Why additional presentations help identify a stimulus

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Abstract

Nosofsky (1983) reported that additional stimulus presentations within a trial increase discriminability in absolute identification, suggesting that each presentation creates an independent stimulus representation, but it remains unclear whether exposure duration or the formation of independent representations improves discrimination in such conditions. Experiment 1 replicated Nosofsky's result. Experiments 2 (masking the ISI between two presentations) and 3 (manipulating stimulus duration without changing number of presentations or overall trial duration) ruled out an explanation in terms of extended opportunities for stimulus sampling, from either a sensory buffer during additional ISIs or increased stimulus exposure, respectively. Experiment 4 (comparing two and three presentations, other factors controlled) provided some limited additional support for Nosofsky's original claim that additional stimulus presentations can create either independent or duplicate representations. Experiments 5 and 6 (both manipulating ISI) demonstrated that a key factor in the additional stimulus presentation effect is the overall trial duration. We discuss the results in relation to models of absolute identification, their relative emphasis on stimulus sampling versus response selection, and the mechanisms by which duplicate representations could be created.

Keywords: Absolute identification; stimulus sampling; perceptual cognition; mathematical models.

Why additional presentations help identify a stimulus

In absolute identification participants must identify the rank position of a randomly selected stimulus drawn (with replacement) from a set of stimuli that vary (typically in equal psychophysical increments) along a single psychological dimension, such as pitch or length (see Stewart, G.D.A. Brown, & Chater, 2005 for a review). Once a response is given, feedback (the correct response) is usually given. The most perplexing aspect of absolute identification is its overall difficulty, considering the simplicity of the task. Participants perform surprisingly poorly when as few as six stimuli (and response options, Lacouture, Li, & Marley, 1998) are used (e.g., Miller, 1956) and typically improve only very slightly with practice (e.g., Lacouture, et al., 1998; Nosofsky & Shiffrin, 1994; but see Rouder, Morey, Cowan, & Pfaltz, 2004). Moreover, when information transmitted is measured, a dimension-specific upper limit is obeyed with increases in the number of stimuli. This severe performance limit is found no matter what stimulus modality or single psychological dimension is used, suggesting a modality independent limitation in the cognitive system (see S. D. Brown, Marley, Donkin, & Heathcote, 2008, and Stewart et al., 2005, for a review of the typical findings). The simplicity of the task, combined with the severe performance limit, has intrigued theorist for a long time (e.g., Wever & Zener, 1928) with considerable interest recently (e.g., S. D. Brown et al., 2008; Kent & Lamberts, 2005; Lacouture & Marley, 2004; Mathews & Stewart, 2009; Stewart et al. 2005; Petrov & Anderson, 2005).

Current theories of absolute identification differ in the emphasis they place on the mechanisms underlying performance. In particular, the Extended Generalized Context Model, (EGCM; Kent & Lamberts, 2005) emphasizes the perceptual

processing stage of identification. According to the model, over time, perceptual information is repeatedly sampled and accumulated to build a representation of the stimulus. In categorization, the sampled elements correspond to separable dimensions (Lamberts, 1998), but in the application to absolute identification, each dimension is composed of multiple elements contributing to discriminability. This gradual build-up of information means that the perceptual representation (and its relation to other representation in memory) changes over time from a relatively ambiguous representation to a distinct representation of the stimulus. In the model, a probabilistic response is made once a probabilistic threshold on available perceptual information is reached.

The centrality of the perceptual sampling process in the EGCM differentiates it from other models of absolute identification. In the EGCM, the time course of the perceptual sampling process links the identification response and the time it takes to make the response. In contrast, other models such as the Relative Judgment Model (RJM; Mathews & Stewart, 2009; Stewart et al., 2005) and the Selective Attention, Mapping, and Ballistic Accumulator model (SAMBA; S. D. Brown et al., 2008) place more emphasis on the response selection stage of identification. Both these models assume a process of ballistic accumulation of evidence for each response (S. D. Brown & Heathcote, 2005). Each accumulator's activation (and accumulation rate) is determined by the competition amongst accumulators and the response strength for that accumulator. However, the RJM and SAMBA differ in the type of input that is fed to the accumulators. In SAMBA, the response strengths are determined by the output of a mapping process that maps the estimate of the stimulus magnitude onto the response accumulators. In RJM, the response strengths are determined by a spread of activation arising from recent feedback on the difference between the

current and the last (or last-but-one) stimulus. In either model, an identification response is selected when one of the accumulators reaches a given threshold. Thus in SAMBA and the RJM, perceptual processes play a relatively minor role in comparison with the EGCM.

Evidence for the importance of perceptual processes in absolute identification comes from Nosoksky's (1983) experiments using multiple within-trial stimulus presentations. Presenting additional presentations during a trial tests the ability to extract and integrate perceptual information over time. Current models do not currently have mechanisms that allow them to make predictions about the impact of additional stimulus presentations, making this an important area for further research. Nosofsky required participants to respond either after all stimulus presentations when there were one, two, three or four stimulus presentations in a trial (Experiment 1) or after every presentation when each trial consisted of four stimulus presentations (Experiment 2). Nosofsky reported increased discriminiability with increased stimulus presentations across both experiments, concluding that each presentation creates an independent representation, and these representations are then averaged to give a less noisy overall stimulus representation. However, there are alternative interpretations of the multiple presentation effect, which are not ruled out by Nosofsky's experiments.

One explanation for the increased discriminability with increased stimulus presentations is that, rather than the actual additional presentation(s), the related increase in stimulus exposure time improved performance. This explanation is consistent with the findings of Ward (1991) and Hsieh and Saberi (2007) that demonstrated increasing exposure duration increases accuracy in an absolute identification task. However, Nosofsky (1983) suggested that pilot work had shown that stimulus repetition had a greater effect on performance than increasing exposure

time in absolute identification. Thus, it remains unclear whether exposure duration or the formation of independent representations within an absolute identification trial was responsible for the improved discrimination with additional presentations described by Nosofsky (1983).

As well as the overall increase in stimulus duration, in the design used by Nosofsky (1983), stimulus sampling could also have taken place during the inter-stimulus intervals (ISIs), the number of which increased with every additional presentation. It is possible that a short-term sensory buffer could be sampled during each ISI unless the ISI is masked (e.g., Loftus, Duncan, & Gehrig, 1992; Loftus & McLean, 1999; Massaro, 1972a). Moreover, other, non-perceptual, processes may occur during the ISI and throughout the trial, suggesting that overall trial length should also be a concern.

The experiments presented here address the concerns with the method used by Nosofsky (1983) and are designed to determine whether the effect of additional presentations is caused by the increased opportunity for stimulus sampling, because total stimulus exposure duration is increased, because of the introduction of an additional ISI, and/or because total processing time is increased. As well as extending the findings of Nosofsky (1983) we investigate the nature of the processes underlying stimulus sampling and the flexibility of the cognitive system to integrate perceptual information from additional discrete stimulus presentations in absolute identification. We also investigate response times (RTs) in an attempt to gain a more complete understanding of the nature of the component processes underlying absolute identification and provide a robust set of data to constrain future models.

The cause of the additional presentation effect will have important implications for how models of absolute identification implement a stimulus sampling

mechanism. If the additional presentation effect were caused by increasing exposure duration, this would suggest that information can be effectively accumulated into a single representation across successive presentations of the same stimulus in an absolute identification task. If the additional presentation effect is not caused by increasing stimulus exposure, this would suggest that perceptual information from each additional stimulus presentation is represented independently and perhaps integrated at a later stage by a mechanism that averages over perceptual representations (e.g., Nosoksky, 1983, Schwarz & Kühn, 2008).

