Executive processes and timing: comparing timing with and without reference memory.

Ruth S Ogden[1], Rhiannon MacKenzie-Phelan[1], Catharine Mongtomery[1], John E Fisk[2] & John H Wearden[3]

1 School of Natural Sciences and Psychology, Liverpool John Moores University, L3 3AF, UK.

2 School of Psychology, University of Central Lancashire, PR1 2HE, UK

3 School or Psychology, Keele University, ST5 5BG, UK.

Abstract

Temporal perception is influenced by executive function. However, performance on different temporal tasks is often associated with different executive functions. The current study examined whether using reference memory during a task influenced how performance was associated with executive resources. Participants completed temporal generalization and bisection tasks, in their normal versions involving reference memory, and episodic versions without reference memory. Each timing task had two difficulty levels; easy and hard. Correlations between performance on these tasks and measures of executive function (updating, inhibition, task switching, and access to semantic memory) were assessed. Accuracy on the temporal generalization task was correlated with memory access for all versions of the task. Updating correlated with accuracy only for the reference memory-based version of the task. Temporal bisection performance presented a different pattern of correlations. The bisection point was negatively correlated with inhibition scores, except for the easy episodic condition. The Weber ratio, considered a measure of temporal sensitivity was negatively correlated with memory access only in the hard episodic condition. Together, the findings suggest that previous models of generalization and bisection may not accurately reflect the underlying cognitive processes involved in the tasks.

Key words: time perception, timing, executive function, memory.

Introduction

Recent years have seen growing interest in what Wearden (2016) calls “predictive studies” of timing. Such studies relate performance on timing tasks to performance on other psychological tasks, for example, tests of memory, attention, or executive function, with the general aim being to relate performance on the different tasks by examining individual differences. For example, do people with better short-term memory perform differently on some particular timing task than those with poorer memory?

To date, predictive studies have tested the relationship between “general cognition”, for example, intelligence, short-term memory, working memory, attention, executive function and temporal perception, in typically developing and clinical populations. This research has typically shown that greater “general cognitive capacity” is associated with more accurate and less variable temporal perception (for recent examples see Brown & Perreault, 2017; Droit-Volet, 2013; Droit-Volet, Wearden, & Zelanti, 2015; Mioni, Mattalia, & Stablum, 2013; Ogden, Samuels, Simmons, Wearden, & Montgomery, 2017; Ogden, Wearden, & Montgomery, 2014; Troche & Rammsayer, 2009).

Importantly, however, not all measures of cognition are related to temporal perception, and the extent to which any measure of cognition is predictive of timing ability is determined by the task used to assess timing (Droit-Volet et al., 2015; Ogden et al., 2014). This is true when looking at the relationship between executive function and temporal perception (Brown, 2006, 2014; Brown, Collier, & Night, 2013; Brown & Perreault, 2017; Droit-Volet & Zelanti, 2013; Fortin Schweickert, Gaudreault, & Viau-Quesnel, 2010; Mioni et al., 2013; Ogden, Salominaite, Jones, Fisk, & Montgomery, 2011; Ogden et al., 2014; Zelanti & Droit-Volet, 2011, 2012). Miyake et al., (2000) fractionated executive processes into three core functions; updating, switching and inhibition. Updating refers to an individual’s ability to monitor incoming information and update the contents of working memory accordingly. Switching refers to an individual’s ability to switch their attention between tasks or different elements of the same task. Inhibition refers to an individual’s ability to inhibit or supress a dominant or automatic response. Fisk and Sharp (2004) added a fourth component, access, which refers to the efficiency with which an individual can access the contents of semantic memory.

Typically, studies show that accuracy of performance on a temporal generalization task (where people have to judge whether or not a comparison stimulus has the same duration as a previously-presented standard, see Wearden, 1992, for examples) is influenced by updating and access to semantic memory (Droit-Volet et al., 2015; Ogden et al., 2014). Better updating and access capacity are associated with more accurate, less variable generalization performance. Temporal bisection (where people receive examples of short and long standard durations and then have to judge whether each comparison stimulus is more similar in duration to the short or long standard) is influenced by inhibition (Droit-Volet et al., 2015; Ogden et al., 2017) and, when the long/short ratio is very small, access to semantic memory (Ogden et al., 2017). Better inhibitory capacity and access capacity are associated with less variable performance as indexed by the Weber Ratio (WR), a measure of temporal sensitivity discussed in more detail later in this article. Verbal estimation performance, however, is unrelated to executive capacity (Ogden et al., 2014), perhaps suggesting that tasks requiring categorical decisions (generalization and bisection) are sub-served by different executive functions to non-categorical tasks.

Individual differences studies have proved successful in demonstrating "between task" differences in executive recruitment (for example, task X uses different executive resources to task Y), however, they have not been used to test how component processes within a timing task relate to executive resources. For example, in a temporal generalization or bisection task, which executive resources are involved in retrieving standard durations from reference memory? This type of analysis can be achieved by comparing the way in which different variants of the same temporal task recruit executive resources.

Temporal bisection and temporal generalization have two forms; normal and episodic (Wearden & Bray, 2001). In the normal variant of temporal generalization participants are presented with a standard duration which they are told to compare to multiple subsequent comparison durations. The learnt standard is valid for multiple trials throughout the task and is therefore thought to be stored in reference memory (Wearden, 1992, 2004). In the episodic variant of temporal generalization, participants are presented with a pair of stimuli and have to judge whether or not they are equal in duration. The durations of the stimuli presented vary from trial, so are not therefore thought to be stored in reference memory but, instead, in STM.

In the normal variant of bisection, participants learn standard durations labelled as short and long: they are then asked to decide whether multiple subsequently presented comparison stimuli are more similar in duration to the short or the long standard. As the standards are valid for multiple trials they are thought to be stored in reference memory, whereas the comparisons are stored in STM. In the episodic variant of bisection, participants are presented with a short standard, a long standard and a single comparison stimulus on each trial. Their task is to decide whether the comparison is more similar in duration to the short or the long standard. The short and long "standards" are only valid for a single trial and are therefore not thought to be encoded into reference memory. By comparing the executive functions associated with these normal and episodic tasks, we may be able to establish which executive functions are involved in the encoding and retrieval of duration from long-term reference memory.

