (2003). Age-related changes and gender differences in time estimation. *Acta Psychologica, 112*, 221-232.

Etnier, J.L., Salazar, W., Landers, D.M., Petruzzello, S.J., Han, M., & Nowell, P. (1997). The Influence of Physical Fitness and Exercise Upon Cognitive Functioning: A Meta-Analysis. *Journal of Sports and Exercise Psychology, 19*, 249-277.

Etnier, J.L., Nowell, P.M., Landers, D.M., & Sibley, B.A. (2006). A meta-regression to examine the relationship between aerobic fitness and cognitive performance. *Brain Research Reviews, 52,* 119-130.

Evarts, E.V., Teravainen, H., & Calne, D.B. (1981). Reaction time in Parkinson’s disease. *Brain, 104*, 167-186.

Fair, D. G. (1984). *Temporal distortion*. Unpublished Manuscript, Department of Safety Science, University of Southern California. Los Angeles, CA.

Falk, J.L., & Bindra, D. (1954). Judgment of time as a function of serial position and stress. *Journal of Experimental Psychology, 47,* 279-282.

Farber, I.E., & Spence, K.W. (1956). Effects of anxiety, stress and task variables on reaction time. *Journal of Personality, 25,* 1-18.

Fox, R.H., Bradbury, P.A., Hampton, I.F.G., & Legg, C.F. (1967). Time judgment and body temperature. *Journal of Experimental Psychology, 75,* 88-96.

Fox, E., Russo, R., Bowles, R., & Dutton, K. (2001). Do threatening stimuli draw or hold visual attention in subclinical anxiety? *Journal of Experimental Psychology: General, 130,* 681-700.

Fox, E., Russo, R., & Dutton, K. (2002). Attentional bias for threat: Evidence for delayed disengagement from emotional faces. *Cognition and Emotion, 16,* 355-379.

Fozard, J.L., Vercryssen, M., Reynolds, S.L., Hancock, P.A., & Quilter, R.E. (1994). Age differences and changes in reaction time: the Baltimore Longitudinal Study of Aging. *Journal of Gerontology, 49,* 179-189.

Fraisse, P. (1984). Perception and estimation of time. *Annual Review of Psychology, 35,* 1–37.

Franks, H.M., Hagedorn, H., Hensley, V.R., Hensley, W.J., & Starmer, G.A. (1975). The effect of caffeine on human performance, alone and in combination with ethanol. *Psychopharmacologia, 45,* 177-181.

Frewer, L.J., & Lader, M. (1991) The effects of caffeine on two computerised tests of attention and vigilance. *Human Psychopharmacology, 6,* 119-128.

Garrett, B. L., & Silver, M. P. (1976). The use of EMG and alpha biofeedback to relieve test anxiety in college students. In I. Wickramasekera (Ed.), *Biofeedback, behavior therapy and hypnosis.* Chicago, IL: Nelson-Hall.

Gescheider, G.A. (1976). *Psychophysics: Method and Theory.* Hillsdale, NJ: Lawrence Erlbaum.

Gibbon, J. (1977). Scalar expectancy theory and Weber’s Law in animal timing. *Psychological Review, 84,* 279-335.

Gibbon, J., Church, R.M., & Meck, W.H. (1984). Scalar timing in memory. *Annals of New York Academy of Science, 423,* 52-77.

Gibbon, J., & Church, R.M. (1984). Sources of variance in an information processing theory of timing. In Roitblat, H.L., Bever, T.H. and Terrace, H.S. *Animal Cognition,* 465- 489.

Gibbon, J., & Church, R.M. (1990). Representation of time. *Cognition, 37,* 23-54.

Gibbon, J., Malapani, C., Dale, C.L., & Gallistel, C.R. (1997). Towards a neurobiology of temporal cognition: advances and challenges. *Current Opinion in Neurobiology, 7,* 170 – 184.

Gibbons, H., & Rammsayer, T.H. (2004). Current-source density analysis of slow brain potentials during time estimation. *Psychophysiology, 41,* 861-874.

Giedke, H., Their, P., & Bolz, J. (1981). The relationship between P3-latency and reaction time in depression. *Biological Psychology, 13,* 31-49.

Gil, S., Niedenthal, P.M., & Droit-Volet, S. (2007). Anger and time perception in children. *Emotion, 7,* 219-225.

Gil, S., Droit-Volet, S., & Rousset, S. (2009). How liked and disliked foods affect time perception. *Emotion, 9,* 457-463.

Gil, S., & Droit-Volet, S. (2009). Time perception, depression and sadness. *Behavioural Processes, 80*, 169-176.

Gil, S., & Droit-Volet, S. (2009). How do emotional facial expression influence our perception of time? *Attention, Representation, and Human Performance: Integration of Cognition, Emotion and Motivation*. PsyPress.

Gil, S., & Droit-Volet, S. (in press). Time perception in response to ashamed faces in children and adults. *Scandinavian Journal of Psychology*.

Gilden, D.L., & Marusich, L.R. (2009). Contraction of time in attention-deficit hyperactivity disorder. *Neuropsychology, 23,* 265-269.

Gillings, A. (2006) Time out of mind. Time, BBC 4. Accessed on 19th October 2007. http://news.bbc.co.uk/1/hi/magazine/4741340.stm

Glenberg, A.M., Mann, S., Altman, L., Forman, T., & Procise, S. (1989). Modality effects in the coding and reproduction of rhythms. *Memory and Cognition, 17,* 373-383.

Glicksohn, J. (1992). Subjective time estimation in altered sensory environments. *Environment and Behavior, 24*, 634-652.

Goldman, R.I., Stern, J.M., Engel Jr, J., & Cohen, M.S. (2002). Simultaneous EEG and fMRI of the alpha rhythm. *Brain Imaging, NeuroReport, 13*, 2487-2492.

Goodrich, S., Henderson, L., & Kennard, C. (1989). On the existence of an attention-demanding process peculiar to simple reaction time: Converging evidence from Parkinson's disease. *Cognitive Neuropsychology, 1464-0627, 6,* 309 – 331.

Goldstone, S., & Goldfarb, J.L. (1964). Auditory and visual time judgment. *Journal of General Psychology, 70,* 368-287.

Goldstein, J. (1994). Sex differences in toy play and use of video games. Chapter 6. In Goldstein, J. (Eds.) *Toys, Play and Child Development.* Cambridge University Press.

Goldstone, S., & Lhamon, W.T. (1974). Studies of auditory-visual differences in human time judgment: sounds are judged longer than lights. *Perceptual and Motor Skills, 39,* 63-82.

Goody, W. (1958). Time and the nervous system: The brain as a clock. *Lancet*, 1139-1144.

Green, T.R.G., & Simpson, A.J. (1977). Time and temperature: a note on Bell. *Quarterly Journal of Experimental Psychology, 29*, 337-340.

Grice, G.R. (1955). Discrimination reaction time as a function of anxiety and intelligence. *Journal of Abnormal Psychology, 50*, 71-74.

Grommet, E.K., Droit-Volet, S., Gil, S., Hemmes, N.S., Baker, A.H., & Brown, B.L. (2011). Time estimation of fear cues in human observers. *Behavioural Processes, 86,* 88-93.

Grondin, S. (2001). From physical time to the first and second moments of psychological time. *Psychological Bulletin, 127,* 22-44.

Grosjean, M., Rosenbaum, D.A., & Elsinger, C. (2001). Timing and reaction time. *Journal of Experimental Psychology General, 130*, 256–272.

Groves, P.M., & Eason, R.G. (1969). Effects of attention and activation on the visual evoked cortical potential and reaction time. *Psychophysiology, 5,* 394-398.

Gruber, R.P., & Block, R.A. (2003). Effect of caffeine on prospective and retrospective duration judgments. *Human Pharmacology, 18,* 351-359.

Gruzelier, J.H. (1996). New advances in EEG and cognition. *International Journal of Psychophysiology, 24,* 1-5.

Gupta, A., & Khosla, M. (2006). Influence of mood on estimation of time. *Journal of the Indian Academy of Applied Psychology, 32,* 53-60.

Hainaut, J.P., & Bolmont, B. (2005). Effects of mood states and anxiety as induced by the video-recorded stroop color-word interference test in simple response time tasks on reaction time and movement time. *Perceptual and Motor Skills, 101*, 721-729.

Hamann, S.B., Ely, T.D., Grafton, S.T., & Kilts, C.D. (1999). Amygdala activity related to enhanced memory for pleasant and aversive stimuli. *Nature Neuroscience, 2,* 289-293.

Hancock, P.A., & Ganey, H.C.N. (1982). From the inverted-U to the extended-U: the evolution of a law of psychology. *Journal of Human Performance in Extreme Environments, 7,* 5-14.

Hancock, P.A., Szalma, J.L., & Weaver, J.L. (2002). *The distortion of perceptual space-time under stress.* White Paper. DOD Multidisciplinary Research Program: MURI Operator Performance Under Stress (OPUS).

Hancock, P.A., & Weaver, J. L. (2005). On time distortion under stress. Peer Reviewed Journal. *Theoretical Issues in Ergonomics Science, 6*, 193-211.

Hahn, B., Shoaib, M., & Stolerman, I.P. (2002). Nicotine-induced enhancement of attention in the five-choice serial reaction time task: the influence of task demands. *Psychopharmacology (Berl), 162,* 129-137.

Harrington, D. L., Lee, R. R., Boyd, L. A., Rapcsak, S. Z. & Knight, R. T. (2004). Does the representation of time depend on the cerebellum? Effect of cerebellar stroke. *Brain 127,* 561–574.

Hartel, F.W., Uhlenhuth, E.H., Fischman, M.W., & McCracken, S. (1981). Reinforcement, skin conductance and performance in a vigilance-reaction time task. *Psychiatry Research, 4,* 239 – 251.

Hasbroucq, T., Tandonnet, C., Micallef-Roll, J., Blin, O., & Possamaï, C.A. (2003). An electromyographic analysis of the effect of levodopa on the response time of healthy subjects. *Psychopharmacology (Berl), 165,* 313-316.

Hawkins, M.F., & Tedford, A.H. (1976). Effects of interest and relatedness on estimated duration of verbal material. *Bulletin of the Psychonomic Society, 8,* 301-302.

Heilman, K.M., Dawn Bowers, D., Watson, R.T., & Greer, M. (1976). Reaction Times in Parkinson Disease. *Archives of Neurology, 33,* 139-140.

Hermelin, B. (1964). Effects of variation in the warning signal on reaction times of severe subnormals. *Quarterly Journal of Experimental Psychology, 16,* 241-249.