Overview of Experiments 1 to 4

Experiments 1 to 4 examined possible perceptually-based processes underlying the increase in discriminability with additional stimulus presentations within a trial in Nosofsky's (1983) absolute identification experiments. For each experiment, we used two ($N = 6$) sets of stimuli presented in different modalities: tones varying in frequency (experiments suffixed with 'a') and distance between two dots (experiments suffixed with 'b'). A different group of participants were used for each stimulus modality. All experiments involved two within-subject conditions (that varied between experiment) randomly intermixed[1]; we now describe those conditions In Experiment 1, a stimulus was presented once or twice, whereas in Experiments 2-4 a stimulus was always presented at least twice. In Experiments 2-4, the time between the first onset and the offset of the last stimulus was controlled and a pre-mask was presented before the first presentation and a post mask was presented after the offset of the final stimulus presentation.

Experiment 1 attempted to replicate Nosofsky's (1983) finding that additional stimulus presentations within a trial increased discrimination. The crucial manipulation in Nosofsky's experiments and our Experiment 1 was the number of times a stimulus was presented, see Figure 1a. In Nosofsky's Experiment 1, stimuli were presented one to four times, but the greatest gain in discriminability was observed between one presentation and two presentations, and so we used one and two presentations in Experiment 1.

Experiment 2 examined whether the benefit in discrimination for two stimulus presentations compared to one stimulus presentation was, at least in part, due to additional stimulus sampling from a short-term sensory buffer during the ISI (e.g., Massaro, 1972a, b; Sperling, 1959). On each trial of Experiment 2, the stimulus was presented twice with either a mask presented between stimulus presentations, serving to prevent additional sensory buffer sampling (Loftus & McClean, 1999; Sperling, 1963), or no mask, see Figure 1b.

In Experiment 3, the overall exposure duration of the stimulus was manipulated to examine whether the additional stimulus sampling time afforded by the additional presentation was responsible for the improved discriminability. On each trial, a stimulus was presented twice, either for a total of 500 ms or for a total of 250 ms. Importantly, the time from the start of the trial to the offset of the final stimulus was held constant, see Figure 1c.

In Experiment 4, the number of additional stimulus presentations during a trial, either two or three, was manipulated. Crucially, unlike Nosofsky's (1983) experiments, total stimulus exposure time was held constant along with the time from the start of the trial to the final stimulus offset. The ISI when two stimuli were

presented was twice that of each ISI when three stimuli were presented, equating total non-stimulus time, see Figure 1d.

General Method

Participants. 112 (74 female) participants took part, with 28 participants per experiment (14 per modality). Participants were mostly students from the University of Warwick paid £6 (approximately $9) per hour. Participants were excluded if their accuracy was less than 25% correct, resulting in exclusion of four participants: one participant from each of Experiments 1b, 2a, 3a, and 3b. In addition, one participant was excluded from Experiment 2b because they used response '6' on less than 1% of the trials.

Apparatus and Stimuli. Pentium 4 computers were used for stimulus presentation and response registration. In the auditory task, participants sat 100 cm from the center of a 17-inch Cathode Ray Tube (CRT) monitor used to display instructions and other visual cues. Auditory stimuli were presented binaurally through Plantronics Audio 90 Headphones via a SigmaTel soundcard. In the visual task, a GeForce 7800 GTX graphics card was connected to a 17-inch CRT monitor with a resolution of 1,280 x 1,024 pixels with a refresh rate of 75 Hz[2]. Participants sat 160 cm from the center of the monitor in a dimly lit room. In both tasks, responses were made via the number keys on a standard keyboard. Response mappings were counterbalanced across participants. For half the participants response '1' referred to the smallest stimulus magnitude and response '6' referred to the largest stimulus magnitude. For the other half of the participants the mapping was reversed.

In the auditory task, the stimuli consisted of six tones varying in frequency from 752.64 Hz to 1,326.41 Hz, with a 12% difference in frequency between

successive stimuli. In Experiment 1a, the tones were presented with a 50 ms linearly ramped onset and offset. In the no-masking condition of Experiment 2a, the first stimulus presentation in the trial had a 50 ms linearly ramped offset and the second stimulus presentation in the trial had a 50 ms linearly ramped onset (the abrupt onset or offset of a transmitted audio signal causes spectral splatter, producing an audible 'popping' sound that can be eliminated by ramping). In all other experiments, pre, post, and ISI masks (chosen randomly from a set of 10 samples of white noise) avoided the need to ramp the onset and offset of the tones..

In the visual task, six stimuli were created by displaying two white squares (2 x 2 pixels) separated by one of six horizontal distances on a black background. Distances ranged from 75 pixels (0.64° visual angle) to 132 pixels (1.18° visual angle), with a 12% difference in distance between successive stimuli. We gradually increased or decreased the luminance of the dots for the first or last 50 ms to match the equivalent auditory ramping in Experiment 1 and the no-mask condition of Experiment 2. In all other experiments and conditions pre, post, and ISI masks were used and stimulus luminance remained constant. Fifty masks were created by randomly allocating each screen pixel one of three luminance levels (black, grey, white). During each masking period, a randomly selected mask was presented on each screen refresh creating the appearance of dynamic white noise.

Procedure. For either modality, each trial started with a small white fixation cross at the center of the screen for 300 ms, followed by a 500 ms blank interval. The stimulus was then presented a variable number of times for a variable duration, depending on the design of the experiment (e.g., in Experiment 1 the stimulus was presented for 250 ms either once or twice). After the final stimulus presentation a response prompt, consisting of three question marks, was displayed at the center of

the screen. Participants were requested to respond as quickly and as accurately as possible upon the onset of the response prompt.

Premature responses, made before the response prompt, were not registered and were excluded from the analysis. After a premature response, a message was displayed reminding the participant to respond only after the response prompt. Feedback (the correct response) was displayed at the center of the screen for 800 ms (1,300 ms after a premature response). There was an inter-trial interval of 600 ms starting from the offset of response feedback.

In each experiment, participants were first presented with each stimulus and its corresponding response label in ascending order of response. The first 20 trials of each experiment were treated as practice and discarded from the analysis. As well as excluding premature responses, trials with RTs (measured as the time from onset of the response prompt to key press) longer than 6,000 ms were excluded. For each experiment we calculated a repeated measurements 5 (stimulus) x 2 (condition) ANOVA on $d'_{i\,i+1}$ values and a repeated measurements 6 (stimulus pair) x 2 (condition) ANOVA on correct RT[3]. When a Mauchly test indicated sphericity was violated, we applied the Greenhouse Geisser correction to the ANOVA.

Experiment 1

Experiment 1 was designed to replicate the finding from Nosofsky (1983) that additional stimulus presentations within a trial increased discriminability. In Experiment 1, stimuli were presented either once or twice per trial. Each stimulus presentation lasted 250 ms. In the two presentations condition there was a 2,000 ms unfilled ISI (see Figure 1a). No masking was used in Experiment 1, but otherwise the design followed the general method. There were 75 repetitions of each of the cells in

the 6 (stimulus) x 2 (number of presentations) design. Participants were allowed a short break every 100 trials.

Results

Excluded trials constituted 3.8% and 2.2% of the total number of non-practice trials in Experiments 1a and 1b, respectively.

