Time Judgments in Dual-Task Conditions

by

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Abstract

Every day we complete a number of tasks which require us to accurately time events, from estimating how long it will take us to drive to work in the morning to steeping our afternoon tea for the correct duration. Although timing is very important in our everyday lives, we know relatively little about how we process time information.

Many models have been proposed to account for human timing, with the most prominent are the attentional gate model (AGM) and the multiple resources model. The AGM and the multiple resources model make many similar predictions about human timing, and it is often difficult to discriminate between the two. Toward this goal, the present research focused on a situation in which the two models make opposing predictions, that is, conditions which require participants two carry out two tasks concurrently with both of them requiring time-related processing..

Three experiments are reported, in which subjects were asked to estimate various shorter or longer intervals while concurrently carrying out a task that either required processing of time-related information or non-time based information. Results of all three studies seem more supportive of the multiple resources model of timing, rather than the AGM.

Preface

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Acknowledgments

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Background: A Brief Review of Models of Timing Performance

Many of the tasks we complete every day require some form of timing or access to information about time. Some of these tasks directly involve timing, such as when we plan to meet a friend for coffee in 5 minutes or have a dinner reservation for 8 pm. In other cases we use time in a more indirect manner, such as when we must judge which of two routes to a destination will take longer. Time information can be used in a predictive, prospective manner, as illustrated above, or in a reflective, retrospective manner, such as when we judge how long it has been since we last saw a friend.

Accurate timing is also important for animals. Monarch butterflies travel up to 4000 km every fall to spend the winter in Mexico. In order to maintain a route that accurately takes them to their destination, monarch butterflies are assumed to use an internal compass that references the position of the sun and corrects for the time of day based on circadian rhythms (Merlin, Gegear, & Reppert, 2009). If this time correction is disrupted, the butterflies become unable to follow a correct southerly route. Golden shiners, a species of fish, are able to learn where food will appear at specific times over the course of a day, and perform daily migrations to obtain food (Reebs, 1996).

Despite the ubiquity of timing in everyday tasks, we know relatively little about how humans and animals process time information. Part of this information lacuna seems due to the fact that previous research on timing has focused almost exclusively on the production or perception of extremely brief durations, ranging from milliseconds to seconds (e.g., Brown, 1985; Brown 1997; Kladopoulous, Hemmes, & Brown, 2004;

Macar, Grondin, & Casini, 1994), or on extremely long durations that seem to fit well-defined patterns such as circadian rhythms (e.g., Bilgin & LeBoeuf, 2010; Wittman & Paulus, 2009). However, research on medium-length intervals, like the ones we use every day when we estimate how long it will take to walk to a meeting or how long a phone call has lasted, is lacking.

Types of Timing Tasks

Timing tasks, whether performed in or out of the lab, are commonly viewed as belonging to one of four types: temporal production, temporal estimation, temporal reproduction, and temporal bisection. The first type, called temporal production tasks require making a response to indicate that a given interval (e.g., 30 seconds) has elapsed (e.g., Brown, 1997; Esposito et al., 2007). To illustrate this kind of task, consider what we do when following a recipe that requires adding some ingredients, cook for 3 minutes, and then add a second set of ingredients. It seems unlikely that we would set a timer for this task. Instead, we would likely attempt to more or less accurately produce the 3 minute interval, possibly verifying our accuracy with a watch or wall clock. For the second type, called temporal estimation tasks, subjects are exposed to some event (e.g., a sound clip lasting 30 seconds) and asked to estimate its duration (e.g., Brown, 1985; Hicks, Miller, & Kinsbourne, 1976; Kladopoulos et al., 2004; Zakay & Tsal, 1989). For the third type, temporal reproduction tasks, participants are exposed to some event (e.g., 5 minutes) and immediately after they are asked to reproduce its duration, for example, by pressing a computer key to indicate exactly when an interval of the same duration has elapsed (e.g., Brown, 1985; Macar et al., 1994; McClain, 1983). The last type, temporal bisection tasks, involve exposing subjects to two target intervals, respectively labeled “long” and “short”. After learning the two intervals, subjects are presented with a series of test intervals, regularly spaced (in duration) between the “long” and “short” intervals, and they must judge each test interval as being more similar to the “long” or the “short” target. In real life, we perform temporal bisection tasks when we decide if a meeting was long or short, for example.

Each of the four task types can be used for obtaining either prospective or retrospective time judgments. In a prospective timing task, the individual participants know from the outset that they will have to complete some sort of timing task (Block & Zakay, 1997; Brown, 1985). Prospective timing tasks are more frequently used for studying time related processes, because it is easier to obtain multiple judgments in a single session. For example, in a prospective reproduction task, it is easy to expose participants to several intervals over the course of an experimental session, and ask them to reproduce each one in turn. Prospective judgments are also less contaminated by memory of past events (Block & Zakay, 1997).

Retrospective timing tasks require naïve participants who are unaware that they will be asked to estimate or reproduce an interval. In retrospective tasks, participants are distracted in some manner for a desired period of time, and then informed that they are to estimate or reproduce its duration. While many of the timing tasks we complete on a daily basis are retrospective, such as trying to remember how long ago we saved the document we are working on, they are more difficult to study in the lab. One reason for this bias away from retrospective tasks may stem from the fact that once participants have been exposed to an event and asked to estimate or reproduce its duration, they are no longer naïve to the purpose of the study; they are aware that they may be asked to estimate or reproduce the durations of subsequent events. For subjects who come to this realization, the task then becomes prospective. A second difficulty in obtaining retrospective judgments is interference from previous experiences. If asked to retrospectively estimate the time it took to travel from home to work on a particular day, that estimate is likely to be contaminated by previous experiences of the same trip, which may have been longer or shorter in duration.

In their meta-analytic review of time judgment studies, Block and Zakay (1997) concluded that prospective judgments tend to be longer than retrospective judgments, while retrospective judgments are more variable than prospective judgments. This pattern of findings may reflect fundamental differences between the two types of tasks. In a prospective judgment task, participants are able to intentionally encode temporal information, whereas in a retrospective judgment task, participants may encode temporal information in an incidental manner (Block & Zakay, 1997; Brown, 1985). Retrospective judgments may be more variable than prospective judgments because, as temporal information is incidentally encoded, participants are influenced more by concurrent nontemporal processing.

Prospective timing appears to involve attentional resources, and prospective estimates, productions, and reproductions appear to be sensitive to the amount of simultaneous nontemporal processing (Brown, 1985). In contrast, retrospective timing is less sensitive to the effects of nontemporal task demands, possibly because accurate retrospective timing is more reliant on the memory for temporal information that was passively or automatically encoded (Brown, 1985).

Timing Models

Several different models have been proposed to account for how we keep track of time. These models can be classified into two broad groups: internal clock models and attentional models. Both types of models explain some aspects of human timing, but neither is capable of fully explaining the existing data on timing performance. Internal clock models explain both prospective and retrospective timing, but attentional models seem to address only prospective timing (Block & Zakay, 1997; Brown, 1985). The most widely accepted contemporary model, the Attentional-Gate Model (AGM) combines aspects of both types of models to more fully explain human timing, but it may still be limited to prospective timing. Multiple resource models, though not specifically created to explain timing performance, may also account for human timing. All four types of models (internal clock models, attentional models, multiple resource models, and the AGM) are reviewed briefly below. Attentional models are discussed first, followed by the multiple resources model, internal clock models and the AGM

Attentional models. According to all attentional models of timing, a common pool of attentional resources is available and must be divided between temporal and non-temporal tasks, and success on the respective tasks is related to the amount of attention available and allocated to each (Block & Zakay, 1997). The common pool of resources is limited, and when demand for resources is higher on one task, fewer resources are available for other tasks (Kahneman, 1973), provided that the combined demand overwhelms the available attentional resources.

The first attention model, proposed by Thomas and colleagues (Thomas & Cantor, 1975; Thomas & Weaver, 1975), suggests that we have two distinct information processors, one for temporal information and one for non-temporal information. A single pool of attentional resources is divided between the two processors. Timing accuracy is a function of the allocation of attention to the processors. When relatively little nontemporal stimulus information must be processed, the temporal information processor receives the bulk of the attentional resources. If, on the other hand, a great deal of stimulus information is presented, the non-temporal processor requires the bulk of the attentional resources (Block, 1990). According to this model, attention is not under voluntary control, and the weighting or allocation of attention is entirely dependent on the amount of information that must be processed and the level of attention required to process said information (Zakay, Nitzan, & Glicksohn, 1983). However, by contrast to this model, multiple studies have shown that participants are able to voluntarily shift attention towards or away from a timing task, and this shifting affects performance on the timing task (e.g., Hemmes et al., 2004; Kladopoulos et al., 2004; Macar et al., 1994; Zakay & Tsal, 1989).

According to Thomas' and Kahneman's models, the combined demand of two tasks is dependent on their degree of automaticity. More interference should occur when two attention-demanding tasks need to be carried out concurrently than when an attention-demanding task is paired with an automatic task (Wickens, 2002). If the combined attentional demands of two tasks exceed the available resources, decrements in performance should result. These performance decrements, often demonstrated in dual-task situations, should occur when any two attention-demanding tasks are paired and overwhelm available resources (Wickens, 2002). Despite this prediction, however, two phenomena called difficulty insensitivity and difficulty uncoupling have been frequently observed (Brown, 1997). Difficulty insensitivity occurs when increasing the difficulty of one task has no effect on ongoing task performance. Attentional models of timing predict that, if the difficulty of the ongoing task is increased, performance on the temporal task should suffer (Brown, 1997), but this is not always the case (e.g., Brown, 1985, Experiment 2). Difficulty uncoupling occurs when the easy version of a task interferes more with a ongoing task than does the difficult version of the same task (e.g., Brown, 1985, Experiment 1), and this outcome is also contrary to the predictions of attentional models (Brown, 1997). Both difficulty insensitivity and difficulty uncoupling suggest that consideration of the simple demand for resources isn't adequate to explain dual task performance. For this reasons, multiple resource models, which posit that there are multiple pools of resources, have been used to explain human timing in dual-task situations.

Multiple resources models. Multiple resources models have not been specifically formulated to explain human timing; however, multiple resource models (Navon & Gopher, 1979, 1980; Wickens, 2002, 2008) have been engaged in order to address the shortcomings of single capacity theories of attention. According to multiple resource theories, there are multiple pools of specialized processing resources, each of which has its own capacity. Interference occurs to the extent that two tasks share the same resources; if the combined demand for that resource overwhelms the available capacity, performance decrements occur. Tasks which draw resources from separate pools with no overlap should not interfere at all (Brown, 1997).