Hermens, D.F., Williams, L.M., Clarke, S., Kohn, M., Cooper, N., & Gordon, E. (2005). Responses to methylphenidate in adolescent AD/HD: evidence from concurrently recorded autonomic (EDA) and central (EEG and ERP) measures. *International Journal of Psychophysiology, 58,* 21-33.

Hertzog, C., & Bleckley, M.K. (2001). Age differences in the structure of intelligence: Influences of information processing speed. *Intelligence, 29,* 191-217.

Heynen, A.J., & Bear, M.F. (2001) Long-term potentiation of thalamo-cortical transmission in the adult visual cortex in vivo. *Journal of Neuroscience, 21,* 9801–9813.

Hick, W.E. (1952). On the rate of gain of information. *Quarterly Journal of Experimental Psychology, 4,* 11-26.

Hinton, S.C., & Rao, S.M. (2004). “One-thousand one…one-thousand two…”: Chronometric counting violates the scalar property in interval timing. Theoretical and Review Articles. *Psychonomic Bulletin and Review, 11,* 24-30.

Hirsh, I.J., Bilger, R.C. and Deatherage, B.H. (1956). The effect of auditory and visual background on apparent duration. *American Journal of Psychology, 69,* 561-74.

Hoagland, H. (1933) The physiological control of judgments of duration: evidence for a chemical clock. *Journal of General Psychology, 9,* 267-287.

Hoagland, H., & Perkins, C.T. (1935). Some temperature characteristics in man. *The Journal of General Physiology, 18,* 399-408.

Hoagland, H. (1936). Pacemakers of human brain waves in normals and in general paretics. *American Journal of Physiology, 116,* 604-615.

Hockey, G.R.J. (1970). Effect of loud noise on attentional selectivity. *Quarterly Journal of Experimental Psychology, 22,* 28-36.

Hogervorst, E., Riedel, W.J., Schmitt, J.A.J., & Jolles, J. (1998). Caffeine improves memory performance during distraction in middle-aged, but not in young or old subjects. *Human Pharmacology, 13,* 277-284.

Holson, R. R., Bowyer, J. F., Clausing, P., & Gough, B. (1996). Methamphetamine-stimulated striatal dopamine release declines rapidly over time following microdialysis probe insertion. *Brain Research, 739,* 301–307.

Holubar, J. (1961). *The Sense of Time: An electrophysiological study of its mechanisms in man.* The M.I.T. Press.

Humphreys, M.S., & Revelle, W. (1984). Personality, motivation and performance: a theory of the relationship between individual differences and information processing. *Psychological Review, 91,* 153-184.

Hunter, S.K., Thompson, M.V., & Adams, R.D. (2001). Reaction time, strength and physical activity in women aged 20-89 years. *Journal of Aging and Physical Activity, 9,* 32-42.

Ivry, R. B., & Spencer, R. M. (2004). The neural representation of time. *Current Opinion in Neurobiology, 14*, 225–232.

Jackson, S. A. (1993). *Elite athletes in flow: The psychology of optimal sport experience.* (Doctoral dissertation, University of North Carolina at Greensboro, 1992). Dissertation Abstracts International, 54, 124-A.

Jackson, S.A. (1995). Factors influencing the occurrence of flow state in elite athletes. *Journal of Applied Sport Psychology, 7,* 138-166.

Jackson, S. A. (1996). Toward a conceptual understanding to the flow experience in elite athletes. *Research Quarterly for Exercise and Sport, 67,* 76-90.

Jahanshahi, M., Brown, R.G., & Marsden, C.D. (1992). Simple and choice reaction time and the use of advance information for motor preparation in Parkinson’s disease. *Brain, 115,* 539-564.

Jahanshahi, M., Brown, R.G., & Marsden, C.D. (1993). A comparative study of simple and choice reaction time in Parkinson's, Huntington's and cerebellar disease. *Journal of Neurology, Neurosurgery and Psychiatry, 56,* 1169-1177.

Jahanshahi, M., Brown, R.G., & Marsden, C.D. (1992). The effect of withdrawal of dopaminergic medication on simple and choice reaction time and the use of advance information in Parkinson's disease. *Journal of Neurology, Neurosurgery and Psychiatry, 55,* 1168-1176.

Jamin, T., Joulia, F., Fontanari, P., Giacomoni, M., Bonnon, M., Vidal, F., & Crémieux, J. (2004). Apnea-induced changes in time estimation and its relation to bradycardia. *Aviation, Space and Environmental Medicine, 75,* 876–880.

Janet, A., Young, J.A., & Pain, M.D. (1999). The Zone: Evidence of a Universal Phenomenon for Athletes Across Sports. *Athletic Insight – The Online Journal of Sport Psychology, 1.*

Jarvis, M.J. (1993). Does caffeine intake enhance absolute levels of cognitive performance? *Psychopharmacology, 110,* 45-52.

Jaskowski, P., Jaroszyk, F., & Hojan-Jezierska, D. (1990). Temporal-order judgments and reaction time for stimuli of different modalities. *Psychological Research, 52,* 35-38.

Jausovec, N. (1996). Difference in EEG Alpha activity related to giftedness. *Intelligence, 23*, 159-173.

Jausovec, N. (1997). Differences in EEG alpha activity between gifted and non-identified individuals: insights into problem solving. *Gifted Child Quarterly, 41*, 26-32.

Jausovec, N. (1998). Are gifted individuals less chaotic thinkers? *Personality and Individuals Differences, 25,* 253-267.

Jausovec, N., & Jausovec, K. (2000). Differences in resting EEG related to ability. *Brain Topography, 12,* 229–240.

Jones, G. M. M., Sahakian, B. J., Levyl, R., Warburton, D.M., & Gray, J.A. (1992). Effects of acute subcutaneous nicotine on attention, information processing and short-term memory in alzheimer's disease. *Psychopharmacology, 108,* 1432-2072.

Jones, L.A., Allely, C.S., & Wearden, J.H. (2010). Click trains and the rate of information processing: Does "speeding up" subjective time make psychological processes run faster? *Quarterly Journal of Experimental Psychology.*

Jones, L.A., Poliakoff, E., & Wells, J. (2009). Good vibrations: human interval timing in the vibrotactile modality. *Quarterly Journal of Experimental Psychology, 62,* 2171-2186.

Karras, A. (1962). The effects of reinforcement and arousal on the psychomotor performance of chronic schizophrenics. *Journal of Abnormal and Social Psychology, 65,* 104-111.

Kohler, M., Pavy, A., & Van Den Heuvel, C. (2006). The effects of chewing versus caffeine on alertness, cognitive performance and cardiac autonomic activity during sleep deprivation. *Journal of Sleep Research, 15,* 358-268.

Kohsaka, A., & Bass, J. (2006). A sense of time: how molecular clocks organize metabolism. *Trends in Endocrinology and Metabolism, 18,* 4-11.

Klimesch, W. (1996). Memory processes, brain oscillations and EEG synchronization. *International Journal of Psychophysiology, 241,* 61–100.

Klimesch, W. (1997). EEG-alpha rhythms and memory processes. *International Journal of Psychophysiology, 261,* 319–340.

Klimesch, W., Pfurtscheller, G., Mohl, W., & Schimke, H. (1990). Event-related desynchronization, ERD-mapping and hemispheric differences for words and numbers. *International Journal of Psychophysiology, 8,* 297–308.

Klimesch, W., Schimke, H., & Pfurtscheller, G. (1990). The topography of alpha frequency and memory performance. *Journal of Psychophysiology, 4,* 191–192.

Klimesch, W., Schimke, H., Ladurner, G., & Pfurtscheller, G. (1990). Alpha frequency and memory performance. *Journal of Psychophysiology, 4,* 381–390.

Klimensch, W., Schimke, H., & Pfurtscheller, G. (1993). Alpha frequency, cognitive load and memory performance. *Brain Topography, 5,* 241–251.

Klimesch, W. (1994). *The Structure of Long-term Memory: A Connectivity Model for Semantic Processing,* Lawrence Erlbaum, Hillsdale, NJ.

Klimesch, W., Doppelmayr, M., Schimke, H., & Pachinger, T. (1996). Alpha frequency, reaction time and the speed of processing information. *Journal of Clinical Neurophysiology, 13,* 511–518.

Klimesch, W. (1999). EEG alpha and theta oscillations reflect cognitive and memory performance: a review and analysis. *Brain Research Reviews, 29,* 169-195.

Klimesch, W., Sauseng, P., & Gerloff, C. (2003). Enhancing cognitive performance with repetitive transcranial magnetic stimulation at human individual alpha frequency. *European Journal of Neuroscience, 17,* 1129– 1133.

Klimesch, W., Sauseng, P., & Hanslmayr, S. (2007). EEG alpha oscillations: the inhibition-timing hypothesis. *Brain Research Reviews, 53,* 63-88.

Kline, D.W., & Burdick, D.C. (1980). Metronome pacing and age: the effect of irrelevant stimuli. *Experimental Aging Research, 6,* 393-398.

Knyazev, G.G., & Slobodskaya, H.R. (2003). Personality trait of behavioural inhibition is associated with oscillatory systems reciprocal relationships. *International Journal of Psychophysiology, 48,* 247– 261.

Knyazev, G.G., Savostyanov, A.N., & Levin, E.A. (2006). Alpha synchronization and anxiety: implications for inhibition vs. alertness hypotheses. *International Journal of Psychophysiology, 59,* 151-158.

Kohfeld, D. (1969). Effects of the intensity of auditory and visual ready signals on simple reaction time. *Journal of Experimental Psychology, 82*, 88-95. (a)

Kohfeld, D. (1969). Effects of ready-signal intensity and intensity of the preceding response-signal on simple reaction time. *American Journal of Psychology, 82,* 104-110. (b)

Kohler, M., Pavy, A., & Van Den Heuvel, C. (2006). The effects of chewing versus caffeine on alertness, cognitive performance and cardiac autonomic activity during sleep deprivation. *Journal of Sleep Deprivation, 15,* 358-268.

Köpruner, V., Pfurtscheller, G., & Auer, L. M. (1984). Quantitative EEG in normals and in patients with cerebral ischemia. *Progress in Brain Research, 62*, 29–50.

Kraemer, P.J., Brown, R.W., & Randall, C.K. (1995). Signal intensity and duration estimation in rats. *Behavioural Processes*, *34,* 265-268.

Krampe, R.T., Engbert, R., & Kliegl, R. (2001). Age-specific problems in rhythmic timing. *Psychology of Aging, 16,* 12-30.

Krug, M. (1999). Playing Tennis in the Zone. Athletic Insight. *The Online Journal of Sports Psychology, 1*. http://www.athleticinsight.com/Vol1Iss3/Tennis_Zone.htm#Evidence%20That%20Supports%20the%20Theory%20of%20the%20Zone Accessed on 10/10/07.