Figure 2 (top panels) shows the $d'_{i,i+1}$ scores (see Footnote 3 for an explanation of $d'_{i,i+1}$) for the one presentation and two presentations conditions in Experiment 1a (auditory stimuli, left panel) and Experiment 1b (visual stimuli, right panel). Typical bow effects were observed in the $d'_{i,i+1}$ scores resulting in a main effect of stimulus on discriminability in Experiment 1a, $F(4, 52) = 8.67$, $p = .001$, $MSE = 0.481$, $\eta_P^2 = .4$, and Experiment 1b, $F(4, 48) = 15.10$, $p < .001$, $MSE = 0.086$, $\eta_P^2 = .56$ (although in Experiment 1b $d'_{5,6}$ was lower than $d'_{4,5}$). There was a main effect of condition with higher $d'_{i,i+1}$ scores in the two presentations condition compared to the one presentation condition in both Experiment 1a, $F(1, 13) = 6.96$, $p = .02$, $MSE = 0.094$, $\eta_P^2 = .35$, and Experiment 1b, $F(1, 12) = 11.68$, $p = .005$, $MSE = 0.078$, $\eta_P^2 = .49$. There was no interaction between stimulus and number of presentations in either Experiment 1a, $F(4, 52) = 0.83$, or Experiment 1b, $F(4, 48) = 0.90$.

Figure 2 (bottom panels) shows the mean correct RT for each stimulus in the one-presentation and two-presentations conditions of Experiment 1a (auditory stimuli, left panel) and Experiment 1b (visual stimuli, right panel). The typical bow effect was evident, with faster RTs for stimuli towards the end of the range and slower for stimuli towards the middle of the range, resulting in a main effect of stimulus on RT in Experiment 1a, $F(5, 65) = 11.83$, $p < .001$, $MSE = 46492.126$, $\eta_P^2 = .48$, and

Experiment 1b, $F(5, 60) = 18.74$, $p < .001$, $MSE = 64873.072$, $\eta_P^2 = .61$. In both tasks,

the bow effect was more prominent in the two-presentation condition, resulting in a

significant interaction between stimulus and number of presentations in Experiment

1a, $F(5, 65) = 2.63$, $p = .046$, $MSE = 18958.701$, $\eta_P^2 = .17$, and Experiment 1b, $F(5,

60) = 3.48$, $p < .008$, $MSE = 9142.786$, $\eta_P^2 = .23$. Response times were faster in the

two-presentations condition than in the one-presentation condition for Experiment 1a,

$F(1, 13) = 148.30$, $p < .001$, $MSE = 282053.223$, $\eta_P^2 = .92$, and Experiment 1b, $F(1,

12) = 147.69$, $p < .001$, $MSE = 85254.905$, $\eta_P^2 = 93$.

Summary

The results from Experiment 1a and 1b support Nosofsky's (1983) finding that

discrimination in absolute identification improves as the number of stimulus

presentations per trial increases. In Experiment 1, discrimination was better for trials

on which a stimulus was presented twice per trial in comparison to trials on which a

stimulus was presented only once. The multiple presentation effect was therefore

replicated in two different absolute identification tasks; tone pitch identification and

visual distance identification, and extended to include RTs. Faster RTs were observed

in the two-presentation condition compared to the one-presentation condition,

consistent with previous findings showing that accurate absolute identification

responses are associated with faster RTs (e.g. Kent & Lamberts, 2005; Lacouture,

1997; Lacouture et al., 1998; Lacouture & Marley, 2004; although see Lacouture's,

1997, unequal spacing condition for an exception). However, the magnitude of the

difference in RTs between conditions was unusually large (781 ms). It is likely that a

significant proportion of this difference was caused by response preparation and

uncertainty regarding the onset of the response signal. As the one-presentation and two-presentation conditions were randomly inter-mixed, it is likely that participants had a higher degree of uncertainty regarding when the response prompt would appear in the one-presentation condition (i.e., whether the response prompt would follow stimulus offset, or whether a second stimulus would be presented). This uncertainty in the one-presentation condition could have led to slower RTs than in the two-presentation condition (where participants were certain a response prompt would follow the second presentation). Moreover, in the two-presentation condition participants would have had time to prepare their response during the ISI, enabling faster responding upon the onset of the response cue. Although these two factors undoubtedly contributed to faster responding in the two presentation condition, given the size of the RT difference it seems likely that the faster responding in the two presentation condition also reflects a benefit provided by the additional presentation (this is supported by proceeding experiments).

Although discrimination was greater in Experiment 1 when the stimuli were presented twice per trial, compared to when stimuli were presented once, presenting an additional stimulus also introduced an ISI and increased the total stimulus exposure duration. Experiments 2, 3, and 4 were designed to assess whether these confounding variables were responsible for the additional presentation effect.

Experiment 2

Experiment 2 examined whether superior performance in the two-presentation condition in Experiment 1 was due to additional sampling from a short-term sensory buffer during the ISI. In Experiment 2, stimuli were always presented twice per trial. In the unmasked condition, the ISI was unfilled, and in the masked condition, the ISI

was filled with white noise. The mask was used to prevent possible sampling from a sensory representation. If a short-term sensory buffer can be sampled during the ISI and used to aid discriminability, then performance should be worse when the ISI is masked compared to when the ISI is unmasked (e.g., Loftus, Duncan, & Gehrig, 1992; Loftus & McClean, 1999; Sperling, 1963).

The method for Experiment 2 was similar to the general method, with the following exceptions. There was an ISI of 2,000 ms that was either masked or unmasked. When the ISI was masked, the stimuli were not linearly ramped at stimulus onset or offset (in Experiment 2a, a white noise mask was added to the tone to create a continuous sound, preventing spectral splatter). However, when the ISI was unmasked the final 50 ms of the first stimulus was ramped linearly from maximum amplitude (brightness) to silence (black) and the first 50 ms of the second stimulus was ramped linearly from silence (black) to maximum amplitude (brightness). Pre and post masks of 250 ms were used so that no linear ramping was required at the start of the first stimulus presentation or at the end of the second stimulus presentation. The response prompt was presented upon the offset of the post mask. There were 70 repetitions of each of the cells in the 6 (stimulus) x 2 (masking) design. Participants were allowed a short break every 105 trials.

Results

Excluded trials constituted 2.4% and 2.4% of the total number of non-practice trials in Experiments 2a and 2b, respectively.

Figure 3 (top panels) shows the $d'_{i,i+1}$ scores (see Footnote 3) for each for the masked and unmasked conditions in Experiment 2a (auditory task, left panel) and Experiment 2b (visual task, right panel). There were bow effects in the $d'_{i,i+1}$ scores,

resulting in a main effect of stimulus on discriminability in both Experiment 2a, $F(4, 48) = 12.06$, $p < .001$, $MSE = 0.846$, $\eta_P^2 = .50$, and Experiment 2b, $F(4, 48) = 17.98$, $p < .001$, $MSE = 0.111$, $\eta_P^2 = .60$. There was no main effect of masking and no stimulus-masking interaction for $d'_{i,i+1}$ in Experiment 2a or 2b (all $p > .4$).

Figure 3 (bottom panels) shows the mean correct RT for each stimulus for the masked and unmasked conditions in Experiment 2a (auditory task, left panel) and Experiment 2b (visual task, right panel). Typical bow effects were observed. The main effect of stimulus on RT approached significance in Experiment 2a, $F(5, 60) = 2.64$, $p = .084$, $MSE = 55094.477$, $\eta_P^2 = .18$, and was significant in Experiment 2b, $F(5, 60) = 7.53$, $p = .001$, $MSE = 21761.38$, $\eta_P^2 = .39$. There was no main effect of masking and no stimulus-masking interaction for RTs in Experiment 2a or 2b (all $ps > .1$).