Wickens' four resources. Wickens considered four dimensions to account for variance in dual-task performance, each of which is may be thought of as a distinct resource: processing stages, perceptual modalities, visual channels, and processing codes (Wickens, 2002, 2008). Processing stage refers to where in the system processing takes place, either at encoding/input, when the task requires perceptual and cognitive processing or at decoding/output when the task requires a response. Evidence for this dichotomy comes from experiments showing that when the difficulty of making a response is varied, performance on an ongoing, more cognitive or perceptual task is not influenced, and vice versa. Interference can also be caused by sharing perceptual modalities (Wickens, 2002, 2008), and Wickens considered two perceptual modalities –

auditory and visual. Performance advantages are commonly seen when competing streams of stimuli are presented cross-modally compared to intra-modally (Wickens, 2002, 2008). The third dimension, visual channels, refers to the distinction between focal and ambient, or peripheral, vision. Successful resource sharing between focal and ambient vision has been demonstrated (Weinstein & Wickens, 1992). Visual channels are not involved in all tasks, and the distinction between the two may be due to factors other than disjoint resources. Processing codes, Wickens' fourth dimension, refers to the distinction between analogue or spatial processes and categorical or symbolic processes. Manual and verbal responses can often be performed concurrently with relative ease, reflecting disjoint resource pools.

These four dimensions do not account for all dual task performance failures. This model assumes that all tasks are equally prone to overload, and that the qualitative nature of the task does not contribute to interference (Wickens, 2002, 2008). Wickens' four dimensions are unable to account for the finding that an easy version of a task may interfere less with timing than a difficult version of the same task (Brown, 2006). Brown (1985) asked subjects to either trace an outline of a star on a piece of paper (easy version) or trace the same star using a mirror instead of directly looking at the paper (difficult version). Subjects were instructed at the beginning of the experiment that they would be asked to estimate the time it took to trace the star when they were finished. Performance on this prospective time estimation task was poorer when subjects were engaged in the difficult version of the task than when they were engaged in the easy version of the task. Both tasks fall in the same categories on Wickens' four dimensions, and according to Wickens' theory should interfere with the timing task to the same extent. Wickens' four dimensions have also failed to account for other dual-task interference findings (Brown, 1997; Wickens, 2008), and models involving specialized pools of resources for specific tasks may better account for dual-task performance in timing and other domains.

Specialized pools of resources. Another version of multiple resource theory proposes that specific types of tasks rely on specialized pools of processing resources. According to this view, two tasks interfere with one another only to the extent that they share resources (Navon & Gopher, 1979, 1980). However, according to Navon and Gopher, a task may rely on more than one pool of resources, and interference between that task and another is dependent on the number of resources they share (1980).

Boles and Law (1998) described a series of potential resources, including auditory linguistic (recognizing words, digits, syllables), spatial attentive (focusing attention on a point in space), and visual temporal (judging time intervals between visual stimuli). The resources proposed are heavily influenced by Boles and Law's work in human factors analysis, and it seems plausible that other types of resources exist. In a series of experiments, Navon and Gopher (1980) demonstrated that vertical and horizontal visual tracking appear to involve at least partially different resources, despite the similarity of the two tasks on Wickens' four dimensions. Specialized pools of resources may better account for dual-task interference than a dimensional approach, such as that proposed by Wickens, to multiple resources.

A common criticism of attentional models is the lack of specificity of how exactly timing is accomplished (Block, 1990; Zakay, 1990). An internal clock or timer is implied by such models, but not clearly described.

Internal clock models. Internal clock models (e.g., Church, 1984; Treisman, 1963) posit that timing is accomplished by means of a specialized internal clock, which is made up of a variety of components. Most internal clock models consist of a pacemaker, which emits pulses at more or less regularly spaced intervals, a counter, which tallies these pulses, and some sort of mechanism for comparing the pulses to stored representations of time. According to such models, a greater accumulation of pulses is associated with a longer perceived time duration (Grondin, 2001).

According to Treisman (1963) who proposed one of the first internal clock models, the internal clock is composed of a pacemaker, a counter, and a memory store paired with a comparator. The pacemaker emits pulses at a regular rate, which varies with arousal, and these pulses serve to increment the counter. The count of pulses is then stored by the memory store and compared to a long-term memory store that contains verbal labels for different pulse counts (e.g., 30 seconds). While Treisman's model is compelling in its simplicity, it cannot account for many aspects of human timing, notably the effects of attention on timing performance. The model also does not include any mechanism for starting or stopping the timing process.

An improved version of the internal clock model was proposed by Church (1984) and is, to date, the clearest variant of such a model. This model also includes a pacemaker, an accumulator/counter, and a comparator, but adds a switch that responds when timing is required. When an external timing signal is perceived, the switch closes and allows pulses to be accumulated by the counter, and those pulses are then used to look up time durations in reference memory. The rate of the pacemaker is influenced by a variety of factors, both endogenous and exogenous. In a series of experiments on rats, Church and colleagues demonstrated that pacemaker rate can be affected by drugs such as methamphetamine and haloperidol, by dietary changes, and by stress levels (Church, 1984). Church's model was originally proposed to account for timing in animals, and may not be able to account for factors that influence human timing, such as the deliberate allocation of attention and the use of timing strategies (Block, 1990).

Internal clock models such as that provided by Church (1984), though straightforward and simple, do not readily explain why human timing is often inaccurate (Block, 1990; Grondin, 2001). If, as these models propose, pulses are transferred directly into a counter whenever a timing signal has been perceived, and if the pacemaker and counter are relatively reliable, timing should be extremely accurate and should show little variation (Block, 1990). According to internal clock models, failures in timing are due to noise in the system, but these errors should be relatively few and should be stable across varying situations in which attention is or is not available for timing (Taatgen, van Rijn, & Anderson, 2007). However a multitude of studies have shown that the presence of an ongoing, attention-demanding task results in less accurate timing (cf. Hemmes et al., 2004; Kladopoulos et al., 2004; Macar et al., 1994; Zakay & Tsal, 1989).

Internal clock models are also unable to account for the filled duration illusion, that is, the common finding that estimates of unfilled durations (i.e., intervals during which no stimulus processing is required) are longer than estimates of filled durations (i.e., intervals during which participants are engaged in some form of stimulus processing). According to internal clock models, stimulus processing should have no effect on temporal processing, and yet a very common finding is that it shortens perceived time (Zakay & Block, 1996).

The attentional-gate model. The Attentional-Gate Model (AGM) combines features from both internal clock models and attentional models in order to address criticisms levelled at both (Zakay & Block, 1996, 1998), and is currently the dominant model in research on human time perception. The AGM is based on Treisman's internal clock model, but includes an attentional gate to account for the effects of nontemporal information processing and strategies (see Figure 1). According to the AGM, the internal timing mechanism consists of a pacemaker, which emits pulses at regularly spaced intervals, and an accumulator or counter which collects these pulses. A switch and an attentional gate are located between the pacemaker and the accumulator. The attentional gate is controlled by attention to time. When more attention is available for temporal processing, the gate is open wider, allowing more pulses to pass through. When less attention is available for time, because it is allocated/used for processing nontemporal information, the gate is narrowed or closed, and fewer pulses pass through. The switch, which follows the gate, responds to timing signals, and when a relevant timing signal is perceived, the switch closes, much like the switch on an electrical circuit, and pulses are able to transfer into the accumulator. The accumulator counts the pulses that pass into it, and stores this pulse count in short term memory. In order to make a decision about whether a given interval has elapsed (i.e., a temporal production task) or to estimate how long an interval was (i.e., a temporal estimation task), the comparator compares the accumulated pulse count stored in short term memory with a reference memory bank that contains pulse counts for different known intervals.

The necessity of adding an attentional gate to previous internal clock models has been questioned. Lejeune (1998, 2000) argued that the switch can adequately explain the effect of attention on timing, and the gate is unnecessary. Zakay and Block describe the gate as responding to internal attention to time, defining attention as allocation of resources, and the switch as responding to external time-relevant signals, a type of selective attention (1996). Lejeune proposes simplifying the model, combining the gate and switch, so that when an external timing signal is perceived, resources are allocated to timing and the switch closes, allowing pulses to pass (1998). The combined switch can operate in a “flickering switch” mode, opening and closing during the to-be-timed interval as attention is directed towards and away from the external timing signal. This combination of gate and switch fails to account for continued timing when the external signal is not present. Combining the attentional gate and switch also combines perceptual and attentional processes into one unit, inconsistent with the view that attention and perception are separate processes (Zakay, 2000).

The role of reference memory and the comparator varies with the type of timing task being performed (Zakay & Block, 1998). Zakay and Block do not explicitly state how the reference memory and comparator work in different types of tasks, but extending the theory to these tasks is relatively simple. In a prospective time estimation task, participants are instructed that they will be exposed to a stimulus and then asked to estimate how long the stimulus lasted. In prospective time estimation tasks, the comparator compares the accumulated pulse count stored in short term memory with the reference memory values for a number of intervals, and decides which interval the accumulated pulse count most closely matches. If the accumulated pulse count is, for example, 1709, and the reference memory values state that 1600 pulses are equivalent to 2 minutes and 1800 pulses are equivalent to 2.25 minutes, the subject will make an estimate somewhere between 2 and 2.25 minutes. In a prospective time production task, participants are instructed to make a response when they believe a given interval has passed. In time production tasks, the comparator makes a series of comparisons between the accumulated pulse count and the reference memory for the target interval, and prompts a response when the accumulated pulse count is close to or equal to the reference memory pulse count. If, for example, the subject is to produce an interval of 2 minutes, the comparator makes a series of comparisons between the accumulated pulse count and the reference memory for the pulse count of 2 minutes (e.g., 1600 pulses), and when the accumulated pulse count nears 1600, prompts a response. In a prospective time reproduction task, participants are instructed that they will be required to reproduce the duration of an event. After being exposed to the event, participants are asked to make a response when they believe the same amount of time has elapsed. In time reproduction tasks, the comparator makes a series of comparisons between the reference memory for the experienced duration of the stimulus and the accumulated pulse count from the reproduction, prompting a response when the pulse counts match.

The AGM model predicts that when more attention is available for timing, experienced duration should be shorter than when attention is directed away from timing (Zakay & Block, 1998). When attention is directed away from time, the attentional gate is closed or narrowed, and pulses accumulate more slowly. In reproduction and production tasks, this results in longer response times when attention is directed away from timing, as it takes longer for the accumulated pulse count to match the reference memory for the target interval. In estimation tasks this results in shorter estimates when attention is directed away from timing, as the accumulated pulse count is lower and corresponds to the reference memory for a shorter interval. To investigate this prediction, experimenters commonly employ a dual-task methodology in which participants must complete a central timing task (production, reproduction, or estimation) while occupied by an ongoing, nontemporal task.

In order to manipulate the amount of attention available for the prospective timing task, previous studies have used either a directional manipulation or a load manipulation. Directional manipulations focus on voluntarily directing attention towards or away from time. Using a dual-task method, participants complete a prospective timing task and an ongoing, nontemporal task [e.g., memorizing words (Kladopoulos et al., 2004)]. Participants are instructed to focus more of their attention either on the timing task or on the ongoing task. Such studies have demonstrated that experienced duration is longer when participants are focusing on the prospective timing task than on the ongoing task, consistent with the predictions of the AGM (Hemmes et al., 2004; Kladopoulos et al., 2004; Macar et al., 1994; Zakay & Tsal, 1989). Kladopoulos et al. (2004) presented subjects with a series of words, and instructed them to read each word aloud and memorize it. Each trial consisted of a series of words presented on a computer screen, for a total of 40 or 60 seconds. Participants were also instructed that at the end of the memorization phase they would be asked to estimate the duration of each trial (i.e., a prospective time estimation task). In order to manipulate the attention allocated to each task, experimenters instructed the participants to either focus primarily on the timing task or primarily on the word memorization task for each trial. Participants produced shorter estimates when they were instructed to focus primarily on the word memorization task than when they were instructed to focus primarily on the timing task, as predicted by the AGM.