Kurrer, C., & Schulten, K. (1995). Noise-induced synchronous neuronal oscillations. *Physical Review E, 51,* 6213-6218.

Kutukcu, Y., Marks, Jr. W.J., Goodin, D.S., & Aminoff M.J. (1999). Simple and choice reaction time in Parkinson's disease. *Brain Research, 815,* 367-372.

Lang, P.J., & Buss, A.H. (1965). Psychological deficit in schizophrenia: II. Interference and activation. *Journal of Abnormal Psychology, 70*, 77-106.

Langer, J., Wapner, S., & Werner, H. (1961). The effects of danger upon the experience of time. *The American Journal of Psychology, 74,* 94-97.

Lansin, R. W. (1957). Relation of brain and tremor rhythms to visual reaction time. *Electroencephalography and Clinical Neurophysiology, 9*, 497-504.

Large, E.W., & Jones, M.R. (1999). The dynamics of attending: how people track time-varying events. *Psychological Review, 106,* 119-195.

Laufs, H., Kleinschmidt, A., Beyerle, A., Eger, E., Salek-Haddadi, A., Preibisch, C., & Krakow, K. (2003). EEG-correlated fMRI of human alpha activity. *Neuroimage, 19,* 1463-1476.

Lebedev, A. N. (1994). The neurophysiological parameters of human memory. *Neuroscience and Behavavioral Physiology, 24,* 254–259.

Ledford, H. (2007). Excessive body fat intake can throw out the body clock: Dietary factors shown to influence sleep pattern. Nature News. Website: http://www.nature.com/news/2007/071106/full/450141b.html

LeDuc, P.A, Caldwell Jr, J.A., & Ruyak, P.S. (2000). The Effects of Exercise as a Countermeasure for Fatigue in Sleep-Deprived Aviators. *Military Psychology, 1532-7876, 12*, 249–266.

Lees, A.J., & Smith, E. (1983). Cognitive deficits in the early stages of Parkinson’s disease. *Brain, 106*, 257-270.

Lewis, R.D., & Brown, J.M. (1994). Influence of muscle activation dynamics on reaction time in the elderly. *European Journal of Applied Physiology and Occupational Physiology, 69*, 344-349.

Lewis, P. A., & Miall, R. C. (2003) in *Functional and Neural Mechanisms of Interval Timing* (ed. Meck, W. H.) 515–532 (CRC, Boca Raton, Florida, USA, 2003).

Lieberman, H.R., Wurtman, R.J., Emde, G.G., Roberts, C., & Coviella, I.L. (1987). The effects of low doses of caffeine on human performance and mood. *Psychopharmacology (Berl), 92,* 308-312.

Lippold, O. (1970). Origin of the alpha rhythm. *Nature, 22,* 616-618.

Logothetis, N.K., Pauls, J., Augath, M., Trinath, T., & Oeltermann, A. (2001). Neurophysiological investigation of the basis of the fMRI signal. *Nature, 412,* 150–157.

Loftus, G.R., Johnson, C.A., & Shimamura, A.P. (1985). How much is an icon worth? *Journal of Experimental Psychology: Human Performance and Perception, 11,* 1-13.

Loftus, E.F., Schooler, J.W., Boone, S.M., & Kline, D. (1987). Time went by so slowly: overestimation of event duration by males and females. *Applied Cognitive Psychology, 1,* 3-13.

Lopes da Silva, F.H., Vos, J.E., Mooibroek, J., & Van Rotterdam, A. (1980). Relative contributions of intracortical and thalamo-cortical processes in the generation of alpha rhythms, revealed by partial coherence analysis. *Electroencephalography and Clinical Neurophysiology, 50,* 449-456.

Lopes da Silva, F. H. (1991). Neural mechanisms underlying brain waves: From neural membranes to networks. *Electroencephalography and Clinical Neurophysiology, 79,* 81–93.

Loveless, N. E. (1973). The contingent negative variation related to preparatory set in a reaction situation with variable fore-period. *Electroencephalography and Clinical Neurophysiology, 35,* 369-374.

Loveless, N. E., & Sanford, A. J. (1975). The impact of warning signal intensity on reaction time and components of the contingent negative variation. *Biological Psychology, 2*, 217-226.

Lustig, C., & Meck, W.H. (2001). Paying attention to time as one gets older. *Psychological Science, 12,* 478-484.

Lustig, C., Matell, M., & Meck, W. (2005). Not just a coincidence: frontal–striatal interactions in working memory and interval timing. *Memory, 13,* 441–448.

MacDonald, C.J., & Meck, W.H. (2004). Systems-level integration of interval timing and reaction time. *Neuroscience and Biobehavioral Reviews, 28,* 747-769.

Magnié, M.N., Bermon, S., Martin, F., Madany-Lounis, M., Suisse, G., Muhammad, W., & Dolisi, C. (2000). P300, N400, aerobic fitness and maximal aerobic exercise. *Psychophysiology, 37,* 369-377.

Malapani, C., Dubois, B., Rancurel, G., & Gibbon, J. (1998). Cerebellar dysfunctions of temporal processing in the seconds range in humans. *Neuroreport, 9,* 3907–3912.

Malapani, C., Deweer, B., & Gibbon, J. (2002). Separating storage from retrieval dysfunction of temporal memory in Parkinson's Disease. *Journal of Cognitive Neuroscience, 14,* 311-322.

Malenka, R.C., & Nicoll, R.A. (1999). Long-Term Potentiation: A Decade of Progress? *Science, 285,* 1870-1874.

Marsh, A. A., Ambady, N., & Keck, R. E. (2005). The effects of fear and anger facial expressions on approach- and avoidance-related behaviors. *Emotion, 5,* 119–124.

Martin, I., & Rees, L. (1966). Reaction times and somatic reactivity in depressed patients. *Journal of Psychosomatic Research, 9,* 375-382.

Martin, K.E., Phillips, J.G., Iansek, R., & Bradshaw, J.L. (1994). Inaccuracy and instability of sequential movements in Parkinson's disease. *Experimental Brain Research, 102,* 131-40.

Mathes, E.W. (1982). Peak experience tendencies: scale development and theory testing. *Journal of Humanistic Psychology, 22*, 92-108.

Mattes, S., & Ulrich, R. (1998). Directed attention prolongs the perceived duration of a brief stimulus. *Perception and Psychophysics, 60*, 1305-1317.

Matell, M.S., & Meck, W.H. (2000). Neuropsychological mechanisms of interval timing behavior. *BioEssays: News and Reviews in Molecular, Cellular and Developmental Biology 22*, 94–103.

Matell, M.S., & Meck, W.H. (2004). Cortico-striatal circuits and interval timing: Coincidence detection of oscillatory processes. *Brain Research Cognitive Brain Research, 21*, *1*39–170.

Mayeux, R., Stern, Y., Cote, L., & Williams, J.B. (1984). Altered serotonin metabolism in depressed patients with Parkinson's disease. *Neurology, 34,* 642-646.

McCormack, T., Brown, G.D., Maylor, E.A., Darby, R.J., & Green, D. (1999). Developmental changes in time estimation: comparing childhood and old age. *Developmental Psychology, 35,* 1143-1155.

McMorris, T., Hill, C., Sproule, J., Potter, J., Swain, J., Hobson, G., & Holder, T. (2005). Supra-maximal effort and reaction and movement times on a non-compatible response time task. *Journal of Sports Medicine and Physical Fitness, 45,* 127-133.

McMorris, T., Collard, K., Corbett, J., Dicks, M., & Swain, J.P. (2008). A test of the catecholamines hypothesis for an acute exercise-cognition interaction. *Pharmacology, Biochemistry and Behavior, 89,* 106-115.

Meck, W.H. (1983). Selective adjustment of the speed of internal clock and memory storage processes. *Journal of Experimental Psychology: Animal Behavior Processes, 9,* 171–201.

Meck, W.H. (1986). Affinity for the dopamine D2 receptor predicts neuroleptic potency in decreasing the speed of an internal clock. *Pharmacology, Biochemistry and Behavavior, 25,* 1185-1189.

Meck, W.H. (1996). Neuropharmacology of timing and time perception. Brain Research. *Cognitive Brain Research, 3,* 227-242.

Meck, W. H., & Benson, A. M. (2002). Dissecting the brain’s internal clock: how frontal-striatal circuitry keeps time and shifts attention. *Brain and Cognition, 48,* 195–211.

Meerlo, J.A.M. (1981). *The time sense in psychiatry. The Voices of Time: a cooperative survey of man’s views of time as expressed by the sciences and by the humanities,* 2nd Ed. Edited by Fraser, J.T.

Mikalsen, A., Bertelsen, B., & Flaten, M.A. (2001). Effects of caffeine, caffeine-associated stimuli and caffeine-related information on physiological and psychological arousal. *Psychopharmacology (Berl),* 157, 373-380.

Miller, J., & Ulrich, R. (1998). Locus of the effect of the number of alternative responses : Evidence from the lateralized readiness. Journal of Experimental Psychology. *Human Perception and Performance, 24,* 1215-1231.

Miller, J., Ulrich, R., & Rinkenauer, G. (1999). Effects of stimulus intensity on the lateralized readiness potential. *Journal of Experimental Psychology: Human Perception and Performance, 25,* 1454-1471.

Mitrani, L., Shekerdjiiski, S., Gourevitch, A., & Yanev, S. (1977). Identification of short time intervals under LSD25 and mescaline. *Activitas Nervosa Superior (Praha), 19,* 103-104.

Mondillon, L., Niedenthal, P.M., Gil, S., & Droit-Volet, S. (2007). Imitation of in-group versus out-group members’ facial expressions of anger: A test with a time perception task. *Social Neuroscience, 2*, 223-237.

Monsell, S. (2003). Task-switching. *Trends in Cognitive Sciences, 7,* 134–140.

Moukhles, H., Amalric, M., Nieoullon, A., & Daszuta, A. (1994). Behavioural recovery of rats grafted with dopamine cells after partial striatal dopaminergic depletion in a conditioned reaction-time task. *Neuroscience, 63,* 73-84.

Müller, G., Richter, R.A., Weisbrod, S., & Klingberg, F. (1991). Reaction time prolongation in the early stage of presenile onset Alzheimer's disease. *European Archives of Psychiatry and Clinical Neuroscience, 241,* 46-48.

Naatanen, R. (1972). Time uncertainty and occurrence uncertainty of the stimulus in a simple reaction-time task. *Acta Psychologica, 36,* 492-503.

Neher, A. (1961). Auditory driving observed with scalp electrodes in normal subjects. *Electroencephalography and Clinical Neurophysiology, 13,* 449-451.