Current models of generalization and bisection suggest that in normal task variants the contents of reference memory and STM are compared (e.g., Allan & Gibbon, 1991, Wearden 1991) but in episodic tasks reference memory is not used (Wearden, 2004, Wearden & Bray, 2001). These models fit the data well and are supported by the framework of Scalar Expectancy Theory in which two separate memory stores are posited (Gibbon, Church, & Meck, 1984). However, Wearden and Ferrara (1995) demonstrated that bisection could be performed in the absence of specifically labelled standard durations. This suggests that models, like those of Allan and Gibbon (1991) and Wearden (1991), which assume that the task is performed by comparing the to-be-judged stimulus with the standards are inadequate. One way to address the problem of exactly which underlying processes are involved in particular tasks is to establish whether the cognitive processes implicated in a model which is used to account for the task (e.g., storage and retrieval of standard from long-term memory) correspond to the cognitive functions which are predictive of performance on that task.

The current study therefore aimed to establish whether different executive resources were recruited during normal and episodic temporal generalization and bisection tasks. Participants completed four tasks designed to assess the executive functions of updating (N-back, Kirchner, 1958), switching (number-letter task, Rogers & Monsell, 1995), inhibition (Random Letter Generation, Baddeley, 1998) and access to semantic memory (Chicago Word Fluency Test, Thurstone & Thurstone, 1938). These functions and tasks were selected because of their previous association with temporal perception. Participants also completed eight temporal tasks: easy and difficult versions of normal and episodic temporal generalization, and easy and difficult versions of normal and episodic bisection. The relationships between measures of timing and executive function were tested.

The primary hypothesis was that performance on the “normal” task variants would be related to access to semantic memory whereas performance on the “episodic” task variants would not be. Forming a representation of the standard for later retrieval, would require access to semantic memory because the participant would have to encode new information (i.e., the perceived duration of a stimulus) to their existing representation of the word “standard”. The efficiency and accuracy of this encoding and retrieval would therefore be positively related to timing task performance, as has been found in other studies (Ogden, et al., 2014; Ogden et al., 2017). In contrast, it was not expected that access to semantic memory would be related to episodic task performance, as models of episodic task performance do not suppose the use LTM because the stimuli presented are only valid for a single trial (Wearden, 2004; Wearden & Bray, 2001).

Further hypotheses were developed for the remaining three executive functions: Updating was expected to be positively related to normal generalization performance, as in Ogden et al., (2014). This reflects the use of updating when performing multiple retrievals of the standards from LTM whilst maintaining the comparisons in working memory. Episodic generalization requires two stimuli to be encoded and retained over a short delay; therefore, updating ability may be positively related to episodic generalization performance. Previous research has not found a relationship between updating and bisection performance (Ogden et al., 2017), perhaps reflecting that bisection appears to impose a lower cognitive demand than generalization. It was therefore expected that updating capacity would not be related to normal or episodic bisection.

Inhibition ability was expected to be positively related to normal bisection performance (Droit-Volet et al., 2015; Ogden et al., 2017). Droit-Volet et al., (2015) suggest that this relationship reflects the use of inhibitory control to supress the prepotent response “short”. Short is thought to be prepotent in bisection because durations are first short before they are long, and, because populations with poor inhibitory control produce a greater number of short than long responses on bisection tasks (Droit-Volet & Rattat, 2007). Although no previous studies have explored the relationship between inhibition and episodic bisection we expect similar relationships to be observed wherein inhibitory control will influence the ability to inhibit the prepotent response “short” which will affect task performance. For updating, access and inhibition it was expected that stronger relationships between executive function and task performance would be observed for the hard than the easy temporal tasks. Previous research has not demonstrated a relationship between task switching ability and temporal generalization or bisection performance (Ogden et al., 2014; Ogden et al., 2017). Therefore, it was not expected that task switching ability would relate to any measure of timing performance.

Method

Participants

Forty-five Liverpool John Moores University students (mean age = 22.20 years, SD = 3.69, 18 male) were paid £15 for participating. Payment was not contingent on performance.

Apparatus

An IBM compatible computer running Microsoft Windows and a 17" LCD monitor were used to present and record experimental events. For the temporal generalization, temporal bisection and N-back tasks, stimulus presentation and recording of keyboard responses were controlled via E-Prime version 2.0 (Psychology Software Tools, Inc., Pittsburgh, PA). The Random Letter Generation task (RGL) task, the number-letter task, were programmed in MS-DOS. Responses on the Chicago Word Fluency Task (CWFT) were recorded with a pen and answer sheet and timed with a stop-watch.

Procedure

Participants were tested in a single experimental session lasting approximately 90 minutes. Participants completed 12 tasks in a pseudo-random order which ensured that participants did not complete more than three temporal tasks in a row. Temporal perception was assessed using four types of task: normal temporal generalization, episodic temporal generalization, normal temporal bisection, episodic temporal bisection. All participants completed an easy and a hard version of each temporal task, giving a total of eight timing tasks. Executive function was assessed using four tasks designed to assess the executive functions identified by Miyake et al., (2000) and Fisk & Sharp (2004); updating, inhibition, switching and access to semantic memory. Updating was assessed using the N-back task (Kirchner, 1958). Inhibition was assessed using random letter generation (RLG, Baddeley, 1998). Switching was assessed using the number letter task (adapted from Rogers & Monsell, 1995). Access was assessed with the Chicago Word Fluency Test (Thurstone & Thurstone, 1938). Participants were advised that they could take breaks between each of the tasks.

Normal Temporal Generalization: Easy

Participants were informed that they would be presented with a standard duration which would be followed by some comparison durations. Participants were told that their task was to decide whether each comparison had the same duration as the standard or not. At the start of each block of trials, participants were presented with three presentations of the standard duration. The standard duration was a 400 ms 500 Hz tone. Each presentation of the standard was followed by a delay, the duration of which was drawn from a uniform distribution ranging from 1000-1500 ms. Following the presentations of the standard, participants were informed that they would be presented with some comparisons durations. The comparison durations were 100, 200, 300, 400 (presented twice in each block), 500, 600 and 700 ms 500 Hz tones. Following each comparison, participants were asked to indicate whether it had the same duration as the standard pressing Y for yes or N for no. A total of five blocks were presented. No feedback was given.

Normal Temporal Generalization: Hard

All experimental details were the same as for the easy version of the normal temporal generalization task, except that the standard duration was 400 ms and the comparison durations were 250, 300, 350, 400 (presented twice in each block), 450, 500 and 550 ms.