Summary

Experiments 2a and 2b demonstrated that presenting a mask during the ISI had little effect on discrimination or RT in two absolute identification tasks. A mask was presented in the ISI to prevent additional sampling from a short-term sensory buffer. Assuming that masking did prevent (or at least reduce) additional sampling, the lack of impairment in the masked condition, relative to the unmasked condition, suggests that any additional sampling from a sensory buffer during the ISI had little influence on performance. It is therefore unlikely that the opportunity for additional sampling in the two-presentation condition, relative to the one-presentation condition of Experiment 1, resulted in higher discriminability. Although care must be taken drawing conclusions from a null result, masking effects tend to be robust (e.g., Breitmeyer & Öğmen, 2006) and it is therefore surprising that masking had no effect

on performance in Experiment 2. The design of Experiment 2 produced typical bow

effects and performance levels were similar to the other experiments in this series.

The results suggest that sampling from a sensory buffer provided at most limited

benefit, possibly because enough stimulus information had already been sampled with

which to reach asymptotic performance.

Experiment 3

In Experiment 1, the overall stimulus exposure time in the two-presentation condition

was twice as long as the overall stimulus exposure time in the one-presentation

condition (500 ms versus 250 ms). It is possible that this additional exposure time

resulted in improved performance in the two-presentation condition, rather than the

fact that there were two stimulus presentations *per se*. Experiment 3 examined

whether increasing the exposure duration of a stimulus (over a minimum time for

stimulus detection) improves absolute identification performance. In Experiment 3,

stimuli were presented twice on each trial but the total exposure duration of a stimulus

was manipulated, whilst the time from stimulus onset to stimulus offset was held

constant by increasing the ISI in the shorter exposure time condition (2,250 ms)

compared to the longer exposure time condition (2,000 ms; see Figure 1c). Stimulus

presentations were 250 ms and 125 ms in the long exposure-duration and short-

exposure duration conditions, respectively. In all other respects the method was

identical to that detailed in the general method. There were 70 repetitions of each of

the cells in the 6 (stimulus) x 2 (exposure duration) design. Participants were allowed

a short break every 105 trials.

Results

Excluded trials constituted 4.4% and 8.0% of the non-practice trials in Experiment 3a

and 3b, respectively.

Figure 4 (top panels) shows $d'_{i,i+1}$ (see Footnote 3) for the long and short

exposure conditions in Experiment 3a (auditory task, left panel) and Experiment 3b

(visual task, right panel). Bow effects were observed in the $d'_{i,i+1}$ scores, resulting in

a main effect of stimulus on discriminability in Experiment 3a, $F(4, 48) = 10.77$, $p <$

.001, $MSE = 0.643$, $\eta_P^2 = .47$, and Experiment 3b, $F(4, 48) = 6.45$, $p < .001$, $MSE =$

0.127, $\eta_P^2 = .35$. In Experiment 3b, discrimination of stimuli at the lower end of the

range was highest in the long exposure condition, whereas discrimination of stimuli at

the higher end of the range was lowest in the long exposure condition, resulting in an

interaction between stimulus and exposure duration, $F(4, 48) = 2.88$, $p = .032$, $MSE =$

0.061, $\eta_P^2 = .19$. There was no interaction between stimulus and exposure duration in

Experiment 3a, $F(4, 48) = 1.27$ and no main effect of exposure duration on $d'_{i,i+1}$ in

either Experiment 3a, $F(1, 12) = 0.04$, or Experiment 3b, $F(1, 12) = 0.66$.

Figure 4 (bottom panels) shows the mean correct RT for each stimulus in the

long and short exposure conditions of Experiment 3a (auditory task, left panel) and

Experiment 3b (visual task, right panel). There were bow effects in RTs resulting in a

main effect of stimulus on RT for Experiment 3a $F(5, 60) = 4.67$, $p = .01$, $MSE =$

59980.998, $\eta_P^2 = .28$, and Experiment 3b, $F(5, 60) = 5.33$, $p = .023$, $MSE =$

137674.670, $\eta_P^2 = .30$. There was no main effect of exposure duration and no

stimulus by exposure duration interaction for RTs in Experiment 3a or 3b (all $ps > .1$).

Summary

In Experiment 3, the total stimulus exposure duration in the long exposure-duration condition was twice that of the short exposure-duration condition. Nevertheless, both Experiment 3a and 3b demonstrated that doubling stimulus exposure time had no observable effect on discrimination, or RT. These results contrast with those in Experiment 1, where overall exposure duration in the (superior performance) two-presentation condition was twice that of the one-presentation condition. As overall exposure duration in the short and long exposure-duration conditions of Experiment 3 was matched with exposure duration in the one-presentation and two-presentation conditions of Experiment 1, respectively, this indicates that factors other than stimulus exposure duration caused the improved performance observed in the two-presentation condition of Experiment 1.

The absence of an exposure duration effect suggests that the shorter exposure duration (2 x 125 = 250 ms) was sufficiently long to be able to perceptually process a stimulus to asymptotic accuracy. Thus, providing additional time for stimulus sampling did not benefit performance in Experiment 3. This finding is consistent with other absolute identification studies in which exposure duration is manipulated and participants tend to respond at asymptotic accuracy relatively rapidly. Previous studies typically show that full information is accumulated after about 135 ms to 405 ms for tone intensity information (e.g. Ward, 1991), and under 100 ms for tone frequency (Hsieh & Saberi, 2007; although Hsieh & Saberi, 2007, show that some information about tone frequency is accumulated between 100 ms and 1,000 ms). The results of Experiment 2 are also consistent with the claim that full stimulus processing occurred very rapidly. Sampling from a sensory buffer would only be beneficial if full stimulus sampling had not already been completed, and hence the

masking of the ISI would not be expected to worsen performance relative to an unmasked ISI unless there was still information to accumulate during the ISI.

The results of Experiments 2 and 3 indicate that increased duration of stimulus sampling is not responsible for the advantage of the additional stimulus presentation observed in Experiment 1. Alongside previous research (e.g., Hsieh & Saberi, 2007; Ward, 1991), Experiments 2 and 3 indicate that stimulus sampling in absolute identification is relatively rapid. The apparent rapidity of stimulus sampling suggests that stimulus sampling processes do not constitute the majority of the RTs in absolute identification which are relatively long compared to other cognitive tasks (e.g., Kent & Lamberts, 2005; Lacouture, 1997). Rather, it appears that other, non-perceptual, processes play a greater role in determining absolute identification RTs. However, the precise time course of the different component processes in absolute identification cannot be estimated from either Experiments 2 and 3, or from previous research indicating rapid perceptual processing, because RTs were delayed until a response prompt (Experiments 2 and 3) or were not measured (e.g. Hsieh & Saberi, 2007; Ward, 1991). This is a more general question than that of the influence of additional stimulus presentations.

<div align="center">Experiment 4</div>

Experiment 4 examined Nososfsky's (1983) original claim that discrimination is improved when a stimulus is presented more times during a trial because the ultimate representation used to judge identity is an average of the independent representations yielded on each presentation. If this claim is true, then it is the number of stimulus presentations (over and above the minimum amount of time necessary to encode the stimulus, Schwarz & Kühn, 2008) that is responsible for the increase in

discriminability between the one-presentation and two-presentation conditions of

Experiment 1. In Nosofsky's experiments, the manipulation of the number of

stimulus presentations was confounded with total exposure duration and trial length.