Nettelbeck, T., & Wilson, C. (1994). Childhood changes in speed of information processing and mental age: A brief report. *British Journal of Developmental Psychology, 12,* 277–280.

Niedenthal, P.M. (2007). Embodying emotion. *Science, 316,* 1002-1005.

Nickerson, R.S. (1973). Intersensory facilitation of reaction time: energy summation or preparation enhancement? *Psychological Review, 80,* 489-509.

Nideffer, R.M. (2007). http://www.peaksports.com/pdfs/Calming_The_Mind-RNideffer.pdf. Accessed on 10/10/07. Calming the mind so the body can perform.

Niemi, P., & Na¨a¨ta¨nen, R. (1981). Foreperiod and simple reaction time. *Psychological Bulletin, 89*, 133–162.

Noulhiane, M., Mella, N., Samson, S., Ragot, R., & Pouthas, V. (2007). How emotional auditory stimuli modulate time perception. *Emotion, 7*, 697-704.

Noyes, R.Jr., & Kletti, R. (1977). Depersonalization in response to life-threatening danger. *Comprehensive Psychiatry*, *18*, 375-384.

Nuechterlein, K.H. (1977). Reaction time and attention in schizophrenia: a critical evaluation of the data and theories. *Schizophrenia Bulletin, 3,* 373-428.

Ollman, R.T., & Billington, M.J. (1972). The deadline model for simple reaction times. *Cognitive Psychology, 3*, 311–336.

Ornstein, R. (1977). *The psychology of consciousness*, 2nd ed. New York: Harcourt, Brace, Jovanovich.

Ortega, R.T., & Lopez, F. (2008). Effects of visual flicker on subjective time in a temporal bisection task. *Behavioural Processes, 78,* 380–386.

Ortega, L., Lopez, F., & Church, R.M. (2008). Modality and intermittency effects on time estimation. *Behavioural Processes, 81*, 270-273.

Osaka, M., Osaka, N., Koyama, S., Okusa, T., & Kakigi, R. (1999). Individual differences in working memory and the peak alpha frequency shift on magnetoencephalography. *Cognitive Brain Research, 8*, 365-368.

Pascal, G.R., & Swensen, C. (1952). Learning in mentally ill patients under conditions of unusual motivation. *Journal of Personality, 21*, 240-249.

Pascual-Leone, A., Brasil-Neto, J.P., Valls-Sole, J., Cohen, L.G., & Hallett, M. (1992). Simple reaction time to focal transcranial magnetic stimulation. Comparison with reaction time to acoustic, visual and somatosensory stimuli. *Brain, 115*, 109-122.

Pascual-Leone, A., Valls-Solé, J., Wassermann, E.M., Brasil-Neto, J., Cohen, L.G., & Hallett, M. (1992). Effects of focal transcranial magnetic stimulation on simple reaction time to acoustic, visual and somatosensory stimuli. *Brain, 115*, 1045-1059.

Pascual-Leone, A., Valls-Solé, J., Brasil-Neto, J.P., Cammarota, A., Grafman, J., & Hallett, M. (1994a). Akinesia in Parkinson's disease. II. Effects of subthreshold repetitive transcranial motor cortex stimulation. *Neurology, 44,* 892–898.

Pascual-Leone, A., Valls-Solé, J., Brasil-Neto, J.P., Cohen, L.G., & Hallett. M. (1994b). Akinesia in Parkinson's disease. I. Shortening of simple reaction time with focal, single-pulse transcranial magnetic stimulation. *Neurology, 44,* 884–891.

Pouthas, V., Droit, S., & Jacquest, A.Y. (1993). Temporal experiences and time knowledge in infancy and early childhood*.* *Time and Society, 2,* 199-218.

Penney, T.B., Holder, M.D., & Meck, W.H. (1996). Clonidine-induced antagonism of norepinephrine modulates the attentional processes involved in peak-interval timing. *Experimental Clinical Psychopharmacology, 4,* 82–92.

Penney, T.B., Gibbon, J., & Meck, W.H. (2000). Differential effects of auditory and visual signals on clock speed and temporal memory. Journal of Experimental Psychology. *Human Perception and Performance, 26,* 1770-1787.

Penton-Voak, I.S. Edwards, H., Percival, A., & Wearden, J.H. (1996). Speeding up an internal clock in humans? Effects of click trains on subjective duration. *Journal of Experimental Psychology: Animal Behaviour Processes, 22*, 307-320.

Pfurtscheller, G., & Aranibar, A. (1977). Event-related cortical synchronization detected by power measurements of scalp EEG. *Electroencephalography and Clinical Neurophysiology, 42,* 817–826.

Pfurtscheller, G. (1992). Event-related synchronization (ERS): an electrophysiological correlate of cortical areas at rest. *Electroencephalography and Clinical Neurophysiology, 83,* 62-69.

Pfingst, B. E., Hienz, R., Kimm, J., & Miller, J. (1975). Reaction- time procedure for measurement of hearing: I. *Journal of the Acoustical Society of America, 57,* 421-430.

Philip, P., Taillard, J., Quera-Salva, M.A., Bioulac, B., & Akerstedt, T. (1999). Simple reaction time, duration of driving and sleep deprivation in young versus old automobile drivers. *Journal of Sleep Research, 8,* 9-14.

Philips, L.W., & Sternthal, B. (1977). Age differences in information processing: A perspective on the aged consumer. *Journal of Marketing Research, 14,* 444-457.

Polich, J., & Lardon, M.T. (1997). P300 and long-term physical exercise. *Electroencephalography and Clinical Neurophysiology, 103,* 493-498.

Posner, M., Nissen, M-J., & Klein, R. (1976). Visual dominance: An information-processing account of its origins and significance. *Psychological Review, 83*, 157-171.

Posner, M.I., Snyder, C.R., & Davidson, B.J. (1980). Attention and the detection of signals. *Journal of Experimental Psychology, 109,* 160-174.

Posthuma, D., Neale, M.C., Boomsma, D.I., & de Geus, E.J.C. (2001). Are smarter brains running faster? Heritability of alpha peak frequency, IQ and their interrelation. *Behavior Genetics, 31*, 567-579.

Pouthas, V., Droit, S., & Jacquet, A.Y. (1993). Temporal experiences and time knowledge in infancy and early childhood. *Time and Society, 2*, 199-218.

Predebon, J. (1996). The effects of active and passive processing of interval events on prospective and retrospective time estimates. *Acta Psychologica, 94,* 41-58.

Pribram, K.H., & McGuinness, D. (1975). Arousal, activation and effort in the control of attention. *Psychological Review, 82,* 116-149.

Prinzmetal, W., McCool, C., & Park, S. (2005). Attention: reaction time and accuracy reveal different mechanisms. *Journal of Experimental Psychology, General. 134,* 73-92.

Pullman, S.L., Watts, R.L., Juncos, J.L., & Sanes, J.N. (1990). Movement amplitude choice reaction time performance in Parkinson’s disease may be independent of d opaminergic status. *Journal of Neurology, Neurosurgury and Psychiatry*, *53,* 279-283.

Pullman, S.L., Watts, R.L., Juncos, J.L., Chase, T.N., & Sanes, J.N. (1988). Dopaminergic effects on simple and choice reaction time performance in Parkinson’s disease. *Neurology, 38,* 249-254.

Rafal, R.D., Posner, M.I., Walker, J.A., & Friedrich, F.J. (1984). Cognition and the basal ganglia: Separating mental and motor components of performance in Parkinson’s disease. *Brain, 107,* 1083-1094.

Rafal, R.D., Inhoff, A.W., Freidman, J.H., & Bernstein, E. (1987). Programming and execution of sequential movements in Parkinson’s disease. *Journal of Neurology, Neurosurgery and Psychiatry, 50,* 1267–1273.

Rammsayer, T. (1989). Is there a common dopaminergic basis of time perception and reaction time? *Neuropsychobiology, 21*, 37-42.

Rammsayer, T. H. (1992). Effects of benzodiazepine-induced sedation on temporal processing. *Psychopharmacology, 7,* 311-318.

Rammsayer, T.H., Lima, S.D., & Vogel, W.H. (1993). Aging and temporal discrimination of brief auditory intervals. *Psychological Research*, *55*, 15-19.

Rammsayer, T. H., Hennig, J., Haag, A., & Lange, N. (2001). Effects of noradrenergic activity on temporal information processing in humans. *The Quarterly Journal of Experimental Psychology B, 54,* 247-258.

Rammsayer, T.H., & Lima, S.D. (1991). Duration discrimination of filled and empty auditory intervals: cognitive and perceptual factors. *Perception and Psychophysics, 50,* 565-574.

Ratcliff, R., Thaper, A., Smith, P.L. and McKoon, G. (2006). Aging and response times: a comparison of sequential sampling models. In J. Duncan, L. Philips and P. McLeod (Eds.), Measuring the Mind (pp 3-31). Oxford, U.K.: Oxford University Press. Website accessed on 17/07/08. http://books.google.co.uk/books?hl=en&lr=&id=nlWZHJnbEg8C&oi=fnd&pg=PA3&dq=aging+and+response+times+AND+ratcliff&ots=qobyXVqPb7&sig=e7M_RflKmUiZTfVHnToYaxJCREc#PPA8,M1

Richards, W. (1973). Time reproductions by H.M. *Acta Psychologica, 37,* 279-282.

Rihet, P., Possamaï, C.A., Micallef-Roll, J., Blin, O., & Hasbroucq, T. (2002). Dopamine and human information processing: a reaction-time analysis of the effect of levodopa in healthy subjects. *Psychopharmacology (Berl), 163*, 62-67.

Roberts, S., & Sternberg, S. (1992). The meaning of additive reaction-time effects: Tests of three alternatives. In DE Meyer & S. Kornblum (Eds.), *Attention and performance XIV: Synergies in experimental psychology, artificial intelligence, and cognitive neuroscience – a silver jubilee.* Cambridge, MA. M.I.T. press, 611-653.

Rohrbaugh, J. W., Syndulko, K., & Lindsley, D. B. (1976). Brain wave components of the contingent negative variation in humans. *Science, 191*, 1055-1057.

Rohrbaugh, J. W., Syndulko, K., & Lindsley, D. B. (1978). Cortical slow negative waves following non-paired stimuli: Effects of task factors. *Electroencephalography and Clinical neurophysiology, 45,* 551-567.

Rose, J.E. (1987). Cigarette smoking blocks caffeine-induced arousal. *Alcohol and Drug Research, 7,* 49-55.

Roufs, J.A.J. (1963). Perception lag as a function of stimulus luminance. *Vision Research, 3,* 81-91.

Russ, M.O., & Seger, L. (1995). The effect of task complexity on reaction times in memory scanning and visual discrimination in Parkinson's disease. *Neuropsychologia, 33,* 561-575.