Load manipulations focus on varying the difficulty of the ongoing, non-temporal task, with the assumption that as more attention is required to complete the ongoing task, less attention is available for the prospective timing task, and the attentional gate is narrowed or partially closed. Such studies have demonstrated that an experienced duration is longer when participants are completing an easier ongoing task, and shorter when the ongoing task is more difficult (Brown, 1985; Brown, 1997; Hicks et al, 1976;

Kladopoulos et al., 2004; McClain, 1983). To illustrate, Brown (1997) created two versions of a math verification task, in which participants were required to verify whether the answers provided for a series of subtraction problems were correct. In the “easy” version of the task, each problem consisted of a single digit number subtracted from a larger single digit number, resulting in a positive answer (e.g., 9-4=5). In the “difficult” version of the task, each problem consisted of a single digit number subtracted from a two-digit number (e.g., 93-7=86). All incorrect answers were within one digit of the correct answer for the problem. While engaged in this task, participants completed a prospective time production task, which required them to click a computer mouse button with their non-dominant hand every 2 or 5 seconds. Participants were instructed to be as accurate as possible on both tasks. As predicted by the AGM, productions were longer when paired with the “difficult” version of the math verification task than when paired with the “easy” version of the task.

Summary of Existing Literature

Both the AGM and the multiple resources model explain large amounts of data in the existing timing literature, but it is difficult to distinguish between the two models. In many cases, both models are able to explain the same data, and it is not clear which provides a more accurate account of human timing.

The AGM readily explains why time estimates are longer when less attention is directed towards timing tasks, but it is not clear how attention to timing controls the attentional gate. According to the AGM, when attention is directed towards time, the gate is open wider than when attention is directed away from time. What is not clear is what mechanism is responsible for opening and closing this gate.

The multiple resources model explains why timing is more accurate under single-task than dual-task conditions, and when timing is paired with an easy ongoing task versus a difficult ongoing task. A timer is implied by the model but not described in any detail, so it is unclear how timing is actually accomplished.

When a temporal task is paired with a nontemporal task, the AGM predicts that productions will be longer than when the temporal task is performed in isolation, because the attentional gate is narrowed or partially closed, and pulses accumulate less quickly. The multiple resources model predicts that performance on either the temporal or nontemporal task will suffer, if the combined demand exhausts available resources. Each task, however, may require a combination of resources, some of which overlap. For example, the primary timing task and the ongoing task may both rely on working memory, and when combined, may exhaust the available resources. If performance is worse when the two tasks are performed concurrently than when either task is performed in isolation, the multiple resources model assumes that the two tasks share resources. What is not clear, however, is whether there is a distinct pool of resources dedicated to timing, or whether the interference effects commonly reported are due to the other, nontemporal requirements of the paired tasks.

Methodological issues. In the existing literature on timing, performance on the ongoing task is seldom measured or reported, and yet such performance on the ongoing task is critical, at least to the multiple resources model. Many different types of ongoing task have been used as the ongoing nontemporal task, including word memorization (Kladopoulos et al., 2004), visual search (Brown, 1997), assembling puzzles (Zakay & Tsal, 1989), pursuit rotor tracking (Brown, 1997), word categorization (Macar et al., 1994), figure tracing (Brown, 1985), card sorting (Hicks et al., 1976), and mental arithmetic (Brown, 1997). In many cases, performance on the ongoing task is not reported, either in isolation or in combination with the primary temporal task.

According to the multiple resources model, if two tasks compete for the same or overlapping resources, and if they exhaust the available resources, performance deficits should occur. These performance deficits may be expressed in one of the two competing tasks or in both tasks.

Most studies on interference in timing, however, only measure performance on the primary temporal task (Brown, 1997, 2006). Although some studies do include measures of performance on the ongoing task, they often do not include a condition in which the ongoing task is performed in isolation, to obtain a baseline measurement of performance (Brown, 1997). Without such a baseline, it is not possible to know whether performance on the ongoing task decreases when combined with the primary temporal task.

According to the multiple resources model, if performance on two (or more) combined tasks is worse than performance on either task performed in isolation, the two tasks are assumed to share resources and overwhelm the available resources with their combined demand. If, however, performance on the primary temporal task is not worse when paired with another task, it has often been assumed that the two tasks do not share resources, but it is possible that the performance decrements are being expressed in the ongoing task and not the primary temporal task. Without measuring ongoing task performance in isolation and when combined with the primary temporal task, it is not possible to know whether performance decrements are not present or whether they are being expressed in the ongoing task.

Experiment 1: Performance on Concurrent Timing Tasks

The main objective of my research was to differentiate more clearly between the AGM and multiple resource models. For this purpose, I focused on a situation in which the two models would seem to make opposite predictions. Specifically, I examined participants' ability to make prospective time estimates while they were engaged by means of an ongoing task that either required or did not require time-related processing.

According to the AGM, time estimates should be shorter with the first task combination. That is, when engaged in an ongoing task that requires attention to time, this requirement should open the attentional gate, allowing a more rapid accumulation of pulses, and as a consequence, subjects' time estimates should be shorter. By contrast, when engaged by an ongoing task which does not require attention to time, the gate would be less open, restricting the accumulation of pulses, and subjects' time estimates would be longer (i.e., it would take longer to accumulate the required number for a duration stored in reference memory). It is critical to note, however, that longer productions may be more or less accurate depending on whether time estimates are too short or too long. When the mean productions are underestimates, a lengthening of productions would result in more accurate estimates for participants completing the pitch judgment task. When the mean productions are overestimates, a lengthening of productions would result in less accurate estimates for participants completing the pitch judgment task.

By contrast to these predictions, the multiple resources model suggests that if two tasks which require attention to time-related information are paired, and if the combined demands of these tasks overwhelm the available resources, performance on one or the other task (or both) should suffer. If the multiple resources model is correct, productions should be more accurate when the prospective interval production task is paired with the pitch judgment task than when it is paired with the duration judgment task. According to this model, timing and pitch judgments rely on different resources, each with its own store of resources. Performance can be maintained when participants are focused on a timing task and a non-timing task (as is the case for participants completing the pitch judgment task), because the two tasks draw on separate pools of resources. Neither the AGM nor the multiple resources model predict whether participants will under- or overestimate.

In order to investigate these predictions, participants in Experiment 1 were assigned to one of two ongoing task types, which either required or did not require attention to timing. Both ongoing tasks required subjects to discriminate between two tones, which varied either in duration (the temporal ongoing task) or pitch (the nontemporal ongoing task). While engaged in this task, subjects were to produce 2 and 5 minute intervals by pressing a key on the computer keyboard to indicate they thought the to-be-produced interval had elapsed.

Method

Participants and design. Forty undergraduate student volunteers from the University of British Columbia participated in this experiment in return for course credit. The experiment had one between subjects factor, type of ongoing task (duration judgment or pitch judgment), and one within subjects factor, prospective interval duration (2 or 5 minutes). Twenty participants were randomly assigned to each ongoing task type.

Materials. The tone discrimination task required pure tones that were created using WavePad Sound Editor (NCH Software, Greenwood, CO.). Three types of tones were required: a “standard tone” with a frequency of 4000 Hz and duration of 100 ms, and 2 sets of “target tones”, one for each of two ongoing tasks. The pitch target tones (PTT) were 100 ms in duration, and had frequencies of 4020 Hz, 4040 Hz, 4060 Hz ... 4180 Hz, with adjacent tones separated by 20 Hz increments. The duration target tones (DTT) had a frequency of 4000 Hz and durations of 130 ms, 135 ms, 140 ms ... 165 ms, with adjacent tones separated by 5 ms increments.

Procedure. The main parts of the experiment were carried out with a desktop computer equipped with a CRT monitor and running E-Prime 1.1 (Psychology Software Tools, Pittsburgh, PA). Participants wore headphones for the duration of the study. Participants were asked to remove watches and place any time-tracking electronics out of sight. All participants were tested individually. The experiment took approximately one hour to complete. The experiment was conducted with the approval of the University of British Columbia Behavioural Research Ethics Board.

Volume adjustment phase. To begin the session, participants were given an opportunity to adjust the sound volume. A series of 10 standard tones was played through the headphones and participants were instructed to adjust the volume to a comfortable level.

Calibration Phase. The purpose of this phase was to find the tone pairing (standard tone versus target tone) for each individual which he or she could correctly discriminate about 80% of the time. The instructions emphasized both speed and accuracy.

Pitch calibration. For the pitch judgment task, the calibration phase involved 50% standard tones randomly interspersed with 50% PTTs. Participants were instructed to press “1” on the keyboard if the tone they heard was low (the standard tone) or “2” if the tone they heard was high (the PTT). The calibration phase was arranged into blocks of 50 trials. For the first block, each participant was presented with a random series of 25 standard tones (i.e., tones of 4000 Hz & 100 ms), interspersed with 25 of the highest frequency PTT (i.e., a tone of 4180 Hz & 100 ms). At the end of the block the program assessed performance. If performance was above 80%, the program presented the next block of 50 trials, consisting of the standard tone paired with the next lower frequency of the PTTs. This procedure continued, with the PTT lowered one step for each subsequent block of trials, until the participant reached a performance level at or just below 80%. When performance was at or below 80%, the calibration phase terminated and participants progressed to the critical phase of the experiment. The PTT used for the last calibration phase block (the “selected PTT”) was used for the remainder of the experiment.

Duration calibration. For the duration judgment task, the calibration phase involved 50% standard tones randomly interspersed with 50% DTTs. Participants were instructed to press “1” on the keyboard if the tone they heard was short (the standard tone) or “2” if the tone they heard was long (the DTT). The calibration phase was arranged into blocks of 50 trials. For the first block, each participant was presented with a random series of 25 standard tones (i.e., tones of 4000 Hz & 100 ms), interspersed with 25 of the longest duration DTT (i.e., a tone of 4000 Hz & 165 ms). At the end of the block the program assessed performance. If performance was above 80%, the program presented the next block of 50 trials, consisting of the standard tone paired with the next lower duration of the DTTs. This procedure continued, with the DTT lowered one step for each subsequent block of trials, until the participant reached a performance level at or just below 80%. When performance was at or below 80%, the calibration phase terminated and participants progressed to the critical phase of the experiment. The DTT used for the last calibration phase block (the “selected DTT”) was used for the remainder of the experiment.

Critical phase. In order to assess the effect of an ongoing task type (pitch judgment or duration judgment) on prospective interval production, a dual task methodology was used. The target task was the prospective interval production task, in which participants were asked to indicate by key press when a given interval had elapsed. At the same time, participants were engaged in the ongoing task – either making pitch or duration judgments.