Episodic Temporal Generalization: Easy

Participants were informed that they would be presented with two tones and that their task was to decide whether the tones were the same length. Both stimuli were presented as 500Hz tones and their presentation was separated by a delay, the duration of which was drawn from a uniform distribution ranging from 400-600 ms. On 50% of trials the first tone was 400 ms. On the remaining 50% of trials the duration of the first tone was selected at random from a uniform distribution ranging from 200-600 ms. The duration of the second tone was determined by multiplying the standard by .25, .50, .75, 1.00 (presented twice in each block), 1.25, 1.50 and 1.75. Following the presentation of both tones participants were asked to indicate whether the tones were the same length by pressing Y for yes or N for no. A total of trials 80 were presented.

Episodic Temporal Generalization: Hard

All experimental details were the same as for the easy version of the episodic temporal generalization task however the duration of the second tone was derived by multiplying the first tone by .625, .750, .875, 1.00 (presented twice in each block), 1.125, 1.250, 1.375.

Normal Temporal Bisection: Easy

Participants were informed that they would be presented with two standard durations, one labelled as short and one as long, which would be followed by a series of comparison durations. Participants were told that their task was to decide whether the duration of each comparison was more similar to the short or long standard. At the start of each block participants were presented with three examples each of the short standard (200 ms) and three examples of the long standard (800 ms). A delay, the duration of which was drawn at random from a uniform distribution ranging from 500-1,000 ms, was interposed between each presentation of the standards. Following the presentation of the standards, comparison durations were presented and participants were instructed to indicate whether each comparison was more similar to the short or long standard by pressing the S key on the keyboard for short and the L key for long. Each block contained 7 comparison stimuli; 200, 300, 400, 500, 600, 700 and 800 ms, presented in a random order. Standards and comparisons were 500 Hz tones. Five blocks of comparisons were completed by each participant giving a total of 35 trials. No performance feedback was provided.

Normal Temporal Bisection: Hard

All experimental details were the same as for the easy version of the normal temporal bisection task however the standard durations were 400ms and 800 ms and the comparison durations were 400, 466, 532, 600, 667, 733 and 800ms.

Episodic Temporal Bisection: Easy

Participants were informed that they would be presented with three durations in the form of 500 Hz tones. The first two were described as the short and long standards, the third was labelled as the comparison. Participants were told that their task was to decide whether the comparison (additionally labelled as third tone) was more similar in duration to the short or the long standard, providing their response with the keyboard. No feedback was given. Participants completed 10 blocks, each containing seven trials as described above. In five blocks, the first standard was 200 ms and the second standard 800 ms. Comparisons in these blocks were 200, 300, 400, 500, 600, 700 and 800ms. In the remaining five blocks, the duration of the short standard was drawn at random from a uniform distribution ranging from 100-300 ms. The duration of the long standard was calculated by multiplying in the duration of the first standard by four. Comparison durations in these blocks were then derived by multiplying the duration of the first standard by 1.00, 1.50, 2.00, 2.50, 3.00, 3.50 and 4.00. These trials were included to disguise the repeated use of 200 and 800 ms standard durations. Only data from trials in which the standards were 200 and 800 ms were analysed. In all trials, the presentation of each stimulus was separated by a delay, the duration of which was drawn at random from a 500-750 ms distribution. Trials were presented in a random order.

Episodic Temporal Bisection: Hard

All experimental details were the same as for the easy version of the normal temporal bisection task. However the for five blocks the standard durations were 400 ms and 800 ms and the comparison durations were 400, 466, 532, 600, 667, 733 and 800 ms. For the remaining five blocks, the duration of the first standard was drawn at random from a uniform distribution ranging from 200-600 ms. The duration of the second standard was calculated by multiplying in the duration of the first standard by two. Comparison durations for these blocks were then derived by multiplying the duration of the first standard by 1.00, 1.16, 1.33, 1.50, 1.66 and 2.00.

N-Back (adapted from Kirchner, 1958): updating

A visual N-back task was used to assess working memory updating, at the 2-back level of difficulty. In this continuous performance task, participants are required to monitor letters that are presented sequentially on a computer screen. Participants are required to press one key if the item currently on the screen matches the item presented 2 items back, and another key if the current stimulus does not match the specified item. Stimuli were presented for 1000 ms with an interstimulus interval of 500 ms. Scores were calculated for the number of hits (pressing the correct key when the stimuli matched) and correct rejections (pressing the correct key when the stimuli didn't match). These scores were then used to calculate overall % accuracy which was the number of hits as a percentage of total trials completed.

Random Letter Generation (RLG; Baddeley, 1998): Inhibition

A computer display and concurrent auditory signal was used to pace participants' responses. Participants were asked to speak aloud a letter every time the signal was presented. Each participant was told to avoid repeating the same sequence of letters, to avoid producing alphabetic sequences, and to try to speak each letter with the same overall frequency. Each participant attempted to produce one set of 100 letters at a rate of 1 letter every second. Four separate scores were then calculated: First, the number of alphabetically ordered pairs; second, a repeat sequences score corresponding to the number of times that the same letter pair is repeated; third, a "redundancy" score, which measures the extent to which all 26 letters of the alphabet are produced equally often (0% being truly random); and fourth, the number of letters produced. In the first three cases, higher scores indicate poor performance; in the fourth the opposite is the case. Participants were not informed of the frequency of the computer display to prevent using this as a cue for tapping. A high score indicates poorer inhibitory capacity.

Number-letter Task: Switching

Adapted from Rogers and Monsell (1995) and Miyake et al., (2000), in this task number-letter pairs (e.g., J6) were presented one at a time in one of four quadrants on a computer screen. If the number-letter pair appeared in one of two top quadrants, the participant had to attend to the letter and respond as to whether it was a vowel or a consonant. If it was in the one of the two bottom quadrants, the participant was required to attend to the number and respond to whether it was odd or even. Responses were made via pressing the "Z" key for consonant and odd and the "/" key for vowel and even. The task started with a practice version of three sets. The target was presented in the top half of the screen for 12 trials, then the bottom half for 12 trials and then in a clockwise rotation around all four quadrants for a further 12 trials. The main task then followed the same structure but with 64 trials in each block. The third block of both the practice and main task required participants to switch between making letter and number judgements, meaning that the first two blocks required no switching, whereas the third block did. The switch cost was then calculated as the difference between the average reaction times of the third block and the averages of the first two blocks.