Rutter, J., Reick, M., Wu, L.C., & McKnight, S.L. (2001). Regulation of clock and NPAS2 DNA binding of the redox state of NAD cofactors. *Science, 293,* 510–514.

Sackett, A.M., Meyvis, T., Nelson, L.D., Converse, B.A., & Sackett, A.L. (2010). You're Having Fun When Time Flies: The Hedonic Consequences of Subjective Time Progression. *Psychological Science, 21,* 111–117.

Sanders, A.F., & Wertheim, A.H. (1973). The relation between physical stimulus properties and the effect of foreperiod duration on reaction time. *Quarterly Journal of Experimental Psychology, 25,* 201-206.

Sanes, J.N. (1985). Information processing deficits in Parkinson's disease during movement. *Neuropsychologia*, *23,* 381-392.

Sanford, A.J. (1970). Rating speed of a simple reaction. *Psychonomic Science, 21,* 333-334.

Sanford, A.J. (1971). Effects of changes in the intensity of white noise on simultaneity judgments and simple reaction time. *The Quarterly Journal of Experimental Psychology, 23,* 296-303.

Santi, A., Weise, L., & Kuiper, D. (1995). Amphetamine and memory for event duration in rats and pigeons: disruption of attention to temporal samples rather than changes in the speed of the internal clock. *Psychobiology*, *23*, 224–232.

Sauer, H., & Oertel, W.H. (1994). Progressive degeneration of nigrostriatal dopamine neurons following intrastriatal terminal lesions with 6-hydroxydopamine: a combined retrograde tracing and immunocytochemical study in the rat. *Neuroscience, 59,* 401-415.

Sawamoto, N., Piccini, P., Hotton, G., Pavese, N., Thielemans, K., & Brooks, D.J. (2008). Cognitive deficits and striato-frontal dopamine release in Parkinson's disease. *Brain, 1,* 1294-1302.

Schreckenberger, M., Lange-Asschenfeldt, C., Lochmann, M., Mann, K., Siessmeier, T., Buchholz, H.G., Bartenstein, P., & Gründer, G. (2004). The thalamus as the generator and modulator of EEG alpha rhythm: a combined PET/EEG study with lorazepam challenge in humans. *Neuroimage, 22,* 637-644.

Schedlowski, M., & Tewes, U. (1992). Physiological arousal and perception of bodily state during parachute jumping. *Psychophysiology, 29,* 95-103.

Scheirs, J.G.M., & Brunia, C.H.M. (1982). Effects of stimulus and task factors on achilles tendon reflexes evoked early during a preparatory period. *Physiology and Behavior, 28*, 681-685.

Scholey, A. (2004). Chewing gum and cognitive performance: a case of a functional food with function but no food? *Appetite, 43,* 215-216.

Schubotz, R.I., Friederici, A.D., & von Cramon, D.Y. (2000). Time perception and motor timing: a common cortical and subcortical basis revealed by fMRI. *Neuroimage, 11,* 1-12.

Shaw, J.C. (2003). *The Brain's alpha rhythms and the mind. A review of classical and modern studies of the alpha rhythm component of the electroencephalogram with commentaries on associated neuroscience and neuropsychology*. Elsevier.

Simon, J.R., & Small, A.M. Jr. (1969). Processing auditory irrelevant information: interference from an irrelevant cue. *Journal of Applied Psychology, 53,* 433-435.

Smed, J., Niinisalo, H., & Hakonen, H. (2005). Realizing the bullet time effect in multiplayer games with local perception filters. *Computer Network, 49,* 27-37.

Smit, H.J., & Rogers, P.J. (2000) Effects of low doses of caffeine on cognitive performance, mood and thirst in low and higher caffeine consumers. *Psychopharmacology, 152*, 167-173.

Smith, B.D., & Tolla, K. (1998). Caffeine: effects on psychological functioning and performance. In *Caffeine,* Spiller GA (Ed) CRC Press: Boca Raton, 251 – 300.

Smith, B.D., Tola, K., & Mann, M. (1999). Caffeine and arousal: a biobehavioral theory of physiological, behavioral and emotional effects. Chapter Six. In *Caffeine and Behavior: Current views and research trends*. Gupta, B.S. and Gupta, U. CRC Press.

Sperling, G. (1960). The information available in brief visual presentations. *Psychological Monographs, 74,* 1-29.

Spiegel, E.A., Wycis, H.T., Orchinik, C.W., & Freed, H. (1955). The thalamus and temporal orientation. *Science, Technical Papers, 121*, 771-772.

Staddon, J.E.R., & Higa, J.J. (1999). Time and memory: towards a pacemaker-free theory of internal timing. *Journal of Experimental Analysis of Behaviour, 71,* 215-251.

Starkstein, S.E., Esteguy, M., Berthier, M.L., Garcia, H., & Leiguarda. R. (1989). Evoked potentials, reaction time and cognitive performance in on and off phases of Parkinson's disease. *Journal of Neurology, Neurosurgery and Psychiatry, 52*, 338-340.

Stelmach, G.E., Worringham, C.J., & Strand, E.A. (1986). Movement preparation in Parkinson’s disease. *Brain, 109,* 1179-1194.

Stephens, R., & Tunney, R.J. (2004). Role of glucose in gum-related facilitation of cognitive function. *Appetite, 43,* 211-213.

Steriade, M., McCormick, D.A., & Sejnowski, T.J. (1993). Thalamocortical oscillations in the sleeping and aroused brain. *Science, 262,* 679-685.

Sterman, M. B. (2000). Basic concepts and clinical findings in the treatment of seizure disorders with EEG operant conditioning. *Clinical Electroencephalography, 31,* 45–55.

Stetson C., Fiesta M.P. and Eagleman, D.M. (2007b). Does time really slow down during a frightening event? *PLoS One, 2,* 1-3.

Stine, M.M., O’Connor, R.J., Yatko, B.R., & Grunberg, N.E. (2002). Evidence for a relationship between daily caffeine consumption and accuracy of time estimation. *Psychopharmacology: Clinical and Experimental, 17,* 361-367.

Stuss, D.T., Stethem, L.L., Hugenholtz, H., Picton, T., Pivik, J., & Richard, M.T. (1989). Reaction time after head injury: fatigue, divided and focused attention and consistency of performance. *Journal of Neurology, Neurosurgery and Psychiatry, 52,* 42-748.

Surwillo, W.W. (1961). Frequency of the ‘Alpha’ rhythm, reaction time and age. *Nature, 191,* 823-824.

Surwillo, W.W. (1962). The relation of simple response time to brain-wave frequency and the effects of age. *Electroencephalography and Clinical Neurophysiology, 15,* 105-114.

Surwillo, W.W. (1964). The relation of decision time to brain wave frequency and to age. *Electroencephalography and Clinical Neurophysiology, 16,* 510-514.

Surwillo, W.W. (1966). Time perception and the ‘internal clock’: some observations on the role of the electroencephalogram. *Brain Research, Short Communications, 2,* 390-392.

Swift, C.G., & Tiplady, B. (1988). The effects of age on the response to caffeine. *Psychopharmacology (Berl), 94,* 29-31.

Tanaka, M., Yoshida, M., Emoto, H., & Ishii, H. (2000). Noradrenaline systems in the hypothalamus, amygdala and locus coeruleus are involved in the provocation of anxiety: basic studies. *European Journal of Pharmacology, 405,* 397-406.

Temel, Y., Blokland, A., Ackermans, L., Boon, P., van Kranen-Mastenbroek, V.H., Beuls, E.A., Spincemaille, G.H., & Visser-Vandewalle, V. (2006). Differential effects of subthalamic nucleus stimulation in advanced Parkinson disease on reaction time performance. *Experimental Brain Research, 169,* 389-399.

Teyler, T.J., Hamm, J.P., Clapp, W.C., Johnson, B.W., Corballis, M.C., & Kirk, I.J. (2005). Long-term potentiation of human visual evoked responses. *Short Communication, European Journal of Neuroscience, 21,* 2045-2050.

Thaut, M.H., McIntosh, G.C., & Rice, R.R. (1997). Rhythmic facilitation of gait training in hemispheric stroke rehabilitation. *Journal of Neurological Sciences, 151*, 207-212.

Thayer, S., & Schiff, W. (1975). Eye-contact, facial expression and the experience of time. *The Journal of Social Psychology, 95,* 117-124.

Theios, J. (1975). The components of response latency in simple human information processing tasks. In PMA Rabbitt & S. Dornic (Eds.), *Attention and Performance, V,* 418-440. London: Academic Press.

Thompson, D., Yarnold, P., Adams, S., & Spacone, A. (1996). How Accurate Are Waiting Time Perceptions of Patients in the Emergency Department?. *Annals of Emergency Medicine, 28,* 652-656.

Tinklenberg, J.R., Walton, T.R., & Kopell, B.S. (1976). Marijuana and Ethanol: differential effects on time perception, heart rate and subjective response. *Psychopharmacology, 49*, 275-279.

Tipples. J. (2006). Fear and fearfulness potentiate automatic orienting to eye. *Cognition and Emotion, 20,* 309-320.

Tipples, J. (2008). Negative emotionality influences the effects of emotion on time perception. *Emotion, 8,* 127-131.

Tomporowski, P.D., & Ellis, N.R. (1986). Effects of exercise on cognitive processes: a review. *Psychological Bulletin, 99,* 338-346.

Tomporowski, P. D. (2003). Effects of acute bouts of exercise on cognition. *Acta Psychologica, 112,* 297–324.

Treisman, M (1963). Temporal discrimination and the indifference interval: Implications for a model of the “internal clock”. *Psychological Monographs, 77,* whole number 576.

Treisman, M. (1984) Temporal rhythms and cerebral rhythms. Annals of the New York Academy of Sciences, 423, Issue: *Timing and Time Perception,* 542-565.

Treisman, M., Faulkner, A., Naish, P.L.N., & Brogan, D. (1990). The internal clock: evidence for a temporal oscillator underlying time perception with some estimates of its characteristic frequency. *Perception, 19,* 705–743.

Treisman, M., Faulkner, A., & Naish, P.L.M. (1992). On the relation between time perception and the timing of motor action: Evidence for a temporal oscillator controlling the timing of movement. *The Quarterly Journal of Experimental Psychology, 45A,* 235–263.

Treisman, M. (1993). On the structure of the temporal sensory system. *Psychologica Belgica 33,* 271–283.

Treisman, M., Cook, N., Naish, P.L.N., & MacCrone. (1994). The internal clock: electroencephalographic evidence for oscillatory processes underlying time perception. *Quarterly Journal of Experimental Psychology, 47A,* 241-289.