In Experiment 4, we manipulated the number of stimulus presentations, whilst

controlling the total stimulus exposure duration and the time from stimulus onset to

offset of the final stimulus. Stimuli were either, 250 ms in duration and presented

twice during a trial with a 4,000 ms ISI, or were 167 ms long and presented three

times during a trial with two 2,000 ms ISIs (see Figure 1d). In all other respects, the

method was identical to that detailed in the general method. There were 50

repetitions of each of the cells in the 6 (stimulus) x 2 (number of presentations)

design. Participants were allowed a short break every 75 trials.

Results

Excluded trials constituted 0.6% and 2.56% of the non-practice trials in Experiments

4a and 4b respectively.

Figure 5 (top panels) shows the $d'_{i,i+1}$ scores (see Footnote 3) for the three

presentations and the two presentations conditions in Experiment 4a (auditory task,

left panel) and Experiment 4b (visual task, right panel). Bow effects were observed in

the $d'_{i,i+1}$ scores, resulting in a main effect of stimulus on discriminability for both

Experiment 4a, $F(4, 52) = 12.72$, $p < .001$, $MSE = 0.232$, $\eta_P^2 = .50$, and Experiment

4b, $F(4, 52) = 8.03$, $p < .001$, $MSE = 0.116$, $\eta_P^2 = .38$. Whilst there was no difference

in the $d'_{i,i+1}$ scores between the three-presentations and two-presentation conditions in

Experiment 4a, $F(1, 13) = 0.05$, in Experiment 4b the $d'_{i,i+1}$ scores were higher in the

three-presentation compared to the two-presentation condition, $F(1, 13) = 6.94$, $p = $

$.021$, $MSE = 0.047$, $\eta_P^2 = .35$. There was no interaction between stimulus and number

of presentations for $d'_{i,i+1}$ in Experiment 4a, $F(4, 52) = 0.83$, or Experiment 4b, $F(4, 52) = 1.71$.

Figure 5 (bottom panels) shows the mean correct RT for each stimulus for the three presentations and two presentations conditions in Experiment 4a (auditory task, left panel) and Experiment 4b (visual task, right panel). There were bow effects in RTs resulting in a main effect of stimulus on RT for Experiment 4a, $F(5, 65) = 3.42$, $p = .03$, $MSE = 37631.284$, $\eta_P^2 = .21$, and Experiment 4b, $F(5, 65) = 6.26$, $p < .001$, $MSE = 16134.810$, $\eta_P^2 = .33$. Response times in the three-presentation condition were significantly faster than those in the two-presentation condition in both Experiment 4a, $F(1, 13) = 13.95$, $p = .002$, $MSE = 57534.319$, $\eta_P^2 = .62$, and Experiment 4b, $F(1, 13) = 14.26$, $p = .002$, $MSE = 43719.353$, $\eta_P^2 = .52$. There was no interaction between stimulus and number of stimulus presentations for RTs in either Experiment 4a, $F(5, 65) = 1.21$, or Experiment 4b, $F(5, 65) = .40$.

Summary

Manipulating the number of stimulus presentations whilst controlling stimulus exposure duration and the time between stimulus onset and stimulus offset had a significant effect on RTs, with faster responses when there were three presentations per trial, compared to two presentations per trial. This result replicates the RT effect observed in Experiment 1 and suggests that participants found the three-presentation condition easier than the two-presentation condition. However, the RT effect in Experiment 4 was smaller in magnitude than the RT effect found in Experiment 1, with a mean difference of 781 ms in Experiment 1 and 134 ms in Experiment 4. It is possible that the reduction in the RT difference was due to the diminishing impact of additional stimulus presentations on performance (cf. Nosofsky, 1983). A more likely

explanation is that, factors that contributed to the RT effect in Experiment 1 were less important in determining RT in Experiment 4. For example, in Experiment 1, uncertainty about when the response signal would onset would have been much less in the two-presentation condition, leading to faster responding. In Experiment 4 however, the long 4,000 ms ISI should have been an adequate indicator that there were to be only two stimulus presentations and not three, and so uncertainty over when the response cue would be presented should have had less of an effect on RT. Similarly, in Experiment 1 the ISI between the two stimulus presentations would have enabled additional response preparation in comparison to the one presentation condition. However in Experiment 4 the 4,750 ms from stimulus onset to onset of the response cue should have given ample time to prepare to respond. Thus, it seems unlikely that the RT effect observed in Experiment 4 was determined by either response preparation or uncertainty about when the response signal would onset. Rather it suggests some added benefit provided by the additional stimulus presentation.

The pattern of results for discrimination was less clear than that for RTs in Experiment 4. In Experiment 4b, discrimination was greater in the three presentations condition compared to the two presentations condition, providing some evidence to support Nosofsky's (1983) claim that additional stimulus presentations increase discrimination in absolute identification. However, in Experiment 4b discrimination was not uniformly superior in the three-presentation condition compared to the two-presentation condition across all stimulus positions. Moreover, manipulating the number of presentations had no effect on discrimination in Experiment 4a, suggesting that the addition of independent samples does not always occur.

It is not clear why there were different effects of additional stimulus presentations between the two modalities in Experiment 4. In Nosofsky's (1983) experiments, the greatest benefit in discrimination was gained from one to two stimulus presentations, with a diminishing benefit for additional stimulus presentations. Thus, a reduced effect of an additional stimulus presentation would be expected between the two-presentation and three-presentation conditions in Experiment 4. It is possible that the increased difficulty of the visual task (Experiment 4b) compared to the auditory task (Experiment 4a), which is evident across all experiments, meant that the additional stimulus presentation provided a limited benefit in the visual task only. For example, if stimulus representations were less noisy in the auditory task compared to the visual task, and if additional stimulus presentations serve to reduce perceptual noise (Nosofsky, 1983) then the effect of the third stimulus presentation would be reduced in the auditory task compared to the visual task. Another possibility is that the 167 ms auditory stimulus was too brief in the three presentations condition to provide an additional benefit. When time is held constant, multiple presentations only appear to provide a benefit above single presentation after a minimum time has elapsed (total presentation duration and number of presentations interact, supporting an independent representation for each presentation, with a peaked hazard function for sampling probability [i.e., initially increasing but then decreasing probability of identification, such as the inverse Gaussian or lognormal distribution] see Schwarz & Kühn, 2008, for a discussion[4]). However, previous studies suggest that the majority of sampling is completed by 50 ms for auditory stimuli (Hsieh & Saberi, 2007; Ward, 1991).

The result may also reflect the visual modality's greater susceptibility to extraneous failures such as eye blinks, eye or head movements, and lapses of

attention. A further possibility is that the result arises from the summation of independent samples when the instantaneous probability of perceiving the information first rises, then falls (i.e., the psychophysical hazard is peaked). This could- depending on the exact shape of the peak- have the consequence that an overall advantage for three stimuli over two stimuli is observed only when the total stimulus duration is long, but not when it is short (as in Schwarz & Kühn's, 2008, experiments and analysis). Moreover, it could be the case that a duration is "long" for the visual stimuli in Experiment 4b but "short" for the auditory stimuli of Experiment 4a. However, this account can be ruled out. For performance in the 3 x 167 ms condition of Experiment 4a to be equivalent to that in the 2 x 250 ms condition, the chances of identification (or integrated hazard) in the final 167 ms presentation must be equivalent to that in the two 167-250 ms periods of the 250 ms presentations. But (as we are assuming independence) we know the first 167 ms yields a non-zero probability of identification, because the 2 x 250 ms presentations show no advantage over 2 x 125 ms presentations (Experiment 3a), ruling out the whole 125-250 ms period for identification (similar to previous experiments e.g., Hsieh & Saberi, 2007; Ward, 1991).