Chicago Word Fluency Test: Access to Semantic Memory

Participants were given four minutes during which their task was to write down as many four-letter words beginning with the letter "C" as they could, excluding any place names, people's names or plurals. As plurals were not allowed, words such as "cars" and any repetitions of words were excluded. Participants wrote their responses on an answer sheet provided for this purpose and scores were calculated as the total number of appropriate words produced.

Results

Temporal generalization

Because of a data recording error, data from the episodic easy condition of one participant were not available, although the participant received all experimental conditions correctly.

The proportion of YES responses (judgements that a comparison duration was the standard in the normal case, or judgements that the two stimuli on the trial had the same duration) is plotted against comparison duration in Figure 1. The upper panel shows data from the easy normal and episodic conditions, the lower panel shows data from the hard normal and episodic conditions.

Figure 1 about here

Inspection of the data shows that peak YES responses occurred when the comparison duration was the standard, or when the two stimuli on the trial had the same duration, in all cases. The normal and episodic conditions appeared to produce different behaviour in both the easy and hard comparisons. This was confirmed by a repeated measures ANOVA showing significant main effects of task (normal vs episodic) $F(1, 43) = 58.38$, $p < .001$ $\eta_p^2 = .58$, difficulty (easy vs hard) $F(1, 43) = 218.90$, $p < .001$ $\eta_p^2 = .84$ and comparison duration $F(6, 258) = 217.18$, $p < .001$ $\eta_p^2 = .84$. There were also significant interactions between task and difficulty $F(1, 43) = 18.23$, $p < .001$ $\eta_p^2 = .30$, difficulty and duration $F(6, 258) = 17.61$, $p < .001$ $\eta_p^2 = .29$, and task, difficulty and duration $F(6, 258) = 6.49$, $p < .001$ $\eta_p^2 = .13$. There was no significant interaction between task and duration $F(6, 258) = .60$, $p = .73$. To further explore these interactions measures of gradient skew and response accuracy and response dispersion were compared.

Table 1 here

Gradient skew

The skew of the gradients was compared using a skew statistic (skew = proportion of YES responses to stimuli longer than the standard – proportion to stimuli shorter than the standard). A repeated measures ANOVA showed no significant effect of task $F(1, 43) = .05$, $p = .83$ or difficulty $F(1, 43) = 1.15$, $p = .30$. There was however a significant interaction between task and difficulty $F(1, 43) = 13.82$, $p = .001$ $\eta_p^2 = .24$. *t*-tests confirmed that for the normal task, skew decreased with increasing task difficulty, whereas for the episodic task skew increased with increasing task difficulty (both $p < .02$).

Response accuracy

Response accuracy was calculated [(proportion of hits + proportion of correct rejections)/2]. Hits was the proportion of YES responses to stimuli that were the standard (normal generalization) or when the two stimuli on the trial were the same (episodic generalization). Correct rejections were the proportion of NO responses to stimuli that were not the standard (normal generalization) or not the same (episodic generalization). A greater score indicates better generalization performance. A repeated measures ANOVA showed a significant effect of difficulty $F(1, 43) = 117.48$, $p < .001$ $\eta_p^2 = .73$ and a significant interaction between difficulty and task $F(1, 43) = 15.27$, $p < .001$ $\eta_p^2 = .26$. There was no significant effects of task $F(1, 43) = .19$, $p = .67$. Accuracy was significantly poorer on the hard episodic than the hard normal tasks ($p < .05$).

Dispersion

Dispersion around the peak was calculated using the *mid3* statistic (Wearden, Wearden, & Rabbitt, 1997). The proportion of YES responses to the standard and the durations either side of the standard were divided by the total proportion of YES responses to all stimuli. Higher values indicate that gradients were more peaked around the standard. A repeated measures ANOVA showed significant effects of task $F(1, 43) = 7.18$, $p < .02$ $\eta_p^2 = .14$ and difficulty $F(1, 43) = 209.04$, $p < .001$ $\eta_p^2 = .83$ and a significant interaction between task and difficulty $F(1, 43) = 7.65$, $p < .01$ $\eta_p^2 = .15$. Gradients were significantly more peaked in the normal than the episodic hard conditions ($p < .001$).

The relationship between temporal perception and executive function

Accuracy

Table 2 shows Pearson's correlation assessing the relationship between temporal generalization accuracy and measures of updating, access, inhibition and switching. Table 2 suggests that accuracy on normal tasks was positively related to updating and access to semantic memory. Accuracy on the easy and hard episodic tasks was only related to access to semantic memory. These relationships were further investigated using multiple regression analysis to test whether executive function significantly predicted temporal generalization accuracy (Table 3). This analysis confirmed that normal generalization performance was predicted by updating and access whereas episodic performance was only predicted by access.

Table 2 about here

Table 3 about here

Dispersion

Table 2 shows Pearson's correlation assessing the relationships between dispersion (indexed by the mid3) and measures of updating, access, inhibition and switching. The dispersion measure was positively related to updating and access for the normal tasks. For the episodic tasks, the easy task was unrelated on any measure of executive function however, the hard task was related to access. Table 3 shows multiple regression analysis testing whether executive function significantly predicted dispersion. Normal task performance was predicted by access and updating. Episodic performance was predicted by access and inhibition. The emergence of inhibition as a predictor of performance despite it not being correlated suggests that inhibition may be a suppressor variable (see Thompson & Levine, 1997 for discussion).

Bisection

Psychophysical functions in the form of the proportion of long responses plotted against stimulus duration are shown in Figure 2. Responding was similar in the four conditions. This was confirmed by a repeated measures ANOVA showing a significant effect of comparison duration *F*(6, 264) = 820.64, $p < .001$ $\eta_p^2 = .95$, but no significant main effects of task (normal vs episodic) *F*(1, 44) = .30, $p = .59$, nor difficulty (easy vs hard) *F*(1, 44) = 1.57, $p = .22$. There was a significant interaction between difficulty and comparison duration *F*(6, 264) = 9.40, $p < .001$ $\eta_p^2 = .18$, but no significant interactions between task and difficulty *F*(1, 44) = 2.85, $p = .12$, task and comparison duration *F*(2, 264) = .14, $p = .22$ and task, difficulty and comparison duration *F*(6, 264) = 1.34, $p = .24$.