Ulrich, R., & Mattes, S. (1996). Does immediate arousal enhance response force in simple reaction time? *The Quarterly Journal of Experimental Psychology, 49A,* 972-990.

Ulrich, R., Rinkenauer, G., & Miller, J. (1998). Effects of stimulus duration and intensity on simple reaction time and response force. *Journal of Experimental Psychology: Human Perception and Performance, 24,* 915-928.

Ulrich, R., Nitschke, J., & Rammsayer, T. (2006). Perceived duration of expected and unexpected stimuli. *Psychological Research, 70,* 77-87.

Ursano, R.J., Fullerton, C.S., Epstein, R.S., Crowley, B., Vance, K., Kao, T., & Baum, A. (1999). Peritraumatic dissociation and posttraumatic stress disorder following motor vehicle accidents. *American Journal of Psychiatry, 156,* 1808-1810 .

Valls-Solé, J., Solé, A., Valldeoriola, F., Muñoz, E., Gonzalez, L.E., & Tolosa, E.S. (1995). Reaction time and acoustic startle in normal human subjects. *Neuroscience Letters, 4,* 195, 97-100.

Vanneste, S., & Pouthas, V. (1999). Timing in aging: the role of attention. *Experimental Aging Research, 25,* 49-67.

Vanneste, S., Pouthas, V., & Wearden, J. H. (2001). Temporal control of rhythmic performance: A comparison between young and old adults. *Experimental Aging Research, 27,* 83-102.

Varela, F.J., Toro, A., John, E.R., & Schwartz, E.L. (1981). Perceptual framing and cortical alpha rhythm. *Neuropsychologia, 19,* 675–686.

Venables, P.H., & Tizard, J. (1958). The effect of auditory stimulus-intensity on the reaction-time of schizophrenics. *Journal of Mental Science, 104,* 1160-1164.

Vercruyssen, M., Hancock, P.A., & Mihaly, T. (1989). Time estimation performance before, during and following physical activity. *Journal of Human Ergology (Tokyo), 18,* 169-179.

Vierordt, K. (1868). *Der Zeitsinn nach Versuchen.* Tubingen, Germany: Laupp.

von Stein, A., & Sarnthein, J.(2000). Different frequencies for different scales of cortical integration: from local gamma to long range alpha/theta synchronization. *International Journal of Psychophysiology, 38*, 301-313.

Wagner, E., Florentine, M., Buus, S., & McCormack, J. (2004). Spectral loudness summation and simple reaction time. *Journal of the Acoustical Society of America, 116,* 1681-1686.

Walter, G. (1957). The brain as a machine. Section of Psychiatry. *Proceedings of the Royal Society of Medicine, 50,* 799-808.

Watts, F.N., & Sharrock, R. (1984). Fear and time estimation. *Perceptual and Motor Skills, 59*, 597-598.

Warburton, D.M. (1992). Nicotine as a cognitive enhancer. *Progress in Neuro-psychopharmacology and Biological Psychiatry*, *16,* 181-191.

Ward, D.G., & Cox, R.H. (2004). The Sport Grid-Revised as a Measure of Felt Arousal and Cognitive Anxiety. *Journal of Sport Behavior*, *27,* 93-114.

Wearden, J.H. (1991). Do humans possess an internal clock with scalar timing properties? *Learning and Motivation, 22*, 59-83.

Wearden, J.H., & Penton-Voak, I.S. (1995). Feeling the heat: Body temperature and the rate of subjective time, revisited. *The Quarterly Journal of Experimental Psychology, 48B*, 129-141.

Wearden, J. H., Wearden, A. J., & Rabbitt, P. M. A. (1997). Age and IQ effects on stimulus and response timing. *Journal of Experimental Psychology: Human Perception and Performance, 23*, 962–979.

Wearden, J.H., Edwards, H., Fakhri, M., & Percival, A. (1998). Why “sounds are judged longer than lights”: application of a model of the internal clock in humans. *The Quarterly Journal of Experimental Psychology, 51B,* 97-120.

Wearden, J.H., Philpott, K., & Win, T. (1999a). Speeding up and (…relatively…) slowing down an internal clock in humans. *Behavioural Processes, 46,* 63-73.

Wearden, J.H., Pilkington, R., & Carter, E. (1999). ‘Subjective lengthening’ during repeated testing of a simple temporal discrimination. *Behavioural Processes, 46,* 25-38.

Wearden, J.H. (1999). "Beyond the fields we know ...": exploring and developing scalar timing theory. *Behavioural Processes, 45*, 3-21. Special Issue.

Wearden, J.H. (2002). Traveling in time: a time-left analogue for humans. *Journal of Experimental Psychology: Animal Behavior Processes, 28,* 200-208.

Wearden, J.H. (2003). Applying the scalar timing model to human time psychology: Progress and challenges. In H. Helfrich (Ed.)*, Time and Mind II: Information-processing perspectives* (pp.21-39). Gottingen: Hogrefe & Huber.

Wearden, J.H. (2005a). Origines et développement des théories d'horloge interne du temps psychologique. *Psychologie Francaise, 50*, 7-25.

Wearden, J.H. (2005b). Chapter 6: The wrong tree: time perception and time experience in the elderly. In: *Measuring the Mind: Speed, Control and Age*. Edited by Duncan, J., McLeod, P. and Philips, L.H. Oxford University Press.

Wearden, J.H., Smith-Spark, J.H., Cousins, R., Edelstyn, N.M.J., Cody, F.W.J., & O'Boyle, D.J. (2008). Stimulus timing by people with Parkinson's disease. *Brain and Cognition, 67,* 264-279

Wearden, J.H., Norton, R., Martin, S., & Montford-Bebb, O. (2007). Internal clock processes and the filled-duration illusion. Journal of Experimental Psychology. *Human Perception and Performance, 33*, 716-729.

Wearden, J.H., Smith-Spark, J.H., Cousins, R., Edelstyn, N.M.J., Cody, F.W.J., & O'Boyle, D.J. (2009). Effect of click trains on duration estimates by people with Parkinson's Disease. *The Quaterly Journal of Experimental Psychology, 62*, 33-40.

Wearden, J.H., O'Rourke, S.C., Matchwick, C., Min, Z., & Maeers, S. (2009). Task switching and subjective duration. *The Quarterly Journal of Experimental Psychology, 63*, 531–543.

Wilkinson, L., Scholey, A., & Wesnes, K. (2002). Chewing gum selectively improves aspects of memory in healthy volunteers. *Appetite, 38,* 235-236.

Will, U., & Berg, E. (2007). Brain wave synchronization and entrainment to periodic acoustic stimuli. *Neuroscience Letters, 424,* 55-60.

Williams, C. (2006). Teach your brain to stretch time. From issue 2537 of New Scientist magazine, 04 February 2006, page 34. Accessed on 31/10/07. http://www.newscientist.com/channel/being-human/mg18925371.700-teach-your-brain-to-stretch-time.html

Williams, J. (2001). Frequency-specific effects of flicker on recognition memory. *Neuroscience, 104,* 283-286.

Williams, J., Ramaswamy, D., & Oulhaj, A. (2006). 10Hz flicker improves recognition memory in older people. *BMC Neuroscience, 7,* 1-7.

Wilson, S.A.K. (1925). Some disorders of motility and of muscle tone, with special reference to the corpus striatum. *Lancet*, ii.

Wittman, M., Leland, D.S., Churan, J., & Paulus, M.P. (2007). Impaired time perception and motor timing in stimulant-dependant subjects. *Drug and Alcohol Dependence, 90,* 183-192.

Wohlshlager, A., Engbert, K., & Haggard, P. (2003). Intentionality as a constituting condition of the own self-and other selves. *Consciousness and Cognition, 12,* 708-716.

Woodruff, D. (1975). Relationships among EEG alpha frequency, reaction time and age: A biofeedback study. *Psychophysiology, 12,* 673-681.

Yarrow, K., Haggard, P., & Rothwell, J.C. (2004). Action, arousal and subjective time. *Consciousness and Cognition, 13,* 373-390.

Yanagihara, H., Ando, H., Hayashi, Y., Obi, Y., & Fujimura, A. (2006). High-fat feeding exerts minimal effects on rhythmic mRNA expression of clock genes in mouse peripheral tissues. *Chronobiology International, 23,* 905-914.

Yerkes, R.M., & John D. Dodson, J.D. (1908). The relation of strength of stimulus to rapidity of habit-formation. *Journal of Comparative Neurology and Psychology, 18,* 459-482.

Yoblick, D.A., & Salvendy, G. (1970). Influence of frequency on the estimation of time for auditory, visual and tactile modalities: The kappa effect. *Journal of Experimental Psychology, 86,* 157-164.

Yordanova, J. & Kolev, V. (1998). Event-related alpha oscillations are functionally associated with P300 during information processing. *NeuroReport, 9,* 3159-3164.

Young, J.A. (1999a). *Professional tennis players in flow: Flow theory and reversal theory perspectives.* Unpublished doctoral thesis. Monash University at Melbourne.

Zakay, D. (1992). The role of attention in children's time perception*. Journal of Experimental Child Psychology, 54,* 355-371.

Zakay, D., & Block, R.A. (1996). The role of attention in time estimation processes. In M.A. Pastor & J. Artieda (Eds.), *Time, internal clocks and movement* (pp.143-164). Amsterdam: Elsevier Science.

Zakay, D., & Block, R. A. (2004). Prospective and retrospective duration judgements: An executive control perspective. *Acta Neurobiologiae Experimentalis, 64,* 319–328.

Zhang, L.I., Tao, H.W., & Poo, M. (2000). Visual input induces long-term potentiation of developing retinotectal synapses. *Nature Neuroscience, 3*, 708–715.

Zhong, C-B., & DeVoe, S.E. (2010). You are how you eat: fast food and impatience. *Psychological Science, 21*, 619-622.

The Howling Djinn. (2007). Erowid Experience Vaults. Better than meth: Amphetamines (Dexedrine) and Methylphenidate (Concerta). Website accessed on 6th of December 2007. http://www.erowid.org/experiences/exp.php?ID=34441

"Time" from The Dark Side of the Moon: Pink Floyd.