The findings from Experiments 2-4 suggest that the improvement in absolute identification performance with additional stimulus presentations during a trial is not due to an increased opportunity for stimulus sampling. Presenting a mask in the ISI to prevent sampling of a sensory buffer had no effect on performance (Experiment 2) and neither did increasing total exposure duration (Experiment 3). Stimulus sampling influences arising specifically from the presentation of discrete stimuli (Experiment 4) also only had a very weak effect that was limited (in discriminability) to the visual

stimuli. Such a meager magnitude effect of the additional third presentation suggests the influence of another process.

In Experiment 1 and Nosofsky's (1983) experiments, the time from stimulus onset to final stimulus offset was not controlled, but in our Experiments 2-4 we controlled the time from stimulus onset to final stimulus offset. However, it is possible that the time from stimulus onset to final stimulus offset may influence absolute identification performance, especially given the negligible effect of additional stimulus sampling, and the implication that response selection processes are perhaps critical to performance. Experiment 5 therefore examined whether time from stimulus onset to stimulus offset influenced absolute identification performance.

Experiment 5

In Experiment 5, the time from initial stimulus onset to final stimulus offset was manipulated. Stimuli were presented twice on each trial and the length of the ISI was manipulated (2,000 ms versus 50 ms). In addition, the post mask and response prompt were presented simultaneously upon stimulus offset in both ISI duration conditions. Stimuli were pre-masked, post-masked and masks were presented during the ISI (see Figure 6). Note that stimuli were presented twice per trial so that participants were motivated to fully utilize the time between stimulus repetitions (and hence allow response selection processes to be at least near completion in the long ISI condition). There were 75 repetitions of each of the cells in the 6 (stimulus) x 2 (ISI duration) design. Participants were allowed a short break every 100 trials.

Participants. 28 (17 female) participants took part.

Apparatus, stimuli, design, and procedure. These were identical to that in the general methods section with the following exceptions. Stimuli were always presented twice per trial and the length of the ISI was manipulated (short, 50 ms, or long, 2,000 ms). In order to minimize time from offset of the first stimulus presentation to onset of the response cue, the response cue was presented simultaneously upon offset of the final stimulus. This meant that the post masks in the visual task (Experiment 5b) had to be modified. In Experiment 5b, a set of 50 post masks were created using the technique described in the general method, with the exception that there was a 150 x 100 pixel black rectangle 340 pixels above the horizontal center and at the vertical center of the screen containing the '???' response cue.

Results

Excluded trials constituted 2.1% and 1.6% of the non-practice trial in Experiments 5a and 5b, respectively.

Figure 7 (top row) shows the $d'_{i,i+1}$ scores (see Footnote 3) for each pair of adjacent stimuli for short and long ISI conditions for Experiment 5a (auditory task, left panel) and Experiment 5b (visual task, right panel). There were bow effects, resulting in a main effect of stimulus on discriminability in both Experiment 5a, $F(4, 52) = 22.46$, $p < .001$, $MSE = 0.739$, $\eta_P^2 = .63$, and Experiment 5b, $F(4, 52) = 17.71$, $p < .001$, $MSE = .133$, $\eta_P^2 = .58$ (although in Experiment 5b $d'_{4,5}$ was greater than $d'_{5,6}$). There was a main effect of ISI duration on discriminability with higher $d'_{i,i+1}$ scores for the long ISI condition compared to the short ISI condition in both Experiment 5a, $F(1, 13) = 9.60$, $p = .008$, $MSE = 0.155$, $\eta_P^2 = .43$, and in Experiment 5b, $F(1, 13) = 11.04$, $p = .005$, $MSE = 0.091$, $\eta_P^2 = .46$. However, in Experiment 5a $d'_{5,6}$ was greater in the short presentation-interval condition compared to the long interval condition,

resulting in an interaction between stimulus and ISI duration, $F(4, 52) = 4.67$, $p =$ .003, $MSE = 0.086$, $\eta_P^2 = .26$. There was no interaction between stimulus and ISI duration in Experiment 5b, $F(4, 52) = 1.00$.

Figure 7 (bottom row) shows the mean RT for each stimulus in the short and long ISI conditions for Experiment 5a (auditory task, left panel) and Experiment 5b (visual task, right panel). Bow effects in RTs were evident, however the main effect of stimulus on RT only approached significance in Experiment 5a, $F(5, 65) = 2.94$, $p = .070$, $MSE = 15386.015$, $\eta_P^2 = .18$. The main effect of stimulus on RT was significant in Experiment 5b, $F(5, 65) = 10.66$, $p < .001$, $MSE = 28350.132$, $\eta_P^2 = .45$. Response times were faster for the long ISI condition compared to the short ISI condition in Experiment 5a, $F(1, 13) = 67.19$, $p < .001$, $MSE = 61107.156$, $\eta_P^2 = .84$, and Experiment 5b, $F(1, 13) = 39.79$, $p < .001$, $MSE = 146249.437$, $\eta_P^2 = .75$. There was no interaction between stimulus and ISI duration in Experiment 5a, $F(5, 65) = 1.98$, or Experiment 5b $F(5, 65) = 1.26$.

Summary

Manipulating ISI duration did affect discrimination and RT in both Experiment 5a and 5b. Discrimination was better and RTs faster in the long ISI condition compared to the short ISI condition. The effect of manipulating the ISI duration on all indicators of task difficulty provides considerable evidence that absolute identification performance can be improved by increasing the time from onset of the first stimulus to offset of the second stimulus, at least with the stimuli and range of durations used in these experiments. The findings from Experiment 5, suggest that in Experiment 1 and Nosofsky's (1983) experiments, the improvement in

performance observed between presenting a stimulus once or twice, may have been partly caused by the associated increase in time from onset of the first stimulus to offset of the final stimulus.

An alternative interpretation is that increasing ISI made it more likely that the repeated stimulus presentations were represented independently. If discrimination is improved by averaging the independent representations formed from each stimulus repetition, increasing the likelihood that stimuli are independently represented should aid performance. Indeed, Nosofsky (1983) reported that in pilot studies an ISI of 2 s was optimal in ensuring stimulus presentations were represented independently. In Nosofsky's interpretation, more separated repetitions cause more precise representations than a mere increase in duration because separation in time leads to unrelated (rather than related) samples of noise. However, for such an interpretation to hold for Experiment 5 one would have to posit a source of psychophysical noise in pitch perception that is impervious to presentation of a mask of high intensity and a white spectrum of frequencies, and a corresponding source of psychophysical noise in visual distance perception that is impervious to presentation of a mask of high intensity and a white spectrum of spatial and temporal frequencies. Moreover, Experiment 4 showed that, when trial length and stimulus duration are controlled, additional presentations are of limited benefit, improving discrimination in the visual distance task only. The results of Experiment 5 therefore appear more consistent with the idea that increasing the ISI allows more time to complete non-perceptual processes such as those involved in decision making and response selection and therefore more in line with models proposing an accumulator process in response selection (e.g., S.D. Brown et al., 2008; Lacouture & Marley, 2004; Mathews & Stewart, 2009; Nosofsky, 1997) than models emphasizing the perceptual processing

stage (Kent & Lamberts, 2005). Allowing more time for a response in an accumulator process can reduce the impact of variation in starting position and accumulation rate by increasing the threshold for response production, decreasing the number of trials on which an incorrect accumulator wins.