This phase of the experiment was arranged into blocks, each defined by the requirement to produce an interval of a specified duration, either 2 minutes or 5 minutes. Each block began with a display that instructed participants to press the “enter” key when the desired target interval, either 2 or 5 minutes, had elapsed. Participants then began the ongoing task, making either pitch or duration judgments. Each ongoing task trial consisted of playing a single tone, either the standard tone or the selected target tone. The selection of a tone for each trial, standard or target, was determined randomly. Participants who were assigned to the duration judgment task listened and responded to the standard tone or the selected DTT, and participants assigned to the pitch judgment task listened and responded to the standard tone or the selected PTT. Participants were instructed to press “1” on the computer keyboard to indicate that they heard the standard tone and “2” to indicate they heard the target tone. The next trial began immediately after participants made the pitch or duration judgment for the previous trial. Ongoing task trials continued until the participant completed the prospective interval production task by pressing “enter” to signal the end of the current target interval. Participants were instructed to be as accurate as possible on both tasks.

Each participant completed 5 blocks with a target interval of 2 minutes and 5 blocks with a target interval of 5 minutes, presented in random order. If participants failed to make a response to the target interval production task after 7 minutes, the block terminated and the next block began immediately, with a display giving instructions about the next interval to be produced.

Results

The data for one participant from the duration judgment task and for two participants from the pitch judgment task had to be discarded because they appeared to have used the wrong keys for entering responses.

The critical dependent variables in this experiment were the accuracy and speed of making tone decisions in the ongoing task as well as the accuracy of the interval estimates produced by participants. Also of interest were the target tones that were selected during the calibration phase for each ongoing task. Accuracy on the selected target tones was examined as a measure of task difficulty, to ensure that the two tasks were roughly equally difficult when performed in isolation.

Selected DTTs and PTTs. For the duration judgment task, the mean selected DTT was 4000 Hz and 152.63 ms, and for the pitch judgment task, the mean selected PTT was 4115.56 Hz and 100 ms. At the end of the calibration phase, mean accuracy was 72.22% and 70.67%, respectively, on the selected DTT and PTT. There was no significant difference in accuracy on the selected DTTs and PTTs. With accuracy used as a proxy for task difficulty, these means suggest that at the end of the calibration phase, and when performed alone, both tasks were similarly demanding.

Ongoing task performance. For each subject, the mean accuracy and the median time required for making a decision about each stimulus was calculated for each block of the experiment. Mean accuracy, shown in Figure 2, over both target intervals was 80.92% and 73.72% for the duration and pitch judgment tasks, respectively. Despite this difference between the tasks which is highlighted by the figure, an ANOVA with target interval as a within-subjects factor and ongoing task type as a between-subjects factor revealed no significant main or interaction effects. The largest obtained *F* value was for the main effect of task type, *F* (1, 35) = 3.29, *p* = .08.

In order to explore whether subjects were focused equally on the standard and target tones, I examined the mean ongoing task accuracy data for the standard and target tones. On the pitch judgment task, mean accuracy was 75.17% for standard tones and 73.28% for target tones. On the duration judgment task, mean accuracy was 84.74% for standard tones and 76.68% for target tones. This pattern of data suggests that subjects were not biased towards one or the other tone type. This interpretation was confirmed by an ANOVA with tone type (standard vs. target) as a within subjects factor and ongoing task type as a between subjects factor which revealed no significant main or interaction effects. The largest obtained *F* value was for the main effect of tone type, *F* (1, 35) = 3.03, *p* = .09.

The means of the median times required for making accurate tone decisions, averaged across all target intervals, were 487.14 ms and 620.63 ms on the pitch and duration tasks, respectively, as shown in Figure 3. An ANOVA with target interval as a within-subjects factor and ongoing task type as a between-subjects factor revealed a significant main effect due to task type, *F* (1, 35) = 11.06, *p* < .01, *MSE* = 29796.66, ε^2 = .24. No other effects approached significance. The effect due to tasks, which was not anticipated, might be a result of the different requirements of the two tasks. For the duration judgment task, participants had to wait for the end of each tone to make a decision regarding its duration, whereas for the pitch judgment task they did not have to wait until the end of the tone.

To further investigate whether participants were biased towards the standard tone or target tone, I examined the means of median decision times by tone type on accurate trials only. Figure 4 shows these means of median decision times. Mean decision times in the pitch condition were 493.89 ms and 497.39 ms for standard and target tones, respectively. Mean decision times in the duration condition were 610.05 ms and 632.24 ms for standard and target tones, respectively. As discussed previously, decision times were shorter on the pitch task than the duration task, but there was no difference due to tone type. An ANOVA with tone type (standard vs. target) as a within subjects factor and ongoing task type as a between subjects factor revealed a significant main effect of ongoing task type, F (1, 35) = 11.20, $p < .01$, $MSE = 26006.40$, $\varepsilon^2 = .24$. No other main or interaction effects were significant.

Interval Estimation Performance. The key dependent variable of interest was the closeness of the time estimate produced by each participant. Estimates were converted to a difference score between the estimate and the target interval, expressed as a percentage of the target interval, using the following formula:

$$-1\left[\frac{Target\ Interval - Estimate}{Target\ Interval} \times 100\right]$$

Use of this formula yields a negative value if the estimate was shorter than the target interval (i.e., an underestimate), zero if the estimate was perfect, and a positive value if the estimate was longer than the target interval (i.e., an overestimate). Each participant's median estimate for each target interval (i.e., the median estimate over all of the 2 minute trials, and the median estimate over all of the 5 minute trials) was used in the following analyses.

Figure 5 shows the means of these median estimates for each interval and task type. The figure indicates that the 2-min estimates were more accurate than the 5-min estimates, but it appears that there was only a minimal influence due to the ongoing task type. The results of an ANOVA with target interval as a within-subjects factor and ongoing task type as a between-subjects factor confirmed this summary by revealing a significant main effect due to target interval, F (1, 35) = 7.30, $p < .02$, MSE = 4106.29, ε^2 = .17. No other main or interaction effects reached significance.

Discussion

According to both the AGM and a multiple resources model, performance on the prospective interval production task was expected to be different when it was paired with the duration judgment task versus the pitch judgment task. Specifically, consistent with the AGM I anticipated that subjects' productions would be shorter when they were engaged in the duration judgment task than the pitch judgment task. When engaged in the duration task, subjects should be attending more to timing, causing the gate to be open wider. This wider opening of the gate leads to the more rapid accumulation of pulses in the counter/accumulator and thus a quicker completion of each interval. Therefore, in the case where participants make underestimates (as they did in Experiment 1), productions were expected to be more accurate when participants are concurrently engaged by a task that does not require attention to time (i.e., the pitch judgment task) than when participants were concurrently engaged in a task that does require attention to time (i.e., the duration judgment task). The results of Experiment 1 do not support this hypothesis, as performance on the prospective timing task did not differ based on which ongoing task type participants were assigned to.

The failure to find a difference in prospective interval productions due to ongoing tasks might be regarded as supporting a multiple resources view. By the multiple resources model, no difference due to ongoing tasks (e.g., pitch versus duration) would be expected under conditions where the combined demands of the primary timing task and the concurrent timing task fell short of exhausting the total pool of resources available for timing. Unfortunately, however, in the absence of a direct measure of resource availability, no conclusions seem warranted about the combined demands of either of the task pairs used in Experiment 1.

Another possible reason for the failure to find a difference due to the different concurrent tasks is the large amount of variability in the time estimates. It is conceivable that this variability obscured true differences between the task conditions. Although far from significant, the data pattern in Figure 4 shows that in absolute terms and consistent with the AGM, participants produced shorter time estimates in the duration than pitch task condition.

The overall finding that prospective interval productions were less accurate for 5 than 2 minute intervals is consistent with previous research which shows a positive relationship between event duration and error. Previous research has demonstrated this effect in relatively brief durations (e.g., 5-30 seconds) (e.g., Macar et al., 1994; Taatgen et al., 2007) and thus the present research extends this finding to longer durations which are more relevant in everyday life, such as those involved in steeping a cup of tea or a short phone call. According to the AGM, the absolute value of these errors in timing should increase as interval length increases, such that participants err less in estimating a 2 minute interval than a 5 minute interval. However, the AGM does not readily explain why the error of estimates should be larger for longer durations when the estimate is computed as a proportion as was done in Experiment 1..

Experiment 2: Refining the Method

Experiment 2 was conducted in an effort to replicate and extend the findings of Experiment 1. Experiment 2 used the same general method as Experiment 1, but with method/procedure changes that were used to address the possibility that the variability in prospective interval productions in Experiment 1 may have obscured differences between conditions. It seems conceivable that time estimates were highly variable in Experiment 1 because of participants' inability to remember the exact interval to be produced on each trial. Another objective of Experiment 2 was to investigate whether the difference in the time estimate for the 2 to 5 minute intervals has a positive relation (versus some other relationship) with the duration of the to-be-produced interval.

It is possible that participants in Experiment 1 might, at least on some trials, have failed to remember the exact duration of the interval to be produced on each trial, and this failure augmented the variability of their time estimates. To address this possibility and minimize failures to remember the exact duration of the interval to be produced on each trial, in Experiment 2 participants received an on-screen reminder about the interval to be produced on each trial. In Experiment 1, participants were asked to produce intervals of 2 or 5 minutes. A significant effect of interval was found, such that participants were less accurate in producing 5 minute intervals than in producing 2 minute intervals. While this difference was significant, it was impossible to determine whether the decrease in performance between producing 2 minute intervals and 5 minute intervals was a due to a sudden drop or a more gradual, possibly linear, decline in performance. In order to illuminate this issue, the number of target intervals in Experiment 2 was increased to 3.

Method

Participants and design. Thirty-nine undergraduate student volunteers from the University of British Columbia participated in Experiment 2 in return for course credit. The experiment had one between subjects factor, type of ongoing task (duration judgment or pitch judgment), and one within subjects factor, prospective interval duration (2, 4, or 6 minutes). Twenty and nineteen participants were randomly assigned to the pitch and duration tasks, respectively.

Materials. The materials used in Experiment 2 were identical to those used in Experiment 1.

Procedure. As in Experiment 1, all participants in Experiment 2 were tested individually. The experiment took approximately one hour to complete.

The procedure for Experiment 2 was the same as for Experiment 1, except for the following differences. In Experiment 1, participants were only informed about the to-be-produced interval once at the beginning of each interval. As a memory aid, in Experiment 2 a reminder of the to-be-produced target interval was displayed in the top left corner of the computer screen in 18 pt font, stating “2 minutes”, “4 minutes”, or “6 minutes”.

In Experiment 1 participants completed 5 experimental blocks of each target interval. In Experiment 2, participants completed 3 blocks of each interval type (i.e., 2, 4, and 6 minutes). The number of blocks of each interval type was reduced to ensure the experimental session would be completed within the one hour time frame allotted.

In Experiment 1 participants received verbal instructions regarding the volume adjustment, calibration phase, and critical phase at the beginning of the session, and then written instructions displayed on-screen before each phase. Participants in Experiment 2 received written and verbal instructions at the beginning of the session, as well as at the start of each phase. As in Experiment 1, participants were instructed that during the critical phase of the experiment both the ongoing task and the prospective interval production task were equally important.