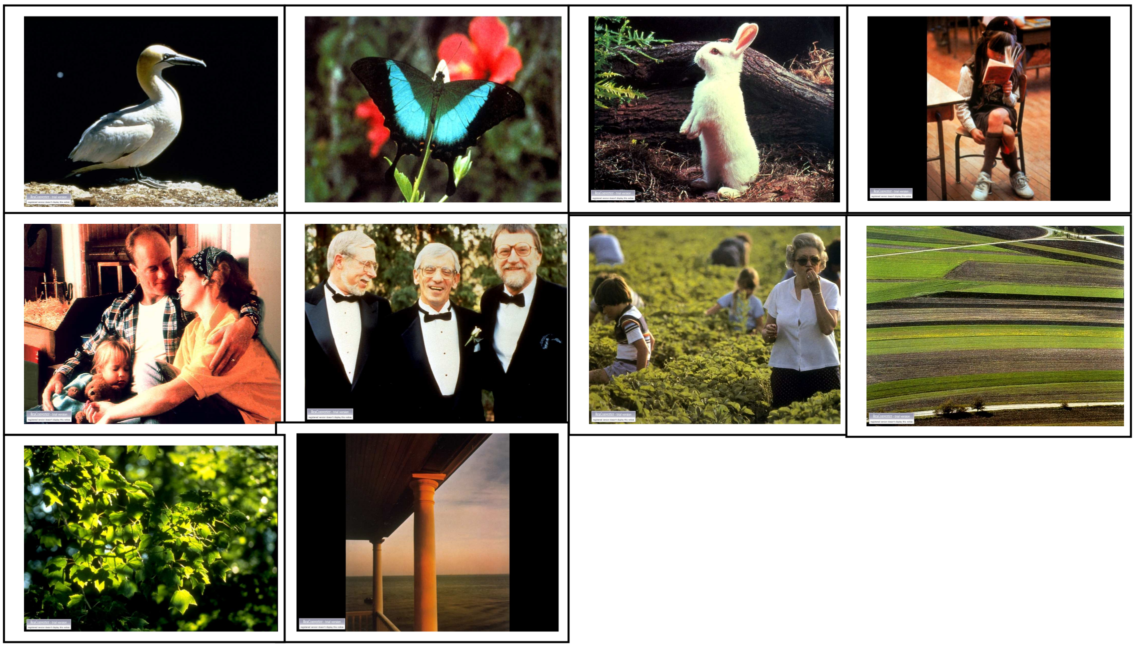
WAIS-III Manual. (1997) (Dutch version). Lisse: Swets and Zeitlinger.

The PXLab Self-Assessment-Manikin Scales. Accessed on 15/10/09. http://www.uni-mannheim.de/fakul/psycho/irtel/pxlab/demos/index_SAM.html

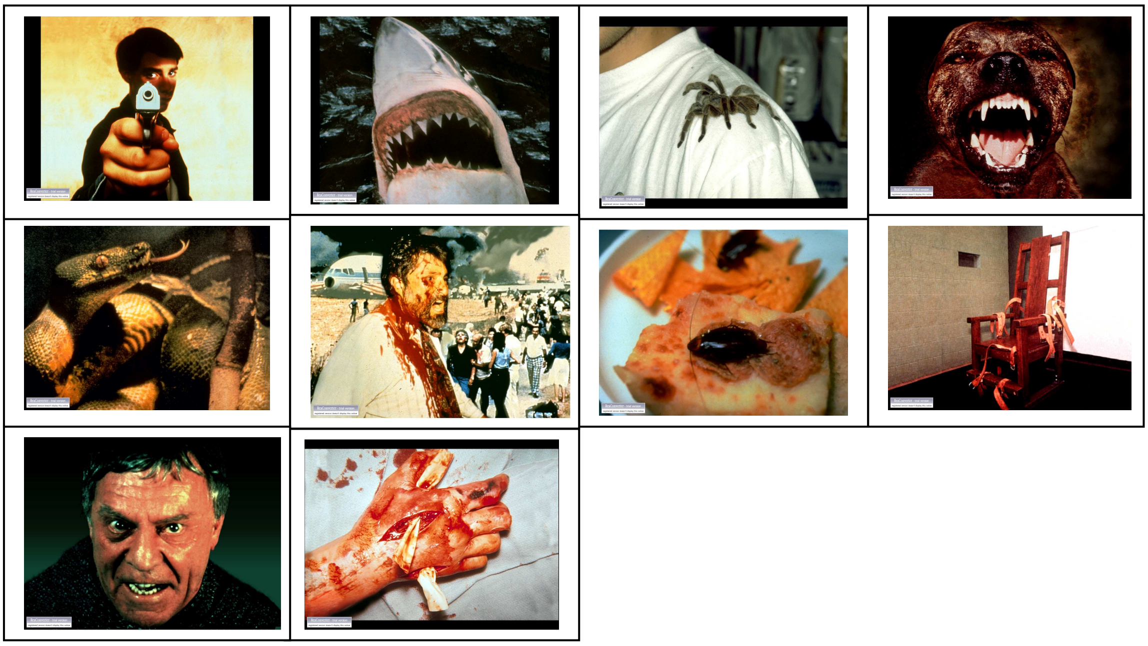
Eagleman, D. M. (2006). 45-metre slo-mo free-fall test. The Daily Telegraph. Website accessed 4/07/08.http://www.news.com.au/dailytelegraph/story/0,22049,22912185-5012895,00.html

Appendix A.

10 Low Arousing Pictures



10 High Arousing Pictures



Appendix B.

High Arousing Stimuli

IAPS no.	**Description**	**Valence Mean**	**Valence SD**	**Arousal Mean**	**Arousal SD**
1040	Snake	3.99	2.24	6.25	2.13
1201	Spider	3.55	1.88	6.36	2.11
1300	Pit Bull	3.55	1.78	6.79	1.84
1930	Shark	3.79	1.92	6.42	2.07
2120	Angry Face	3.34	1.91	5.18	2.52
3550	Injury	2.54	1.6	5.92	2.13
6020	Electric Chair	3.41	1.98	5.58	2.01
6250	Aimed Gun	2.83	1.79	6.54	2.61
7380	Roaches on Pizza	2.46	1.42	5.88	2.44
9405	Sliced Hand	1.83	1.17	6.08	2.4

Low Arousing Stimuli

IAPS no.	**Description**	**Valence Mean**	**Valence SD**	**Arousal Mean**	**Arousal SD**
1450	Gannet	6.37	1.62	2.83	1.87
1602	Butterfly	6.5	1.64	3.43	1.96
1610	Rabbit	7.82	1.34	3.08	2.19
2320	Girl	6.17	1.51	2.9	1.89
2360	Family	7.7	1.76	3.66	2.32
2370	Three Men	7.14	1.46	2.9	2.14
2515	Harvest	6.09	1.54	3.8	2.12
5720	Farmland	6.31	1.6	2.79	2.2
5800	Leaves	6.36	1.7	2.51	2.01
7545	Ocean	6.84	1.72	3.28	2.34

Appendix C.

(a) pleasant high-arousal sounds (e.g., erotic sounds) – 200, 201, 202, 352, 365 & 815.

(b) pleasant low arousal sounds (e.g., brook) – 112, 172, 206, 809, 810 & 812.

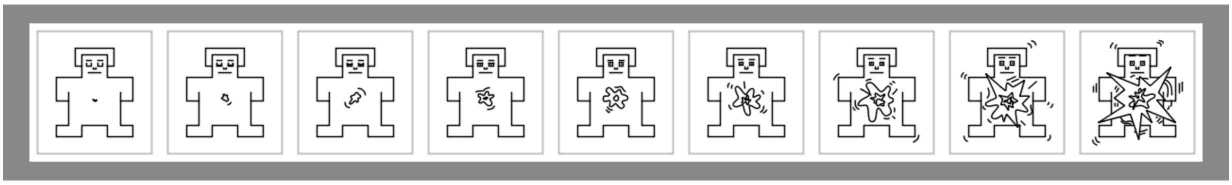
(c) unpleasant low-arousal sounds (e.g., clock) – 130, 700, 708, 720, 723 & 728.

(d) unpleasant high-arousal sounds (e.g., female scream) – 106, 115, 276, 277, 279 & 711.

(e) one group of 6 neutral low-arousal sounds (e.g., rain) – 170, 171, 374, 377, 602 & 705.

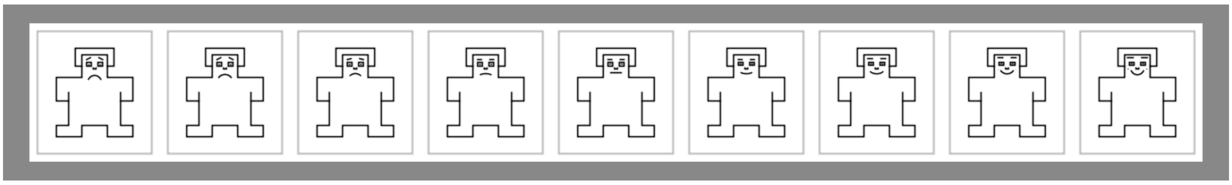
Appendix D.

Arousal Scale



1 2 3 4 5 6 7 8 9

Valence Scale



1 2 3 4 5 6 7 8 9

Appendix E.

Emotional Category	Sound Condition	IADS Database Pleasure Mean	Present Pleasure Mean	IADS Database Pleasure SD	Present Pleasure SD
Pleasant High-Arousal	200	6.31	6.21	1.93	1.97
	201	6.7	6.18	2.22	2.04
	202	6.81	6.29	2.08	1.7
	352	7.17	7.09	1.97	1.4
	365	6.97	6.82	1.9	1.73
	815	7.9	7.24	1.53	1.18
Pleasant Low-Arousal	206	6.2	5.82	1.6	1.11
	172	6.62	6.62	1.69	1.26
	809	7.44	6.68	1.41	1.32
	812	6.9	5.53	1.69	2.25
	112	6.84	7	1.72	1.33
	810	7.51	7.12	1.66	1.12
Unpleasant Low-Arousal	130	4.64	5	2.11	1.74
	708	4.34	3.91	1.42	1.46
	723	4.52	4.47	1.47	1.4
	700	4.68	4.41	1.61	1.02
	728	4.72	4.12	1.26	1.37
	720	4.86	4.53	1.8	1.13
Unpleasant High-Arousal	106	3.37	3.79	1.64	2.03
	115	2.16	3.35	1.33	1.61
	276	1.93	1.76	1.63	1.05
	277	1.63	1.59	1.13	1.02
	279	1.68	1.29	1.31	0.58
	711	2.61	3.06	1.59	1.52
Neutral Sound	170	5.31	5.18	2.12	1.6
	171	5.59	5.56	1.79	1.13
	377	5.84	5.82	1.73	1.62
	374	5.6	4.91	1.35	1.03
	705	5.35	4.76	1.43	0.89
	602	5.99	5.12	2.23	1.67

Emotional Category	Sound Condition	IADS Database Arousal Mean	Present Arousal Mean	IADS Database Arousal SD	Present Arousal SD
Pleasant High-Arousal	200	7.1	7.74	1.93	1.05
	201	7.31	7.62	2.22	1.07
	202	7.13	7.76	2.08	1.21
	352	7.07	7.12	1.97	1.07
	365	6.32	5.97	1.9	1.77
	815	6.85	6.85	1.53	1.31
Pleasant Low-Arousal	206	4.4	3.79	1.6	1.86
	172	3.36	2.62	1.69	1.99
	809	3.36	3.62	1.41	2.19
	812	3.43	3.38	1.69	2.19
	112	4.46	4.79	1.72	1.86
	810	4.18	4.74	1.66	2.34
Unpleasant Low-Arousal	130	4.93	3.24	2.11	1.78
	708	3.51	2.59	1.42	1.97
	723	4.42	3.59	1.47	1.69
	700	4.03	3.12	1.61	1.82
	728	4.35	3.68	1.26	2.06
	720	4.18	3.47	1.8	2
Unpleasant High-Arousal	106	6.39	6.12	1.64	2.03
	115	7.03	5.24	1.33	2.27
	276	7.77	7.82	1.63	1.51
	277	7.79	7.68	1.13	1.98
	279	7.95	8.06	1.31	1.58
	711	7.39	7.24	1.59	1.39
Neutral Sound	170	4.6	3.85	2.12	2.2
	171	3.71	3.32	1.79	1.72
	377	3.93	3.44	1.73	1.67
	374	4.23	2.97	1.35	1.95
	705	4.15	2.47	1.43	1.54
	602	3.77	4.88	2.23	2.04

Appendix F.