Figure 2 about here

The psychophysical function for each individual was analysed to derive two measures, the bisection point, and the Weber ratio. The bisection point is the stimulus duration giving rise to 50% long and 50% short responses. This was derived using a method employed by Maricq, Roberts, and Church (1981), and Wearden (1991). A regression line was fitted to the steepest part of the psychophysical function, and this was used to calculate the stimulus duration which would give rise to 50% long/50% short responses, the bisection point (BP). It was also used to calculate the duration values giving rise to 25 and 75% long responses. Half the difference between these values is the difference limen and half the difference limen divided by the bisection point gives the measure of interest, the Weber Ratio (WR). The WR is a reflection of the steepness of the psychophysical function, and is generally considered to reflect temporal sensitivity: steep curves give rise to smaller WR values, and indicate high temporal sensitivity. For 2 participants in the episodic bisection condition, and one in the normal condition, the BP and WR could not be calculated. Because stimulus durations in easy and hard conditions differ (200 to 800 ms, versus 400 to 800 ms) it is not possible to meaningfully compare the BP for the hard and easy conditions. The bisection points did not differ significantly for the episodic and normal tasks in the easy, *t*(43) = .24, $p = .81$ or hard, *t*(42) = .97, $p = .34$ conditions.

A repeated measures ANOVA conducted on the WR data showed significant effects of difficulty *F*(1, 42) = 63.19, $p < .001$ $\eta_p^2 = .60$ indicating greater sensitivity in the hard conditions. There was no significant effect of task *F*(1, 42) = .35, $p = .56$ and no significant interaction between task and difficulty *F*(1, 42) = .14, $p = .71$.

Table 4 about here

The relationship between temporal bisection and executive function

Bisection point

Table 5 shows Pearson's correlation assessing the relationships between BP and measures of updating, access, inhibition and switching. The BP on normal tasks was related to inhibition, with greater inhibitory control being associated with higher BPs. No significant relationships were observed for the easy episodic BPs. Access and inhibition were related to the hard episodic BP, with greater inhibitory control and access capacity being associated with greater BPs. Table 6 shows multiple regression analysis testing whether executive function significantly predicted BP. Executive functions were not significant predictors of normal hard bisection *F*(4, 39) = 1.19, $p = .33$ or episodic easy bisection *F*(4, 39) = .97, $p = .43$. For the easy normal and the hard episodic tasks, only inhibition was a significant predictor.

Weber Ratio

Table 5 shows Pearson's correlation assessing the relationships between WR and measures of updating, access, inhibition and switching. The only significant relationship was between inhibition and the Weber ratio for the hard episodic task. Multiple regression analysis was used to test whether executive function significantly predicted WR. Executive functions were not predictive of WR in easy normal bisection $F(4, 39) = .46$, $p = .77$, hard normal bisection $F(4, 39) = .39$, $p = .82$, easy episodic bisection $F(4, 39) = 1.56$, $p = .20$ or hard episodic bisection $F(4, 39) = 1.10$, $p = .37$.

Table 5 about here

Table 6 about here

Discussion

Temporal Generalization

Responding on the normal and episodic variants of the temporal generalization task was typical of that seen in other studies (Wearden, 1992; Wearden & Bray, 2001). When comparing the data from the normal and episodic tasks there were some similarities; both typically show rightward skew and both were affected by task difficulty. However, there were also notable differences; firstly, there were more YES responses on the episodic tasks than the normal tasks. Secondly, increasing task difficulty increased skew for the episodic task and decreased skew for the normal task. Therefore, although there are some commonalities, possibly resulting from similar processes involved in deciding whether two stimuli have the same duration, the underlying psychological processes being used appear to differ at least partially.

These suggestions are mirrored in the way in which temporal generalization task performance was related to executive function. Greater access capacity was associated with better performance on the normal and episodic tasks. Updating was only associated with normal task performance and not episodic performance. Greater inhibition capacity was also associated with better performance on the normal (hard) and episodic tasks. Task switching capacity was not predictive of performance on any of the temporal generalization tasks. For the normal task, increasing task difficultly resulted in a greater number of executive resources being related to task performance. Task difficulty did not however influence the way in which episodic temporal generalization performance was related to executive function capacity. Therefore, whilst access and inhibition were predictive of performance on both the episodic and the normal tasks, updating was uniquely associated with normal task performance.

These findings suggest that the behavioural differences observed when comparing normal and episodic generalization are reflected in their associations with executive functions. The ability to update the contents of working memory is uniquely associated with normal, and not episodic, generalization performance. This supports previous findings of relationship between updating and normal temporal generalization performance (Ogden et al., 2014). This relationship may simply reflect that in normal generalization, participants have to maintain and retrieve information about the standard for a longer period of time than in episodic generalization e.g., across a whole block rather than a single trial. Similarly, it may reflect that in normal temporal generalization eight stimuli (comparisons) must be encoded and then removed from memory before the standard is re-presented whereas in episodic generalization only two need encoding and removing. The absence of a relationship between episodic generalization and updating does not necessarily preclude updating resources being used during the task. Instead, it likely reflects the fact the updating load of episodic generalization, in which just two items are stored, is very low, such that both items could just be stored in STM whilst required.

Better normal *and* episodic generalization performance was consistently associated with better access to semantic memory. This finding contradicts our original hypothesis that only normal generalization performance would be associated with semantic memory. SET describes two memory stores which are used during timing, a reference memory store for stimulus valid for more than one trial and a short-term memory store for stimulus valid for a single trial. Because each stimulus in episodic generalization is only valid for one trial, the procedure is thought to discourage the use of reference memory (Wearden & Bray, 2001). One, possible explanation for the association is that both the episodic and normal variants of temporal generalization require participants to access long-term, semantic, representations of duration. Access to semantic memory has previously been found to be associated normal generalization, reproduction and verbal estimation (Ogden et al.,, 2014) perhaps indicates that our ability to access semantic knowledge about duration is critical to our ability to discriminate duration. If this is correct, previous suggestions that episodic tasks do not use LTM appear incorrect. However, an alternative explanation which is discussed later is that the correlations with access result from the measure of access used (verbal fluency) being a component of general intelligence.