Lastly, in Experiment 1 blocks in the critical phase were set to terminate if the participant had not made a response after 7 minutes. In Experiment 2 the maximum time for each block was set to 8 minutes, to accommodate the longer 6 minute interval.

Results

The data from one participant assigned to each ongoing task type were excluded from analyses, as response accuracy was far below chance, probably because they used the wrong keys to enter their responses. The data from one additional participant assigned to each ongoing task type were excluded because the participant failed to respond to two of the three 6 minute blocks before 8 minutes had passed. Following these exclusions, the data from 18 participants remained for the duration judgment task and 17 participants for the pitch judgment task.

As in Experiment 1, the key dependent variables of interest in Experiment 2 were ongoing task accuracy and decision time and interval estimation accuracy. Also of interest were the tones selected during the calibration phase for each task type.

Selected DTTs and PTTs. For the duration judgment task, the mean selected DTT was 4000 Hz and 151.67 ms, and for the pitch judgment task, the mean selected PTT was 4125.00 Hz and 100 ms. At the end of the calibration phase, mean accuracy was 71.68% and 72.17%, respectively, on the selected DTT and PTT. There was no significant difference in accuracy for the selected DTTs and PTTs.

Ongoing task performance. For each subject, the mean accuracy and median time required to make a decision about each stimulus was calculated over each block of the experiment. Mean accuracy, shown in Figure 6, over all target intervals was 84.41% and 73.47% on the duration and pitch judgment tasks, respectively. Accuracy was poorer on the pitch judgment task than the duration judgment task. An ANOVA with target interval as a within subjects factor and ongoing task type as a between subjects factor revealed a significant main effect of task type, F (1, 33) = 5.19, p = .03, MSE = 601.83, ε^2 = .14. No other main or interaction effects were significant.

In order to explore whether subjects were biased towards either the standard or target tones, I examined the mean accuracy from the ongoing task for standard and target tones. Mean accuracy on the pitch judgment task was 72.06% for standard tones and 74.12% for target tones. Mean accuracy on the duration judgment task was 81.5% for standard tones and 87.44% for target tones. These data suggest that participants were not biased towards either tone type. An ANOVA with tone type (standard vs. target) as a within subjects factor and ongoing task type as a between subjects factor revealed a significant main effect of task type, which was identified in the preceding paragraph. No other effects were significant.

The means of the median times required for making accurate tone decisions, averaged over all target intervals were 508.63 ms and 640.31 ms on the pitch and duration tasks, respectively, as shown in Figure 7. An ANOVA with target interval as a within subjects factor and ongoing task type as a between subjects factor revealed a significant main effect of task type, *F* (1, 33) = 16.77, *p* < .001, *MSE* = 27128.00, $\varepsilon^2 = .34$. As in Experiment 1, this difference may be due to the differing requirements of the two ongoing tasks. For the duration judgment task, participants had to wait for the end of each tone to make a decision regarding its duration, whereas for the pitch judgment task they did not have to wait until the end of the tone.

Figure 8 shows the means of median decision times by tone type on accurate trials over all target intervals. Mean decision times for the pitch judgment task were 516.15 ms and 499.09 ms for standard and target tones, respectively. Mean decision times for the duration judgment task were 632.28 ms and 651.31 ms for standard and target tones, respectively. While responses were generally slower on the duration task than the pitch task, the decision times for each task follow a different pattern. For the pitch judgment task, responses to the target tone were slightly faster than responses to the standard tone, but the opposite pattern was found for the duration judgment task. Consistent with this observation, an ANOVA with tone type (standard vs. target) as a within subjects factor and ongoing task type as a between subjects factor revealed a significant main effect of ongoing task type, *F* (1, 33) = 15.48, *p* < .001, *MSE* = 20332.03, ε^2 = .32, and an interaction between tone type and ongoing task type, *F* (1, 33) = 4.57, *p* = .04, *MSE* = 1244.54, ε^2 = .12.

Interval estimation performance. The key dependent variable of interest in Experiment 2 was again the closeness of the estimate for each target interval produced by each participant. Using the method described in Experiment 1, I computed the median estimate for each interval produced by each participant in each ongoing task, and those estimates were used in all analyses.

Figure 9 shows the means of these medians for each target interval and ongoing task type. As in Experiment 1, estimates produced in Experiment 2 became increasingly less accurate as the length of the target interval increased. In addition, however, in this experiment the ongoing task type influenced interval estimation performance. Estimates produced during the duration judgment task were longer, and thus more accurate, than estimates produced during the pitch judgment task. An ANOVA with target interval as a within-subjects factor and ongoing task type as a between-subjects factor revealed a significant main effect of target interval type, *F* (2, 66) = 36.85, *p* <

.001, *MSE* = 154.623, $\varepsilon^2 = .53$, as well as a significant main effect of task type, *F* (1, 33) = 5.94, *p* = .02, *MSE* = 845.03, $\varepsilon^2 = .15$. The interval x task type interaction was not significant.

Discussion

Experiment 2 was conducted to further examine the influence of a secondary temporal task and a secondary nontemporal task on prospective interval production. Specifically, Experiment 2 was designed to further refine the method and address the possibility that variability in prospective interval productions in Experiment 1 obscured differences between conditions. Additionally, in Experiment 2 the number of target intervals was increased to investigate the relationship between duration of to-be-produced intervals and accuracy of prospective interval productions.

In Experiment 2, interval estimates were longer, and thus more accurate, during the duration judgment task than the pitch judgment task. These results are inconsistent with both the AGM and the multiple resources model. The AGM predicts that, when mean productions are underestimates, participants concurrently occupied by the duration judgment task should produce significantly shorter intervals than participants occupied by the pitch judgment task. The opposite pattern was found in Experiment 2.

The multiple resources model predicts that participants concurrently occupied by the duration judgment task should be less accurate on either the ongoing task or the prospective interval production task than participants occupied by the pitch judgment task, a prediction that was not supported. When concurrently engaged in the duration judgment task, participants produced more accurate estimates of the to-be-produced intervals, and performed more accurately on the ongoing task than participants concurrently engaged in the pitch judgment task. One possibility is that the combined demand of the duration judgment and prospective interval production tasks was not high enough to overwhelm available timing resources, in which case performance decrements would not be expected.

In Experiment 1 productions of the longer target interval (5 minutes) were less accurate than productions of the shorter target interval (2 minutes). In Experiment 2, 3 target intervals were used, to further examine the relationship between the to-be-produced interval and production accuracy. Prospective interval production accuracy was best for 2 minute intervals, and worst for 6 minute intervals. It appears that the deterioration of performance is graded from shorter to longer intervals, rather than a sharp drop off in performance at some intermediate point. This finding is consistent with previous research on much shorter intervals (e.g., Macar et al., 1994; Taatgen et al., 2007). The AGM accounts for the increase in absolute error in production, but does not readily explain the increase in production error proportional to target interval length.

Experiment 3: Allocating Attention to Timing

Experiment 3 was designed to investigate a number of assumptions, made in Experiments 1 and 2, about the resource demands of the pitch and duration judgment tasks as well as the time estimation task. Specifically, I assumed that requiring subjects to carry out two tasks concurrently (e.g., making pitch judgments while being engaged in estimating time durations) would challenge their available processing resources. In turn, this challenge was expected to be revealed either by differences due to the ongoing task manipulation (i.e., making pitch versus duration judgments) on ongoing task performance or on time estimates. However, by contrast to this expectation, Experiments 1 and 2 showed no reliable differences, due to the ongoing task types, on ongoing task performance, and they showed different effects due to the ongoing task manipulation on participants' time estimates. In view of these findings (especially the null findings), it is possible that the joint demands of the task pairings (e.g., making pitch judgments while being engaged in estimating time durations) assigned to subjects were not sufficiently challenging and thus failed to exceed their available capacity. If so, there was no reason to expect that the ongoing task manipulation would affect time estimates or that the requirement to carry out two tasks concurrently (as opposed to carrying them out separately) would results in any performance decrements.

To address such questions about the resource demands of different task pairings, Experiment 3 employed a method which differed in two critical ways from that used in the preceding experiments. First, the instructions used in Experiment 3 informed subjects that the time estimation task was more important than the concurrent task.

(For Experiments 1 and 2, the instructions informed subjects that both paired tasks were equally important.) By the assumption that the task pairings used in the preceding experiments challenged the available processing resources, the new instructions used in Experiment 3 were assumed to direct more of those resources toward making time estimates. As a consequence, by the AGM, a greater allocation of attention to time should result in making shorter time estimates.

A second critical difference in Experiment 3 was the inclusion of a manipulation which required participants to carry out the time estimation task either concurrently with the ongoing tasks (as they did in the preceding experiments) or in the absence of any concurrent task. By the assumption that the pitch and duration judgment tasks reduced at least to some extent the resources available for processing time information, the removal of these concurrent tasks was assumed to affect participants' time estimates.

Method

Participants and design. Fifty-four undergraduate student volunteers from the University of British Columbia participated in Experiment 2 in return for course credit. Each participant was tested individually. The experiment took approximately one hour to complete.

The experiment had two between subjects factors, type of ongoing task (duration judgment or pitch judgment) and instruction type (experimental vs. control), and one within subjects factor, prospective interval duration (2, 4, or 6 minutes).

Participants were randomly assigned to one of the 4 cells of the experiment: duration experimental (DE, 13 participants), duration control (DC, 15 participants), pitch experimental (PE, 13 participants), and pitch control (PC, 15 participants).

Materials. The materials used in Experiment 3 were identical to those used in Experiment 1 and 2.

Procedure. The procedure for both experimental groups (DE and PE) was identical to that in Experiment 2, except that participants were instructed that this was a study of prospective interval timing and the ongoing task was intended to fill time. In Experiments 1 and 2, participants were instructed that both tasks (i.e., the prospective time production task and the ongoing task) were equally important. In Experiment 3, participants were instructed that the prospective time production task was more important, and the ongoing task was included to fill the interval and prevent counting.

The control groups (DC and PC) completed the volume adjustment and calibration phases in the same manner as in both preceding experiments. During the critical phase of the experiment, they were instructed to listen to the sounds but to not make any responses to them. The purpose of the control groups was to verify that completing the prospective interval production task alongside the either the pitch or duration judgment task was more difficult than the prospective interval estimation task in isolation.

Results

The data were examined for missing values, error patterns, and outlying values in the same manner as for Experiments 1 and 2. No anomalies were detected, and no data were excluded from analysis in Experiment 3.

Selected DTTs and PTTs. For the duration judgment task, averaged across the experimental and control conditions, the mean selected DTT was 4000 Hz and 152.50 ms, and for the pitch judgment task, the mean selected PTT was 4128.46 Hz and 100 ms. At the end of the calibration phase, mean accuracy was 72.00% and 72.55%, respectively, on the selected DTT and PTT. There was no significant difference in accuracy on the selected DTTs and PTTs.

Ongoing task performance. The following analyses were performed using only the ongoing task data from the pitch experimental and duration experimental groups. The two control groups did not carry out the ongoing task during the critical phase of the experiment.