Emotional Category	Sound Condition	IADS Database Arousal Mean	IADS Database Arousal SD	IADS Database Pleasure Mean	IADS Database Pleasure SD
Pleasant High-Arousal	200	7.1	1.93	6.31	1.93
	201	7.31	2.22	6.7	2.22
	202	7.13	2.08	6.81	2.08
	352	7.07	1.97	7.17	1.97
	810	**4.18**	**1.66**	**7.51**	**1.66**
	815	6.85	1.53	7.9	1.53
Pleasant Low-Arousal	206	4.4	1.6	6.2	1.6
	221	**5.05**	**1.75**	**6.56**	**1.75**
	230	**4.84**	**1.44**	**7.05**	**1.44**
	721	**5**	**1.75**	**6.71**	**1.75**
	811	**4.95**	**1.63**	**7.4**	**1.63**
	820	**5.87**	**1.98**	**6.94**	**1.98**
Unpleasant Low-Arousal	130	4.93	2.11	4.64	2.11
	280	**5.33**	**1.87**	**3.65**	**1.87**
	380	**6.33**	**1.88**	**3.7**	**1.88**
	420	**7.08**	**1.51**	**2.34**	**1.51**
	500	**5.4**	**2.03**	**4.32**	**2.03**
	706	**5.3**	**1.68**	**4.16**	**1.68**
Unpleasant High-Arousal	106	6.39	1.64	3.37	1.64
	115	7.03	1.33	2.16	1.33
	276	7.77	1.63	1.93	1.63
	277	7.79	1.13	1.63	1.13
	279	7.95	1.31	1.68	1.31
	711	7.39	1.59	2.61	1.59
Neutral Sound	170	4.6	2.12	5.31	2.12
	171	3.71	1.79	5.59	1.79
	251	**5.14**	**2.02**	**4.16**	**2.02**
	262	**2.88**	**1.58**	**5.26**	**1.58**
	311	**7.12**	**1.58**	**7.65**	**1.58**
	320	3.77	2.23	5.99	2.23
	322	**4.79**	**1.82**	**5.01**	**1.82**
	358	**4.87**	**1.34**	**4.52**	**1.34**
	425	**5.15**	**1.42**	**5.09**	**1.42**
	602	**3.77**	**2.23**	**5.99**	**2.23**
	708	**3.51**	**1.42**	**4.34**	**1.42**
	726	**4.51**	**1.6**	**6.82**	**1.6**

Appendix G.

SoundType	Mean Difference in Pleasure IADS minus Present Rating	Mean Difference in Arousal IADS minus Present Rating
106	0.1	-0.64
112	0.52	-0.31
115	0.52	-0.63
130	0.08	-0.05
170	0.15	0.35
171	0.66	0
	.	.
	.	.
172	0.38	0.61
200	0	0.74
201	0.76	-0.26
202	1.37	0.05
206	-0.16	-0.33
276	0.39	-0.56
	.	.
	.	.
277	-0.36	1.69
279	0.43	0.92
352	0.05	0.83
365	0.27	0.91
374	0.6	0.67
377	0.33	0.71
	.	.
	.	.
602	-0.42	0.27
700	-1.19	1.79
705	0.17	-0.05
708	0.04	0.11
711	0.39	-0.11
720	-0.45	0.15
	.	.
	.	.
723	0.13	0.75
728	0.03	0.39
809	0.02	0.49
810	0.69	1.26
812	0.59	1.68
815	0.87	-1.11

Appendix H.

Emotional Category	**Sound Condition**	**Arousal Mean**	**Arousal Minimum**	**Arousal Maximum**	**Arousal Range**
Pleasant High-Arousal	200	6.34	6	9	3
	201	6.2	5	9	4
	202	6.43	5	9	4
	352	6.71	5	9	4
	365	6.86	3	9	6
	815	7.09	4	9	5
Pleasant Low-Arousing	206	6.11	1	7	6
	172	6.09	1	7	6
	809	6.8	1	7	6
	812	5.31	1	9	8
	112	7.29	1	8	7
	810	6.77	1	8	7
Unpleasant Low-Arousing	130	5	1	8	7
	708	4.03	1	8	7
	723	4.89	1	7	6
	700	4.6	1	8	7
	728	4.4	1	8	7
	720	4.8	1	7	6
Unpleasant High-Arousing	106	3.57	1	9	8
	115	3.74	1	9	8
	276	2.03	3	9	6
	277	1.83	1	9	8
	279	1.34	1	9	8
	711	3.31	3	9	6
Neutral Sound	170	5.14	1	9	8
	171	5.2	1	7	6
	377	4.83	1	7	6
	374	4.6	1	8	7
	705	4.49	1	6	5
	602	3.74	1	9	8

Emotional Category	**Sound Condition**	**Pleasure Mean**	**Pleasure Minimum**	**Pleasure Maximum**	**Pleasure Range**
Pleasant High-Arousal	200	6.34	1	9	8
	201	6.2	1	9	8
	202	6.43	2	9	7
	352	6.71	2	9	7
	365	6.86	2	9	7
	815	7.09	4	9	5
Pleasant Low-Arousing	206	6.11	3	8	5
	172	6.09	4	9	5
	809	6.8	2	9	7
	812	5.31	1	9	8
	112	7.29	4	9	5
	810	6.77	5	9	4
Unpleasant Low-Arousing	130	5	1	9	8
	708	4.03	1	7	6
	723	4.89	2	8	6
	700	4.6	2	6	4
	728	4.4	1	6	5
	720	4.8	2	6	4
Unpleasant High-Arousing	106	3.57	1	9	8
	115	3.74	1	6	5
	276	2.03	1	4	3
	277	1.83	1	4	3
	279	1.34	1	3	2
	711	3.31	1	7	6
Neutral Sound	170	5.14	1	8	7
	171	5.2	2	8	6
	377	4.83	2	9	7
	374	4.6	2	8	6
	705	4.49	1	6	5
	602	3.74	2	8	6

Appendix I.

SoundType	Mean Difference in Pleasure IADS minus Present Rating	Mean Difference in Arousal IADS minus Present Rating
106	-0.03	-0.13
112	0.5	0.08
115	0.38	-0.27
130	0.46	0.04
170	0.11	0.06
171	0.81	0.08
	.	.
	.	.
172	0.09	0.66
200	0.53	1.16
201	0.64	-0.1
202	1.59	0.49
206	-0.45	-1.11
276	0.74	-0.76
	.	.
	.	.
277	-0.36	0.56
279	0.31	0.6
352	-0.37	-0.01
365	0.08	1.03
374	0.32	-0.14
377	0.06	0.52
	.	.
	.	.
602	-0.2	0.13
700	-1.58	1.52
705	-0.1	-0.14
708	-0.2	-0.35
711	0.34	-0.16
720	-0.7	0.13
	.	.
	.	.
723	0.17	1.2
728	0.39	0.02
809	1.01	0.62
810	1	0.94
812	0.86	1.78
815	2.25	-1.66

Appendix J.

Emotional Category	Sound Condition	Pleasure Mean	Pleasure Minimum	Pleasure Maximum	Pleasure Range
Pleasant High-Arousal	200	6.34	1	9	8
	201	6.2	1	9	8
	202	6.43	1	9	8
	352	6.71	1	9	8
	365	6.86	4	9	5
	815	7.09	5	9	4
Pleasant Low-Arousing	206	6.11	2	8	6
	172	6.09	2	8	6
	809	6.8	5	9	4
	812	5.31	1	8	7
	112	7.29	4	9	5
	810	6.77	5	9	4
Unpleasant Low-Arousing	130	5	1	8	7
	708	4.03	1	6	5
	723	4.89	1	9	8
	700	4.6	2	5	3
	728	4.4	1	7	6
	720	4.8	2	9	7
Unpleasant High-Arousing	106	3.57	1	7	6
	115	3.74	1	8	7
	276	2.03	1	9	8
	277	1.83	1	8	7
	279	1.34	1	3	2
	711	3.31	1	8	7
Neutral Sound	170	5.14	1	9	8
	171	5.2	2	7	5
	377	4.83	2	7	5
	374	4.6	1	6	5
	705	4.49	1	6	5
	602	3.74	1	8	7

Emotional Category	Sound Condition	Arousal Mean	Arousal Minimum	Arousal Maximum	Arousal Range
Pleasant High-Arousal	200	6.34	2	9	7
	201	6.2	4	9	5
	202	6.43	2	9	7
	352	6.71	2	9	7
	365	6.86	2	9	7
	815	7.09	1	9	8
Pleasant Low-Arousing	206	6.11	1	7	6
	172	6.09	1	7	6
	809	6.8	1	7	6
	812	5.31	1	7	6
	112	7.29	1	9	8
	810	6.77	1	9	8
Unpleasant Low-Arousing	130	5	1	8	7
	708	4.03	1	7	6
	723	4.89	1	8	7
	700	4.6	1	8	7
	728	4.4	1	9	8
	720	4.8	1	8	7
Unpleasant High-Arousing	106	3.57	1	9	8
	115	3.74	1	8	7
	276	2.03	1	9	8
	277	1.83	5	9	4
	279	1.34	1	9	8
	711	3.31	2	9	7
Neutral Sound	170	5.14	1	8	7
	171	5.2	1	7	6
	377	4.83	1	9	8
	374	4.6	1	8	7
	705	4.49	1	5	4
	602	3.74	1	9	8