Temporal Bisection

The data, in terms of the location of the BP and the size of the Weber ratios, was typical of that found in other studies (Kopec & Brody, 2010; Wearden, 1991; Wearden & Ferrara, 1995). The data strongly suggest that normal and episodic bisection do not differ behaviourally: the proportion of long responses did not differ when episodic and normal bisection, whether easy or hard, was compared. In addition, neither bisection points nor Weber ratios obtained differed across the normal and episodic procedures. The similarity of performance in normal and episodic bisection suggests that the psychological processes underlying the two tasks are the same or very similar. These behavioural similarities were reflected in the associations with executive function. Executive function was not a significant predictor of Weber Ratio for the normal or episodic task variants. Inhibition was a significant predictor of bisection point, but only for the easy normal task and the hard episodic task, suggesting no consistent overall pattern. Critically, no other executive functions were shown to be predictive of any bisection outcome measure.

Current models of “normal” bisection suggest that a response is generated by comparing the contents of reference memory with the contents of LTM. It was therefore expected that access to semantic memory, or updating, would be predictive of performance on the normal bisection task. The absence of an association between access to semantic memory and normal bisection performance suggests that the standards may not be stored in and retrieved from long-term memory in the way described in such models of bisection (see discussion in Wearden, 2016, pp. 71-83). The similarity of performance in normal and episodic bisection, and the absence of an association between access and performance supports Wearden and Ferrara’s (1995) view that presenting standards which are valid for multiple trials is not necessary for performance and that the standards have no special status.

If participants are not using the short and long standards provided to perform the bisection task, the question arises of how they complete the task at all. Droit-Volet and Rattat (2007) have argued for what could be called a “criterion based” approach. Here, each probe stimulus to be timed is compared with some criterion, and if longer than it, a long response is generated. Their experimental work used partition bisection (Wearden & Ferrara, 1995) where no explicit standards are presented and they showed that adults were able to “partition” the probe stimuli into two sets (short and long) rapidly, within a few series of presentations of the stimulus set. They suggested that this behaviour resulted from the very rapid acquisition of a criterion, which was then used to partition the stimulus set.

All of our bisection tasks actually presented Short and Long standards, so one idea is that performance on our tasks was also criterion-based, with the Short and Long standards giving rise to some criterion, *M* (for example the arithmetic mean of the Short and Long standard, although it could be some other value). So, for some probe duration, *t*, a long response occurs when $t > M$, and a short response otherwise. There are two implications of this approach. The first is that normal and episodic bisection will produce identical performance, as we found, as in both cases standards are presented which could give rise to a criterion. The second implication is that doing bisection this way imposes a very low cognitive load on participants because only the criterion needs to be remembered (rather than both standards). Having such a low cognitive load may be the reason why, in our studies, bisection performance did not correlate strongly with most of the measures of cognitive performance assessed by the non-timing tasks. The simple $t > M$ rule is probably too psychologically simple, and a more complex and psychologically plausible criterion-based model, which includes a threshold, is specified in Wearden and Ferrara (1995).

Generalization and bisection: relation to access

Why was performance on both types of generalization related to access, whereas performance on bisection was not? One possibility is that the critical factor is general intelligence. Rammsayer and Brandler (2007) argued that performance on temporal discrimination tasks is correlated with general intelligence, and one possible reason why performance on both generalization tasks correlates with access is that the verbal fluency measure used to measure access also taps a component of general intelligence. Generalization appears more cognitively demanding than bisection; in the episodic generalization task some stimuli to be discriminated differed in duration by as little as 25%, even in the easy condition, which is a much smaller difference than between the Short and Long standards in bisection, even in our hard conditions. Thus, the association between access and generalization may reflect the fact that it has a greater cognitive load than bisection, if this is performed with a cognitively undemanding criterion-based rule.

This suggestion is supported by previous evidence that temporal generalization performance is related to general intelligence, whereas bisection performance is not. Wearden et al., (1997) found that temporal generalization performance was affected by both age (independent of general intelligence), and intelligence (independent of age), when data from their sample of people from 60 to 80 years old were analysed. In contrast, bisection performance was not affected by either these variables. McCormack, Brown, Maylor, Darby and Green (1999) replicated the result that bisection performance was unaffected by age in their sample of older people, whereas temporal generalization performance was, although IQ was not controlled for in their study, it is possible that their results were also due, at least partially, to intelligence differences between the groups, as IQ will normally decline with age in unselected populations (Salthouse, 1991).

Conclusion

The findings of this study suggest that normal and episodic variants of bisection impose a low cognitive load. Both tasks appear to be performed in similar ways, using similar cognitive resources and there is little evidence that either are using reference memory in the ways described by common models of bisection (e.g., Allan & Gibbon 1991; Wearden 1991). In contrast, normal and episodic generalization differ from one another, and may impose a higher cognitive load than bisection resulting in greater recruitment of executive resources. Performance on both is associated with access to semantic memory, indicating that both tasks are drawing on some long-term memory representations of duration, or, that performance on both tasks is affected by general intelligence. At present, it is not possible distinguish between these two suggestions. Although our tasks of executive function are standard ones used in many studies, each task may not be a pure measure of executive function (see Lehto, 1996 and Miyake et al., 2000 for discussion). However, we chose the tasks because they were conventional ones on which performance has previously been shown to be related to timing. Our results suggest that the measure of LTM function, in particular, may need some refinement, and perhaps a non-verbal test of LTM function may help to further clarify when and how reference memory/LTM is used in timing. Together, however, the findings demonstrate that "predictive" studies can be used to inform models of temporal perception.

References

Allan, L. G., & Gibbon, J. (1991). Human bisection at the geometric mean. *Learning and Motivation*, *22*, 39-58.

Baddeley, A. (1998). Random generation and the executive control of working memory. *Quarterly Journal of Experimental Psychology*, *51*, 819-852.

Brown, S. W. (2006). Timing and executive function: Bidirectional interference between concurrent temporal production and randomization tasks. *Memory & Cognition, 34*, 1464–1471.

Brown, S. W. (2014). Involvement of shared resources in time judgment and sequence reasoning tasks. *Acta Psychologica*, *147*, 92-96.

Brown, S. W., & Perreault, S. T. (2017). Relation between temporal perception and inhibitory control in the Go/No-Go task. *Acta Psychologica*, *173*, 87-93.

Brown, S. W., Collier, S. A., & Night, J. C. (2013). Timing and executive resources: Dual-task interference patterns between temporal production and shifting, updating, and inhibition tasks. *Journal of Experimental Psychology: Human Perception and Performance, 37,* 947-963.

Droit-Volet, S. (2013). Time perception in children: A neurodevelopmental approach. *Neuropsychologia, 51,* 220–234.

Droit-Volet, S., & Rattat, A. C. (2007). A further analysis of time bisection behavior in children with and without reference memory: The similarity and the partition task. *Acta Psychologica*, *125*, 240-256.