Mean accuracy, shown in Figure 10, over all target intervals was lower on the pitch task (65.36%) than on the duration task (81.08%). An ANOVA with target interval as a within-subjects factor and ongoing task type as a between subjects factor revealed a significant main effect of task type, F (1, 23) = 11.43, $p < .01$, MSE = 404.40, $\varepsilon^2 = .33$. No other effects were significant. Both Experiments 1 and 2 showed the same pattern of data, although the effect was not significant in Experiment 1.

In order to explore whether subjects were biased towards either the standard or target tones, I examined the mean accuracy from the ongoing task for standard and target tones. Mean accuracy on the pitch judgment task was 64.08% for standard tones and 67.33% for target tones. Mean accuracy on the duration judgment task was 80.46% for standard tones and 81.46% for target tones. These data suggest that participants were not biased towards either tone type. An ANOVA with tone type (standard vs. target) as a within subjects factor and ongoing task type as a between subjects factor revealed a significant main effect of task type, as noted in the preceding paragraph. No other effects were significant.

The means of the median time required for making accurate tone decisions, averaged over all target intervals were 526.79 ms and 608.31 ms on the pitch and duration tasks, respectively, as shown in Figure 11. An ANOVA with target interval as a within subjects factor and ongoing task type as a between subjects factor revealed no significant effects, but the main effect of task type approached significance, *F* (1, 23) = 1.80, *p* =.06, *MSE* = 2988.53, ε^2 = .07.

Figure 12 shows the means of median decision times by tone type on accurate trials over all target intervals. Mean decision times for the pitch judgment task were 608.38 ms and 557.38 ms for standard and target tones, respectively. Mean decision times for the duration judgment task were 601.57 ms and 621.19 ms for standard and target tones, respectively. While responses were generally slower on the duration task than the pitch task, the decision times for each task follow a different pattern. For the pitch judgment task, responses to the target tone were slightly faster than responses to the standard tone, but the opposite pattern was found for the duration judgment task. Although this pattern appears in the data, it is not supported by statistical analysis. An ANOVA with tone type (standard vs. target) as a within subjects factor and ongoing task type as a between subjects factor revealed no significant effects. The largest obtained *F* value was for the interaction of tone type and task type, *F* (1, 23) = .78, *p* = .39, *MSE* = 15557.98, ε^2 = .03.

Interval estimation performance. The key dependent variable of interest in Experiment 3 was the closeness of the estimate produced by each participant to the target interval. Difference scores, expressed as a percentage of the target interval, were calculated using the same formula as in Experiments 1 and 2. The median estimate for each interval produced by each participant was used in the following analyses, which use data from all participants in all groups.

Figure 13 shows the means of these medians for each target interval and group (experimental vs. control). Productions were longer, and thus more accurate, for the 2 minute target interval, and shorter for the 4 and 6 minute intervals. The difference between the 4 and 6 minute intervals was not significant. Participants in the two control groups produced more accurate estimates than those in the experimental groups. An ANOVA with target interval as a within-subjects factor and ongoing task type (duration vs. pitch judgments) and instruction type (experimental vs. control) as between-subjects factors revealed significant main effects of interval, *F* (2, 104) = 52.26, *p* < .001, *MSE* = 118.53, ε^2 = .50, and instruction type, *F* (1, 52) = 4.18, *p* < .05, *MSE* =

1882.18, $\varepsilon^2 = .07$, but no significant main effect of ongoing task type (pitch vs. duration). No interactions were significant.

Discussion

Experiment 3 was conducted to investigate the assumptions made in Experiments 1 and 2 about the resource demands of the ongoing tasks and the prospective time production task. In order to do so, the instructions for Experiment 3 were changed from those given in the previous two experiments. Participants were instructed that the prospective time production task was most important, and that the ongoing task was a filler, meant to prevent counting. It was assumed that these instructions would direct more attention towards time estimation. Two control conditions were included, in which participants listened to the tones used in the ongoing task but made no response, in order to investigate the assumption that performing the ongoing tasks reduces resources available for processing time information.

According to the AGM, this increased focus on the prospective production task should make productions shorter, and thus productions should be longest in the pitch experimental condition, shortest in the duration experimental condition, with productions on the pitch and duration control conditions falling somewhere in between the two. This pattern of results was not supported by the data.

According to the multiple resources model, if the prospective interval production task and pitch judgment task require completely separate resources, performance on the prospective interval production task should be equally accurate when paired with the pitch judgment task as when performed in isolation. If the two tasks require identical resources, and when combined exhaust the available resources, performance on one or both tasks should suffer.

As predicted by the multiple resources model, prospective interval productions were less accurate in the experimental conditions than the control conditions. Prospective interval productions are more accurate when performed in isolation than when combined with either of the ongoing tasks. This finding suggests that the prospective interval production task shares some resources with both ongoing tasks, and that the combined demand exhausts these shared resources.

Both the AGM and the multiple resources model predict that participants concurrently engaged in the duration judgment task would produce significantly shorter or less accurate prospective interval productions than participants concurrently engaged in the pitch judgment task. The increased demands of the combined tasks due to attentional allocation appear to have had an effect on the prospective interval productions of participants completing the duration judgment task, as productions were much less accurate in Experiment 3 than in Experiment 2. In Experiment 3, when participants were not instructed that both tasks were equally important, and emphasis was placed on the prospective interval production task, no differences emerged between the interval estimates produced in the pitch and duration conditions.

General Discussion

The main goal of the present research was to more clearly discriminate between the AGM and the multiple resources model. Toward this goal, I investigated them in a novel situation in which the two models make opposing predictions. Additionally, the present research was conducted to address a methodological issue in previous research, notably the failure to measure or report ongoing task performance both in isolation and when paired with the primary timing task.

The AGM predicts that when two timing tasks are paired the attentional gate should be open wider than when a timing task and a task that does not require attention to time are paired. As a result of this wider gate, pulses pass through to the counter/accumulator more reliably, filling it up more quickly, and prospective interval productions are shorter. The multiple resources model predicts that, in the case that there is a specific pool of resources available for timing, performance on two time-based tasks should be less accurate than when a timing task and a task that does not require timing are paired, if the combined demand of the two timing task exhausts available resources. To investigate these predictions, I conducted a series of experiments in which a prospective interval production task was paired with an ongoing task that either required or did not require attention to time.

The Attentional-Gate Model

No significant differences on prospective interval productions due to task type (duration or pitch judgments) were found in Experiment 1, although the general pattern of results was as predicted by the AGM. In Experiment 2, participants who were simultaneously completing the pitch judgment task produced significantly shorter prospective interval productions, contrary to the AGM. In Experiment 3, prospective interval productions for participants engaged in either of the two ongoing tasks were significantly shorter than productions by the two control groups, but there was no difference between the pitch experimental group and the duration experimental group. The AGM predicts that when more attention is directed towards timing activities, prospective interval productions should be shorter, so performance was expected to be worst (shortest) in the duration experimental group, followed by the duration control and pitch control groups, and best (longest) in the pitch experimental group. This pattern of results was not supported.

The Multiple Resources Model

In Experiment 2, with equal emphasis on both tasks, the combination of the prospective interval production task and the duration judgment task resulted in more accurate productions than when the prospective interval production task was combined with the pitch judgment task. This pattern of results suggests that the combined demand of the two time-based tasks did not exceed available resources.

In order to increase the combined demand of the two tasks attentional focus was manipulated by instructing participants that the prospective interval production task was more important, and the ongoing task was simply to fill time and keep them from counting. Experiment 3 was conducted to investigate the effects of this attentional manipulation. Prospective interval productions were significantly shorter (less accurate) in the experimental conditions than in the control conditions, suggesting that both the pitch judgment task and the duration judgment task share some resources with the prospective interval production task. No differences emerged between the prospective interval productions in the two experimental conditions.

When the productions from the experimental groups in Experiment 3 are compared with the productions from Experiment 2, it appears that productions paired with the duration judgment task are substantially more accurate when participants are instructed to focus equally on both tasks than when they are instructed that the prospective interval production task is most important. In contrast, productions paired with the pitch judgment task are relatively steady under both instruction conditions. This pattern of results suggests that the combined task demand of the duration judgment and prospective interval production task does not exceed resources when the tasks are equally important, but does exceed resources when the prospective interval production task is more important, consistent with the multiple resources model. It appears that the multiple resources model is more able to explain timing in dual-task conditions than the AGM.

Methodological Issues

The multiple resources model states that when two tasks which require the same resources are combined, and the combined demand exceeds available resources, performance on one or both tasks should suffer. The majority of studies, however, only measure performance on the primary temporal task (be it production, reproduction, or estimation), so it is impossible to know whether performance on the ongoing task has suffered due to the combination of the two tasks (Brown, 1997, 2006). Those studies which do measure performance on the ongoing task rarely include conditions in which performance on the ongoing task is examined in isolation. Without such a baseline measure of performance, it is not possible to know whether the combination of the primary time based task and the ongoing task causes performance deficits on the ongoing task.

In Experiments 1, 2, and 3, performance on the ongoing task was measured both in the calibration phase and in the critical phase. Performance was relatively constant across both the duration and the pitch task in the calibration phase and across all three experiments when the tone judgment task was performed in isolation, with a range of 70.71% to 72.55%. Using accuracy as a proxy for task difficulty, it can be concluded that the two tasks were of relatively the same difficulty. In the critical phase, however, differences in performance emerged. In all three experiments, performance was poorer on the pitch judgment task than the duration judgment task, though this difference was not statistically significant in Experiment 1. In line with the multiple resources model, this pattern of results suggests that there is a concurrence benefit associated with performing the duration judgment task and prospective interval production task simultaneously. This benefit may reflect shared resources (Brown, 1997). When two tasks are performed concurrently, the combined demand is comprised of the demand of each task and the demand associated with switching between the two tasks. Switching is required whenever two tasks are performed concurrently, but switch costs may be higher when switching between two tasks that depend on different resource pools than between two tasks that rely on the same resource pool. This cost of switching may result in poorer performance when two tasks that rely on separate resources are paired.

Limitations and Future Directions

All of the above conclusions are based on single experiments which should be replicated to confirm their validity. Additionally, the present studies were conducted with a between-subjects design. Future research using a within-subjects design in which task instructions were manipulated (i.e., focus equally on both tasks or focus primarily on the prospective interval production task) is necessary to further test the multiple resources model.

Future research should focus on different ongoing task types, to confirm that the effects reported reflect a distinction between processing of temporal information and other types of information, and not specifically between processing of temporal information and pitch information.

Perhaps most importantly, the present research combines two artificial tasks – the prospective interval production task and the ongoing tone judgment task – which are not frequently performed in a similar manner in daily life. It is indeed possible that real world timing differs in some significant way from these relatively simple, though attention-demanding, laboratory tasks. The role of attentional resources and attentional allocation in timing appears to be critical to performance, and real world timing often occurs under more complex conditions, in which multiple distracting tasks and stimuli are present.