Nevertheless, in order to determine whether it is the increase in total trial length that is critical rather than the amount of temporal separation between stimulus repetitions, Experiment 6 included two conditions in which a stimulus was presented once and the response cue was either presented at stimulus offset or after a delay. However, presenting stimuli only once per trial is problematic because there is little incentive to use any additional time after stimulus offset. This was why there were always two stimulus presentations in Experiment 5. To address this issue both trial length (short or long) and number of presentations (one or two) were manipulated in Experiment 6 (see Figure 8). By intermixing trials from each of these conditions, an incentive is provided to utilize the time between offset of the first stimulus and the onset of the response cue because there is a chance that the stimulus will be presented a second time.

In a change from previous experiments, Experiment 6 used an individual participants design with each participant undergoing extensive testing. Nosofsky (1983) used an individual subjects design and it is useful to examine the effects of trial length and number of presentations at the level of the individual subject. Participants completed the auditory absolute identification task only.

Participants. Five participants (two female) took part in the study, the three authors (Participants 1-3) and two naïve participants (Participants 4-5).

Apparatus, stimuli, design, and procedure. These were identical to those described in the general method section with the following exceptions. The design was a 2 (trial length short or long) x 2 (one or two stimulus presentations) x 6 (stimulus) design. Each stimulus presentation lasted 125 ms. The response cue was presented either 250 ms (short condition) or 2,125 ms (long condition) after the offset of the first stimulus. If stimuli were presented twice per trial the second stimulus was presented either 125 ms (short condition) or 2,000 ms after offset of the first stimulus. In all cases white noise was presented for 250 ms following onset of the response cue (see Figure 8). Participants completed eight one hour sessions. There were 25 repetitions of each of the cells in the design within each session. At the start of each session participants were first presented with each stimulus and its corresponding response label in ascending order of response. Trials with RTs (measured as the time from onset of the response prompt to key press) longer than 2,000 ms were excluded.

<div align="center">Results</div>

Excluded trials constituted 1.5%, 0.31%, 2.54%, 3.58% and 0.47% of the total number of non-practice trials for Participants 1-5, respectively.

Figure 9 shows the $d'_{i,i+1}$ scores (see Footnote 3) for each condition for each Participant as well as $d'_{i,i+1}$ scores averaged across participants. First, data were analyzed at the individual subjects level by splitting data from each session into three 200 trial blocks (yielding 24 blocks in total) and calculating $d'_{i,i+1}$ scores for each condition within each block[6]. For each participant a 2 (trial length) x 2 (number of presentations) x 5 (stimulus pair) repeated measures ANOVA was conducted on these $d'_{i,i+1}$ scores with the scores from each block treated as an independent observation. The results of this analysis are shown in Table 1. All participants showed typical bow

effects resulting in a significant main effect of stimulus for each participant. Discrimination was significantly better when trial length was long for all participants except Participant 3. Although discrimination for all participants was slightly better in trials with two stimulus presentations compared with trials with one stimulus presentation, this difference was significant for Participant 5 only (all other ps > .39).

Although only Participant 4 showed an interaction between number of presentations and trial length (with worse discrimination for the two presentations condition for short trials, but the reverse pattern for longer trials) separate analyses were conducted on trials from the one-presentation condition and trials from the two-presentation condition. We felt this necessary as a good indicator of the importance of trial length is whether it affects discrimination even when a stimulus is presented once. A 2 (trial length) x 5 (stimulus pair) repeated measures ANOVA was conducted on $d'_{i,i+1}$ scores from the one-presentation condition only. For the four participants who displayed a main effect of trial length in the omnibus ANOVA, the main effect of trial length was significant (one tailed) for Participant 2, 4 and 5 (p = .095, p = .064 and p = .079, respectively). The same analyses on $d'_{i,i+1}$ scores from the two-presentation condition yielded main effects of trial length for Participants 1, 2, 4 and 5 (p = .006, p = .005, p < .001 and p < .008 respectively). Thus despite a non-significant interaction between trial length and number of stimulus presentations, for four participants, trial length did show a tendency to have a greater effect on discrimination when stimuli were presented twice per trial.

Supposing that an analysis of probability correct that would not require us to average over trials might be more powerful, we also conducted probit regressions on each participant's data. Accuracy was predicted from (centered) dummy-coded trial length, (centered) number of presentations, and their interaction; and session (dummy-

coded, 8 levels), stimulus (dummy-coded, 6 levels) and (signed) difference to last stimulus (dummy-coded, 11 levels) were entered as covariates. An advantage for longer trials was significant for four of the five participants (Wald zs = 3.400, 3.817, 1.228, 4.084, 3.631, for Participants 1-5 respectively). The main effect of number of presentations approached significance for only one participant (zs = 0.355, 0.742, 0.339, 1.118, 1.753), and the interaction was not significant (zs = 0.988, 1.401, 0.138, 0.670, 0.525). We further examined the simple effects in analogous analyses. When there was a single presentation, the advantage for longer trials was significant for two participants and approached significance for two more (zs = 1.806, 1.767, 0.779, 2.460, 2.290). When there were two presentations, the effect of trial length was significant for four participants (zs = 3.102, 3.501, 0.980, 3.299, 2.763). The effect of number of trials reached significance neither when trial length was short (zs = 0.514, 0.470, 0.154, 0.352, 0.891) nor when it was long (zs = 0.972, 1.489, 0.372, 1.477, 1.563).

Figure 10 shows average correct RTs for each condition for each participant as well as RTs averaged across participants. Average correct response times were calculated for each 200 trial block for each participant. For each participant a 2 (trial length) x 2 (number of presentations) x 6 (stimulus pair) repeated measures ANOVA was conducted on these RTs with RTs from each block treated as independent observations. Bows in RT were observed for all participants, leading to a significant main effect of stimulus pair for each participant. For all participants, RTs were much longer when trial length was short and the main effect of trial length was significant for each participant. Number of presentations had little effect on RT, with Participant 2 only showing significantly faster responding in the two-presentation condition compared to the one-presentation condition. Several significant interactions were

observed. Participant 1 showed a significant interaction between trial length and number of stimulus presentation, with faster responding in the two-presentation condition when trial length was short, but the reverse when trial length was long. In addition, Participants 4 and 5 showed a significant interaction between trial length and stimulus, with bows more evident in the one-presentation condition.

Summary

Increasing trial length improved discrimination and reduced RT for the majority of participants in Experiment 6. Moreover, increasing trial length improved performance both in trials where there was one stimulus presentation and in trials where there were two stimulus presentations. This supports the conclusion from Experiment 5 that discrimination is influenced by trial length and that the difference in discrimination between the one- and two-presentation conditions in Experiment 1 may be due to trial length and not number of presentations. Indeed, when trial length was controlled in Experiment 6, increasing the number of stimulus presentations improved discrimination for only one participant. This improvement may have been due to the additional presentation, the extra stimulus time provided by the additional presentation or a combination of both. Regardless, it indicates that the benefit from additional presentations is very limited.

One potential explanation for the weak effect of the additional stimulus presentation is that the use of masking in Experiment 6 prevented stimulus integration. Without stimulus integration an additional stimulus presentation would not lead to improved performance. However, several findings run counter to this argument. In Experiment 2, manipulating the presence of a mask had no influence on any performance indicators. If masking did prevent stimulus integration then

performance in the unmasked condition should have been superior to the masked condition. Second, an additional stimulus presentation did improve discrimination for one participant in Experiment 6, indicating that masking did not interfere with stimulus integration (at least not in an all-or-none manner).