Droit-Volet, S., Wearden, J. H., & Zelanti, P. S. (2015). Cognitive abilities required in time judgment depending on the temporal tasks used: a comparison of children and adults. *Quarterly Journal of Experimental Psychology*, *68*, 2216-2242.

Droit-Volet, S., & Zélanti, P. S. (2013). Development of time sensitivity and information processing speed. *PLoS ONE, 8, e71424.*

Fisk, J. E., & Sharp, C. (2004). Age-related impairment in executive functioning: updating, inhibition, shifting, and access. *Journal of Clinical Experimental Neuropsychology, 26*, 874-890.

Fortin, C., Schweickert, R., Gaudreault, R., & Viau-Quesnel., C. (2010). Timing is affected by demands in memory search but not by task switching. *Journal of Experimental Psychology: Human Perception and Performance, 36,* 580-595.

Gibbon, J., Church, R. M., & Meck, W. H. (1984). Scalar timing in memory. In J. Gibbon & L. Allan (Eds.), *Annals of the New York Academy of Sciences: Vol. 423. Timing and time perception* (pp. 52–77). New York: New York Academy of Sciences.

Kirchner, W. K. (1958). Age differences in short-term retention of rapidly changing information. Journal of Experimental Psychology, *55*, 352-358.

Kopec, C. D., & Brody, C. D. (2010). Human performance on the temporal bisection task. *Brain and Cognition*, *74*, 262-272.

Lehto, J. (1996). Are executive function tests dependent on working memory capacity? *Quarterly Journal of Experimental Psychology*, *49*, 29-50.

Maricq, A. V., Roberts, S., & Church, R. M. (1981). Methamphetamine and time estimation. *Journal of Experimental Psychology: Animal Behavior Processes*, *7*, 18-30.

McCormack, T., Brown, G. D., Maylor, E. A., Darby, R. J., & Green, D. (1999). Developmental changes in time estimation: Comparing childhood and old age. *Developmental Psychology*, *35*, 1143-1155.

Mioni, G., Mattalia, G., & Stablum, F. (2013). Time perception in severe traumatic brain injury patients: A study comparing different methodologies. *Brain and Cognition, 81,* 305-312.

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A. & Wager, T. D. (2000). The unity and diversity of executive functions, and their contributions to complex “frontal lobe” tasks: a latent variable analysis. *Cognitive Psychology, 41,* 49–100.

Ogden. R. S., Salominaite, E., Jones, L. A., Fisk, J. E., & Montgomery, C. (2011). The role of executive functions in human prospective interval timing. *Acta Psychologica, 137,* 352-358.

Ogden, R. S., Samuels, M., Simmons, F., Wearden, J., & Montgomery, C. (2017). The differential recruitment of short-term memory and executive functions during time, number and length perception: An individual differences approach. *Quarterly Journal of Experimental Psychology*, (just-accepted), 1-24.

Ogden, R. S., Wearden, J. H., & Montgomery, C. (2014). The differential contribution of executive functions to temporal generalisation, reproduction and verbal estimation. *Acta Psychologica*, *152*, 84-94.

Rammsayer, T. H., & Brandler, S. (2007). Performance on temporal information processing as an index of general intelligence. *Intelligence*, *35*, 123-139.

Rogers, R. & Monsell, S. (1995). Costs of a predictable switch between simple cognitive tasks. *Journal of Experimental Psychology: General, 124*, 207-231.

Salthouse, T.A. (1991). *Theoretical perspectives on cognitive aging*. Hillsdale, N.J.: Erlbaum.

Thompson, F. T., & Levine, D. U. (1997). Examples of easily explainable suppressor variables in multiple regression research. *Multiple Linear Regression Viewpoints*, *24*, 11-13.

Thurstone, L. L. & Thurstone, T, G. (1938). *Primary Mental Abilities*. Chicago: University of Chicago Press

Troche, S. J., & Rammsayer, T. H. (2009). The influence of temporal resolution power and working memory capacity on psychometric intelligence. *Intelligence*, *37*, 479-486.

Wearden, J.H. (1991). Human performance on an analogue of an interval bisection task. *Quarterly Journal of Experimental Psychology*, *43B*, 59-81.

Wearden, J. H. (1992). Temporal generalization in humans. *Journal of Experimental Psychology: Animal Behavior Processes, 18,* 134–144.

Wearden, J. H. (2004). Decision processes in models of timing. *Acta Neurobiologiae Experimentalis*, *64*, 303-318.

Wearden, J. (2016). *The Psychology of Time Perception*. Palgrave Macmillan, UK.

Wearden, J.H., & Bray, S. (2001). Scalar timing without reference memory? Episodic temporal generalization and bisection in humans. *Quarterly Journal of Experimental Psychology*, *54B*, 289-309.

Wearden, J. H., & Ferrara, A. (1995). Stimulus spacing effects in temporal bisection by humans. *Quarterly Journal of Experimental Psychology*, *48*B, 289-310.

Wearden, J. H., Wearden, A. J., & Rabbitt, P. M. A. (1997). Age and IQ effects on stimulus and response timing. *Journal of Experimental Psychology: Human Perception and Performance*, *23*, 962-979.

Zélanti, P., & Droit-Volet, S. (2011). Cognitive abilities explaining age-related changes in time perception of short and long durations. *Journal of Experimental Child Psychology, 109,* 143–157.

Zélanti, P., & Droit-Volet, S. (2012). Auditory and visual differences in time perception? An investigation from a developmental perspective with neuropsychological tests. *Journal of Experimental Child Psychology, 112*, 296–311.

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Table 1: Mean measures of skew, accuracy and dispersion for the four temporal generalization tasks.

Task	*Skew (SD)*	*Accuracy (SD)*	*Dispersion*
Normal Easy	.42 (.71)	.80 (.10)	.86 (.14)
Normal Hard	.14 (.86)	.70 (.11)	.69 (.14)
Episodic Easy	.25 (.41)	.82 (.07)	.85 (.12)
Episodic Hard	.50 (.48)	.66 (.11)	.60 (.15)

Table 2: The relationship between temporal generalization accuracy and dispersion and executive function.