Conclusions

The present research was conducted to more thoroughly discriminate between the AGM, the current dominant model in research on time perception, and the multiple resources model. Both models are capable of explaining a large portion of the data in the literature on human timing, but discriminating between the two is difficult as they make similar predictions in many situations. To this end, I focused on one situation where the two models make seemingly opposite predictions – the pairing of two timing tasks. The results of the present three experiments seem to offer little support for the AGM. Instead, the data are best explained by the multiple resources model.

Figures

Figure 1*. The Attentional-Gate Model.*

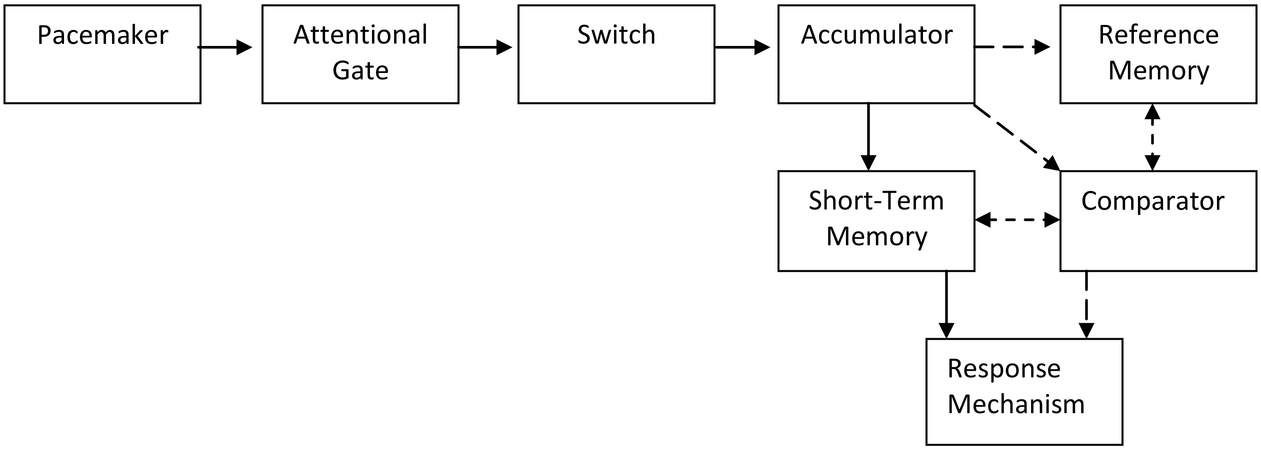


Figure 2. *Mean accuracy on the ongoing tasks in Experiment 1, as a function of target interval duration. Error bars represent the standard error of the mean.*

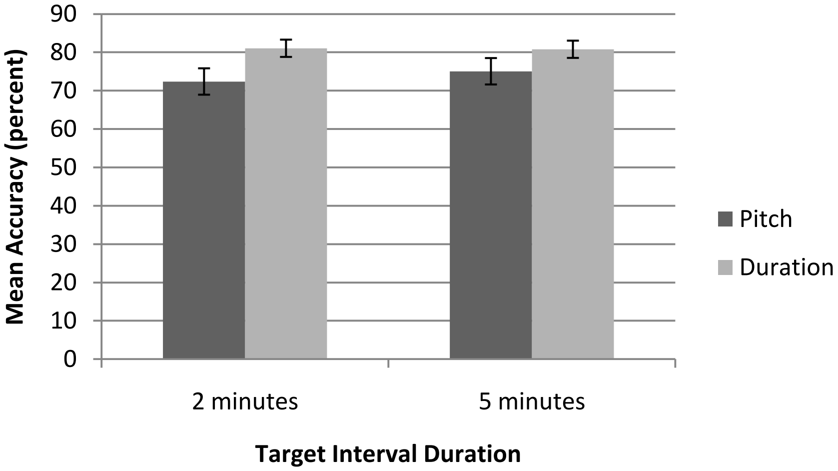


Figure 3. *Means of median decision times on accurate trials on the ongoing tasks in Experiment 1, as a function of target interval duration. Error bars represent the standard error of the mean.*

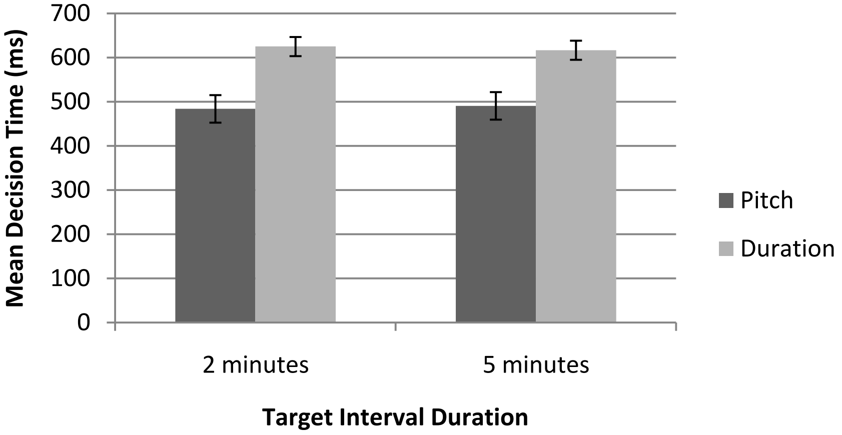


Figure 4. *Means of median decision times on accurate trials on the ongoing task in Experiment 1, as a function of tone type (standard vs. target). Error bars represent the standard error of the mean.*

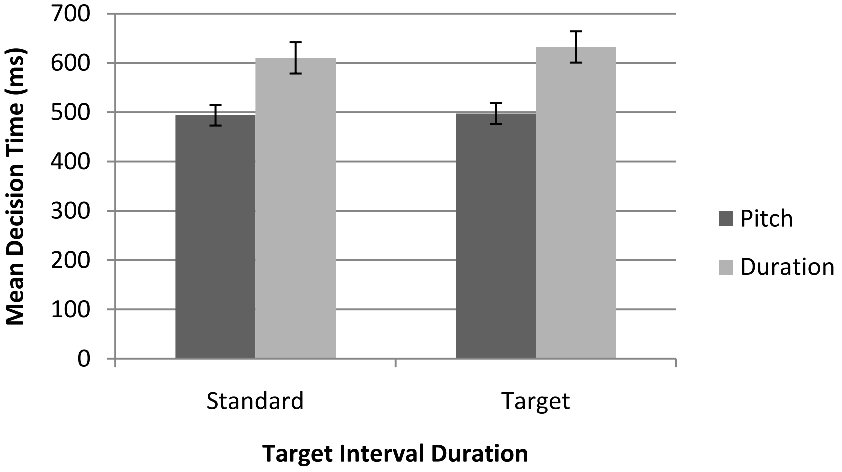


Figure 5. *Mean interval estimates in Experiment 1 as a function of ongoing task type. Negative values indicate that the mean value was an underestimate; positive values indicate that the mean value was an overestimate. Error bars represent the standard error of the mean.*

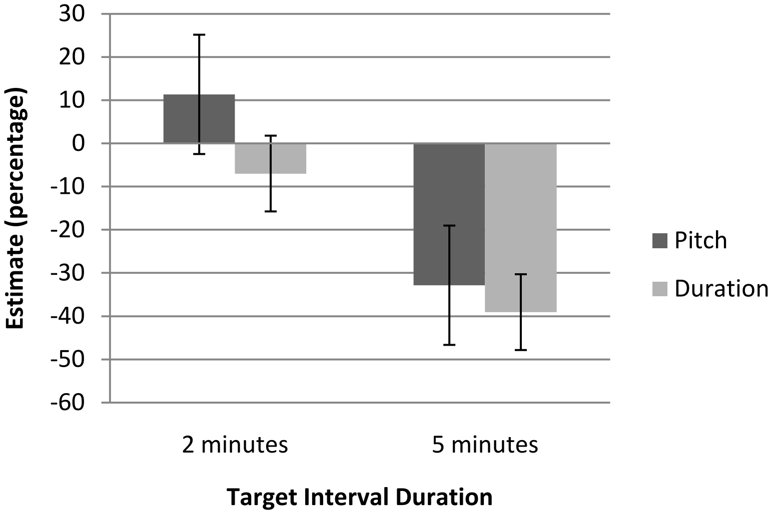


Figure 6. *Mean accuracy on the ongoing tasks in Experiment 2, as a function of target interval duration. Error bars represent the standard error of the mean.*

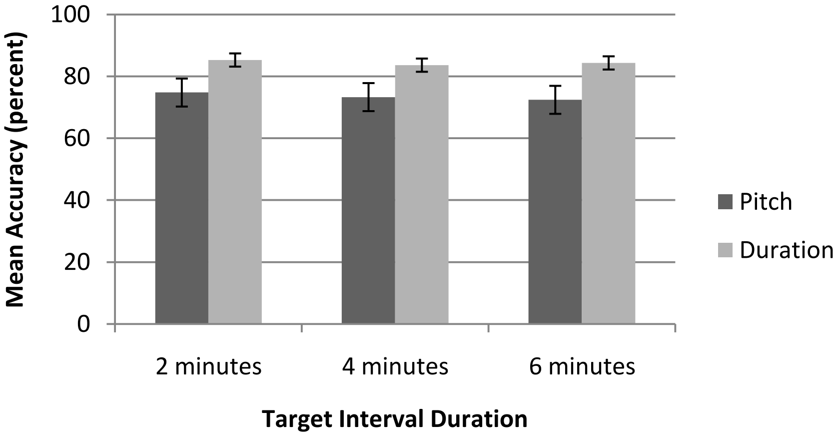


Figure 7. *Means of median decision times on the ongoing tasks in Experiment 2, on correct trials only, as a function of target interval duration. Error bars represent the standard error of the mean.*

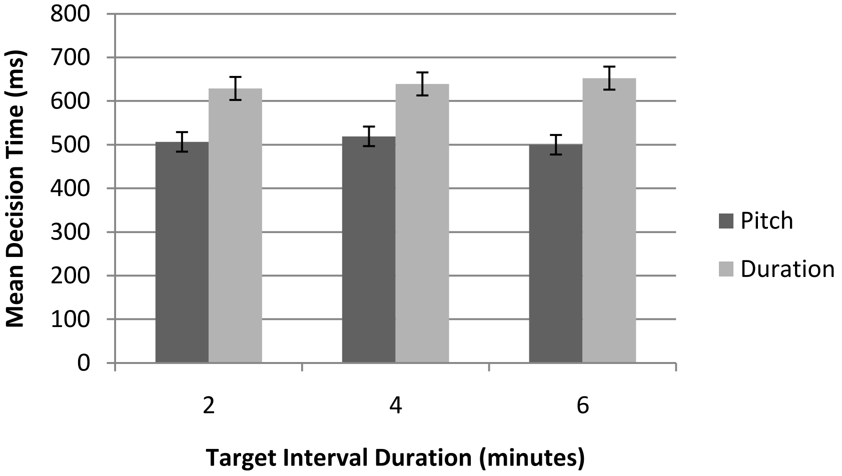


Figure 8. *Means of median decision times on accurate trials on the ongoing task in Experiment 2, as a function of tone type (standard vs. target). Error bars represent the standard error of the mean.*

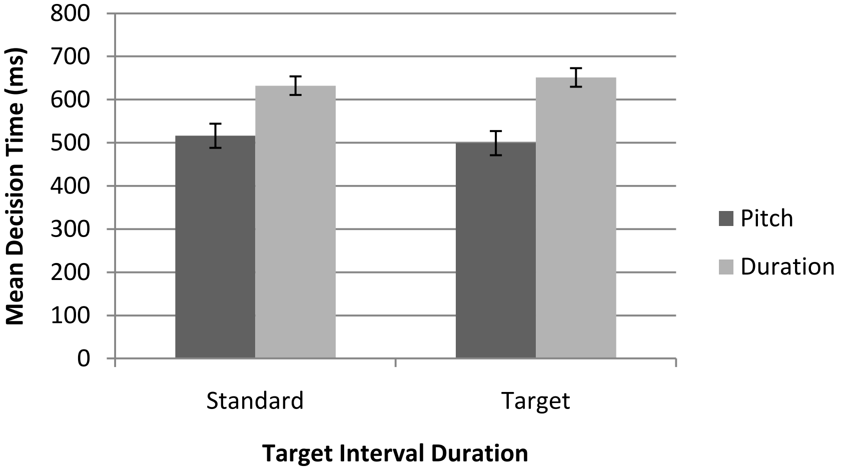


Figure 9. *Mean accuracy of interval estimates (in percentage of target interval) in Experiment 2 ongoing task type. Negative values indicate that the mean value was an underestimate, positive values indicate that the mean value was an overestimate. Error bars represent the standard error of the mean.*

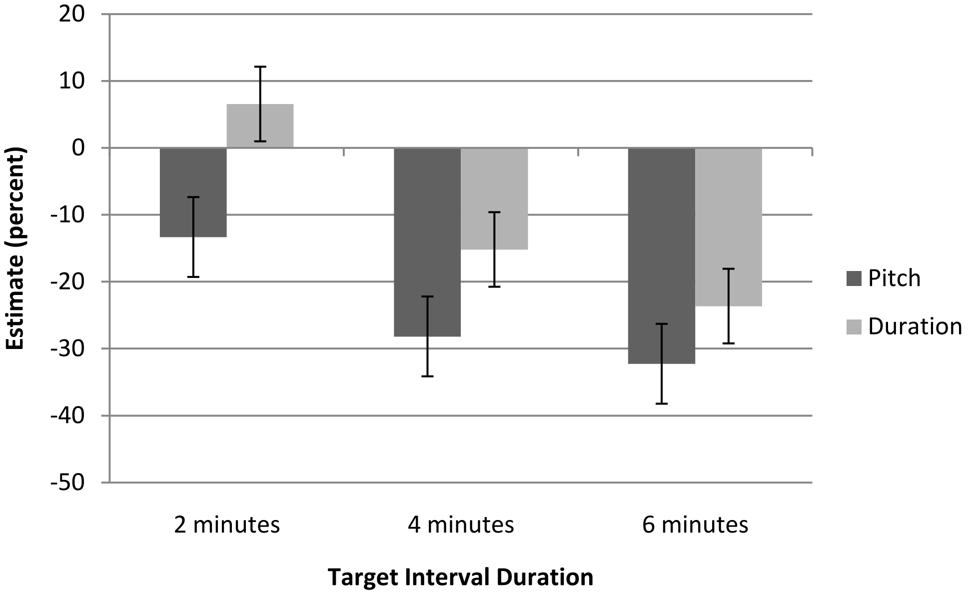


Figure 10. *Mean accuracy on the ongoing tasks in Experiment 3, as a function of target interval duration. Error bars represent the standard error of the mean.*

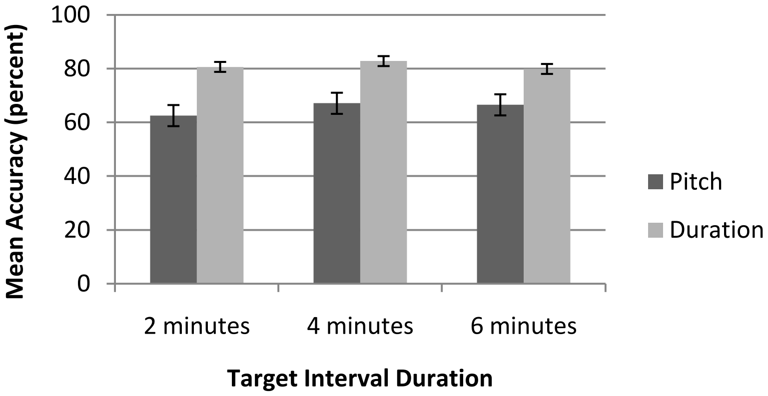


Figure 11. *Means of median decision times on the ongoing tasks in Experiment 3, as a function of target interval duration. Error bars represent the standard error of the mean.*

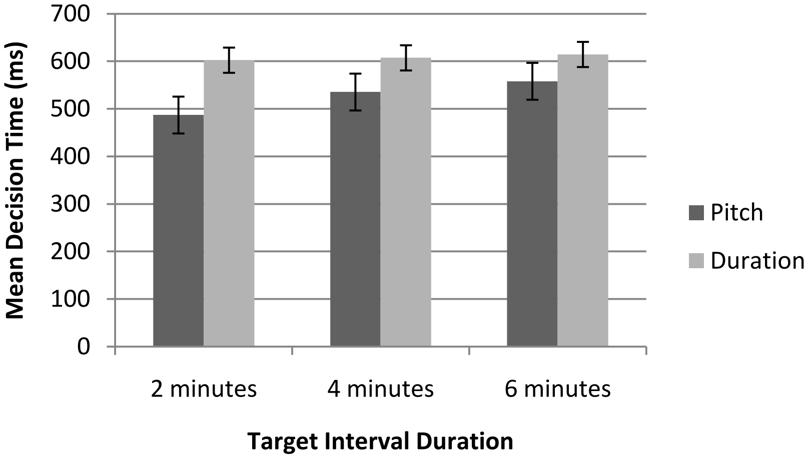


Figure 12. *Means of median decision times on accurate trials on the ongoing task in Experiment 3, as a function of tone type (standard vs. target). Error bars represent the standard error of the mean.*

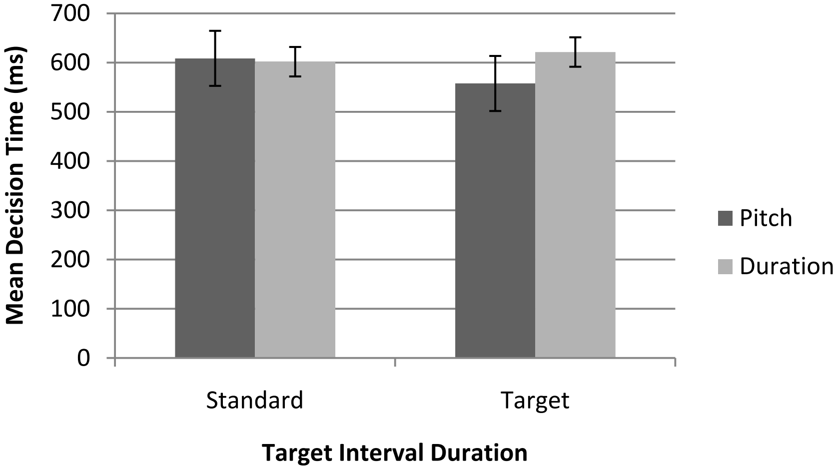
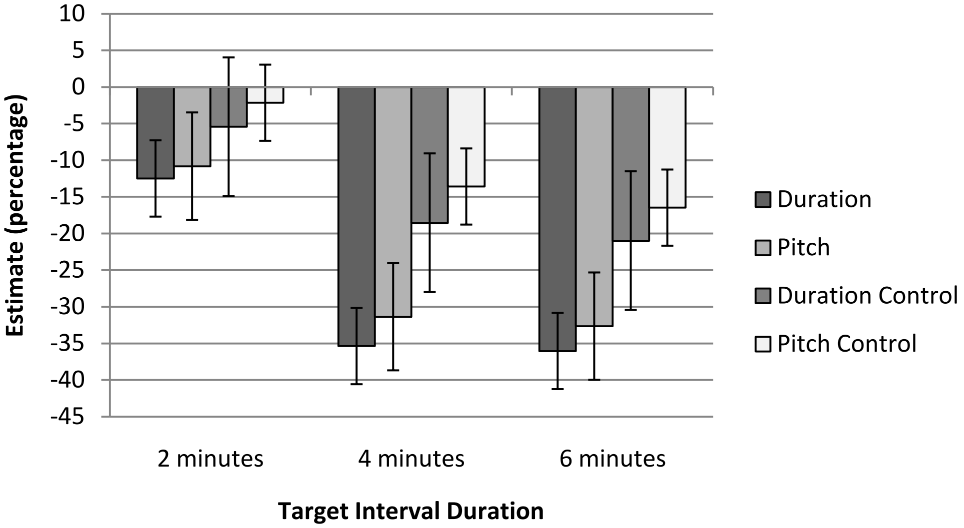


Figure 13. *Mean accuracy of interval estimates (in percentage of target interval) in Experiment 3 ongoing task type. Negative values indicate that the mean value was an underestimate, positive values indicate that the mean value was an overestimate. Error bars represent the standard error of the mean.*



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Appendix – Ethics Certificate

The University of British Columbia
Office of Research Services
Behavioural Research Ethics Board
Suite 102, 6190 Agronomy Road, Vancouver, B.C. V6T 1Z3

CERTIFICATE OF APPROVAL- MINIMAL RISK RENEWAL

PRINCIPAL INVESTIGATOR:	**DEPARTMENT:**	**UBC BREB NUMBER:**
Peter Graf	UBC/Arts/Psychology, Department of	H03-80566

INSTITUTION(S) WHERE RESEARCH WILL BE CARRIED OUT:

Institution	**Site**
UBC	Vancouver (excludes UBC Hospital)

Other locations where the research will be conducted:
n/a

CO-INVESTIGATOR(S):
Jess Gao
Carrie Cuttler

SPONSORING AGENCIES:
Natural Sciences and Engineering Research Council of Canada (NSERC) - "Individual Differences in Memory" - "Prospective Memory Across the Adult Lifespan" - "Individual Differences in Memory: Time Flies"

PROJECT TITLE:
Individual Differences in Memory: Eye Tracks

EXPIRY DATE OF THIS APPROVAL: June 29, 2011

APPROVAL DATE: June 29, 2010

The Annual Renewal for Study have been reviewed and the procedures were found to be acceptable on ethical grounds for research involving human subjects.

Approval is issued on behalf of the Behavioural Research Ethics Board

Dr. M. Judith Lynam, Chair
Dr. Ken Craig, Chair
Dr. Jim Rupert, Associate Chair
Dr. Laurie Ford, Associate Chair
Dr. Anita Ho, Associate Chair

file:///C|/Users/PGAdmin/Desktop/Individual%20Differences%20in%20Memory.html[09/08/2010 11:16:14 AM]