Measure	*Task*	*Updating*	*Switching*	*Inhibition*	*Access*
Accuracy	*Easy Normal*	.40*	-.28	-.18	.30**
	Hard Normal	.45**	-.02	.12	.49**
	Easy Episodic	.24	.20	.02	.45**
	Hard Episodic	.20	.08	.15	.38**
Dispersion	*Easy Normal*	.47**	-.15	.06	.34*
	Hard Normal	.47**	-.03	.12	.43**
	Easy Episodic	.11	.27	.29	.25
	Hard Episodic	.27	.12	.19	.34*

*= p<.05, **= p<.01

Table 3: Regression analysis of the relationship between temporal generalization accuracy, dispersion and executive function.

Measure	*Task*	*adj.* R^2	*Executive Function*	β	B	*SE* B
Accuracy	*Easy Normal*	.20*	Updating	.34*	.58	.09
	Hard normal	.35***	Updating	.37**	.32	.11
			Access	.42**	.01	.01
			Inhibition	.30*	.02	.01
	Easy Episodic	.19*	Access	.46**	.01	.01
	Hard Episodic	.14*	Access	.44**	.01	.01
Dispersion	*Easy Normal*	.24**	Updating	.40**	.45	.16
	Hard normal	.33***	Updating	.37**	.40	.14
			Access	.40**	.10	.04
	Easy Episodic	.17*	Access	.34*	.01	.01
			Inhibition	.36*	.02	.01
	Hard Episodic	.17*	Access	.38*	.01	.01
			Inhibition	.30*	.02	.01

*= *p*<.05, ** = *p*<.01, ***= *p*<.001

Table 4: Mean bisection point and Weber ratios for the four bisection tasks.

Task	*Bisection Point (SD)*	*Weber Ratio (SD)*
Normal Easy	485.01 (101.09)	.15 (.04)
Normal Hard	563.51 (58.84)	.09 (.03)
Episodic Easy	479.76 (69.66)	.14 (.05)
Episodic Hard	574.52 (63.64)	.11 (.05)

Table 5: The relationship between bisection point, Weber ratio and executive function

		Updating	*Switching*	*Inhibition*	*Access*
WR	*Easy Normal*	-.25	-.06	-.41*	.07
	Hard Normal	-.02	.07	-.31*	.23
	Easy Episodic	.26	.09	.07	-.03
	Hard Episodic	.08	.13	-.37*	.32*
BP	*Easy Normal*	-.18	-.04	.03	-.02
	Hard Normal	-.13	.14	.05	-.04
	Easy Episodic	.08	.19	-.25	.08
	Hard Episodic	.10	-.04	-.31*	.02

**=p<.05*

Table 6: Regression analysis of the relationship between BP and executive function. Note that no significant model fits could be found for BP hard normal and easy episodic, nor for any of the WR analysis.

Measure	*Task*	*adj.* R^2	*Executive Function*	β	B	*SE* B
BP	*Easy Normal*	.21*	Inhibition	-.46*	-24.72	7.96
	Hard Episodic	.16*	Inhibition	-.37*	-12.84	5.21

*= p<.05, ** = p<.01, ***= p<.001

Figure 1: Temporal generalization gradients showing the proportion of Yes responses plotted against the comparison duration. Error bars show standard error of the mean. The upper panel shows data from the easy normal and episodic tasks. The lower panel shows data from the hard normal and episodic tasks.

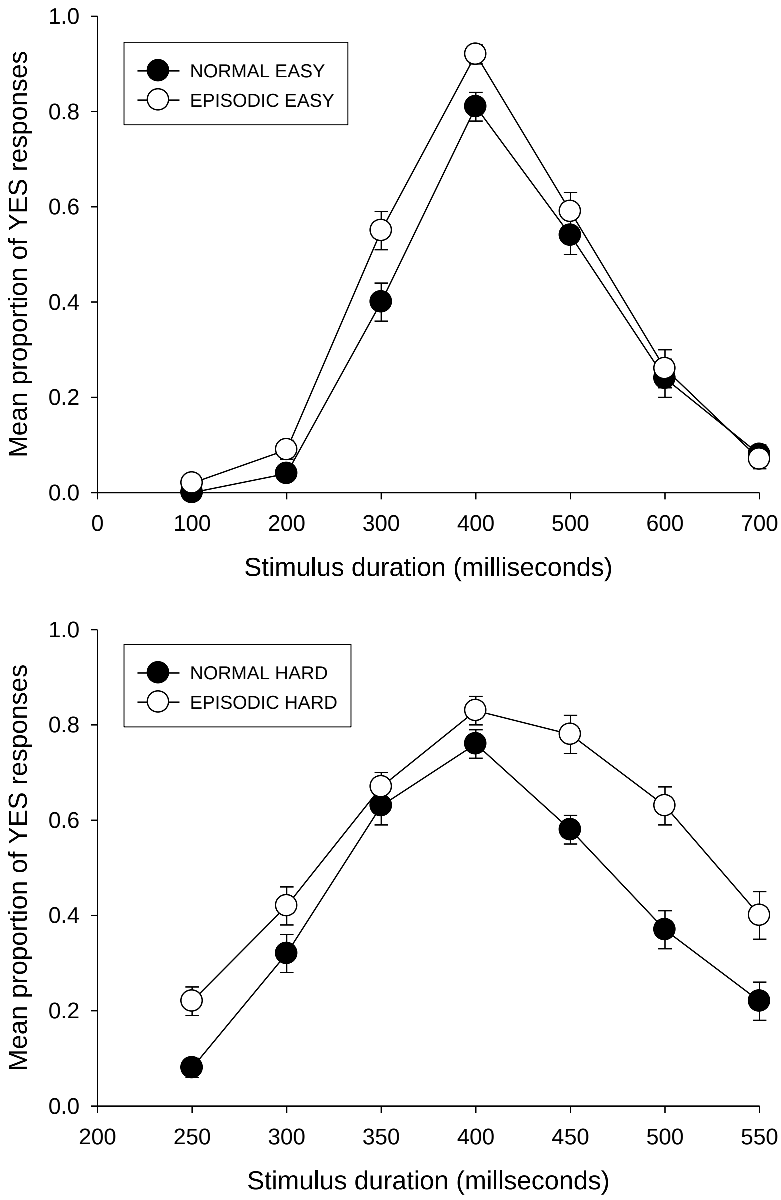

Figure 2: Psychophysical functions showing the proportion of Long responses plotted against the comparison duration. Error bars show standard error of the mean. The upper panel shows data from the easy normal and episodic tasks. The lower panel shows data from the hard normal and episodic tasks.