Although a significant interaction between number of presentations and trial length was evident for only one participant, there was some evidence that the effect of trial length was more prominent when stimuli were presented twice. This is consistent with the idea that two stimulus presentations are more likely to be represented independently when separated by a longer ISI (Nosofsky, 1983; although see arguments against this in the Summary of Experiment 5). Alternatively, a long ISI may be useful in that it provides time for non-perceptual processes (e.g., response selection) to complete following the presentation of the first stimulus. A response derived from the first stimulus presentation could be treated as an estimate that is then used to modify the response selection process before the second stimulus presentation. For example, the involvement of accumulators for stimuli that are far away from the initial stimulus estimate might be inhibited or even drop out of the competition, producing faster and more accurate responses when the second stimulus is presented (cf. Nosofsky, 1997). Whilst either of these alternatives is feasible, the evidence for an interaction between trial length and number of presentations was relatively weak. A simpler explanation is that on a proportion of trials participants were not concentrating at the beginning of the trial, and so made more errors when stimuli were presented in quick succession. The central finding from Experiment 6 is therefore that absolute identification discrimination can be improved by increasing trial length.

General Discussion

Current models of absolute identification allocate different levels of importance to the perceptual processes involved in completing the task. Following models of other cognitive processes (e.g., Cohen & Nosofsky, 2003; Lamberts, 2000; Loftus & McLean, 1999), the EGCM (Kent & Lamberts, 2005) places central importance on the stimulus sampling process. In the EGCM, stimulus sampling links accuracy and RT, with more accurate responding when more information has been accumulated. In comparison, other models of absolute identification give little importance to stimulus sampling and focus more on the dynamics of the response selection process (S.D. Brown et al., 2008; Nosofsky, 1997; Matthews & Stewart, 2009).

In the series of experiments presented here we used a repeated stimulus presentation methodology developed by Nosofsky (1983) to examine the importance of stimulus sampling in absolute identification. Previously, Nosofsky (1983) demonstrated that discrimination in absolute identification improves with additional stimulus presentations during a trial. However, presenting a stimulus more times also increases overall stimulus duration and introduces additional ISIs, both of which can lead to additional opportunities for stimulus sampling, either of the stimulus itself or from a short term sensory buffer (e.g., Massaro, 1972a). We therefore examined in Experiments 2, 3, and 4 whether the improvement in discriminability with additional stimulus presentations was caused by an increased opportunity for stimulus sampling (either directly, or via the sensory buffer).

Experiment 1 replicated the additional stimulus presentation effect observed by Nosofsky (1983) demonstrating that discrimination was better when a stimulus was presented twice per trial as opposed to once per trial. Moreover, we showed that

this improvement in discrimination did not just occur for the central stimuli (Experiment 1a and 1b demonstrated improvement across the full range of stimuli). In addition, we also showed that RTs were considerably shorter when stimuli were presented twice per trial compared with a single stimulus presentation. Response times appear more sensitive to the additional stimulus manipulation than choice proportions; we speculate that some of the difference in RTs is due to response preparation (see below and Summary sections of Experiments 1 and 4).

Experiment 2 demonstrated that the two-presentation benefit in Experiment 1 was not caused by additional sampling from a very short-term sensory buffer during the ISI, as presenting a mask (which effectively eradicates information in the sensory buffer) during the ISI did not reduce performance. Manipulating the duration of stimulus exposure in Experiment 3 also had little effect on performance, demonstrating that the improvement in discrimination in Experiment 1 for the one-presentation condition relative to the two-presentation condition was not caused by increased opportunity for stimulus sampling. In Experiment 4, the number of additional stimulus presentations was manipulated whilst holding the total stimulus exposure time constant. Increasing the number of repetitions only improved discrimination for the visual task. The effect of decreased RTs was present for both tasks, but much smaller than the magnitude of effect observed in Experiment 1. Although Nosofsky (1983) found reduced advantages for three over two stimulus presentations, they were still of a sizable magnitude. However, the total exposure and trial length were not controlled in Nosofsky's experiments.

The results of Experiments 2, 3, and 4 demonstrated that the additional stimulus benefit in absolute identification is not created by increased stimulus sampling *per se*. Moreover, the evidence for the formation of independent

representations (at the beginning of each presentation) contributing to the effect in Experiment 1 was limited: When the number of presentations was manipulated independently of other factors in Experiment 4, the effect on discrimination was small in the visual modality, and absent in the auditory modality. The relatively small influence of stimulus repetition suggests involvement of other processes in contributing to the advantage of the additional stimulus presentation in Experiment 1. Experiments 5 and 6, therefore, investigated whether a non-perceptual factor, the overall trial duration from onset of the first stimulus to onset of the response cue, affected performance. Both Experiments 5 and 6 demonstrated that manipulating non-perceptual processing time influenced both discrimination and RT. Discrimination was worse and RTs were slower when the time from onset of the first stimulus to onset of the response cue was shorter, suggesting multiple contributions to the benefit of the two presentations condition in Experiment 1. In particular, Experiment 6 ruled out the possibility that increasing non-perceptual processing time improves performance simply because it increases the likelihood that two stimulus presentations are represented independently (a possibility in Experiment 5 where stimuli were always presented twice per trial). In Experiment 6, increasing non-perceptual processing time improved performance even when stimuli were presented once per trial. Furthermore only one out of five participants who completed Experiment 6 showed better performance when stimuli were presented twice per trial compared to when they were presented once per trial and the time from offset of the first stimulus presentation to onset of the response cue was controlled. Although additional presentations can provide some benefit, increasing the time available for non-perceptual processes also appears to aid performance.

Perceptual and non-perceptual processing in absolute identification

The experiments presented here demonstrate that stimulus sampling in absolute identification can occur relatively quickly, probably in less than 250 ms, as masking during the ISI did not decrease performance, and increasing exposure duration beyond 250 ms did not improve performance. Stimulus sampling is likely to be important in determining performance, but only at relatively short durations (and certainly less than those we have used). As RTs in absolute identification are typically quite long (> 1,000 ms), such a short duration for stimulus sampling suggests that this process alone does not account for the majority of the processing underlying the time taken to produce a response in absolute identification. The time course of non-perceptual processing may therefore constitute a significant proportion of the RT. This finding has important implication for the EGCM (Kent & Lamberts, 2005) according to which the time course of stimulus sampling is of central importance, directly linking accuracy and RT. Whilst other non-perceptual processes are incorporated into the model in the form of a 'residual time' parameter, the time course of these non-perceptual components is not detailed, and are assumed constant over different stimuli. Previous estimates of the time course of stimulus sampling range from approximately 750 ms to 1,240 ms on average (depending on set size; see the model predictions in Kent & Lamberts, 2005). However, these model estimates were derived from a standard single stimulus absolute identification task in which there were no restrictions on either stimulus duration or time to respond. Further studies manipulating these factors will need to be conducted in order to test whether the stimulus sampling process modelled by the EGCM is of central importance to performing the standard absolute identification tasks (Hsich & Saberi, 2007, and Ward, 1991, also did not control or report RTs).

Perhaps the success of the EGCM at accounting for data from a standard absolute identification experiment (Kent & Lamberts, 2005) relies on the analogous processes involved in perceptual processing and memory retrieval processing (e.g., Kent & Lamberts, 2006a, 2006b, 2008; Lamberts & Kent, 2008). According to such a revised model, the rapid stimulus sampling process would be partnered with a slower process of sampling representations from memory in the response selection stage. The current implementation of the EGCM (Kent & Lamberts, 2005) might be approximating such a process by overestimating the duration of stimulus sampling. Such a revision would allow the EGCM to be independent of stimulus presentation duration and still predict RT differences, consistent with the data presented here[5]. Of course, such a model would retain the close link between RT and accuracy, which we (e.g., the current Experiment 4; Adelman & Stewart, 2006) and others (Donkin, S. D. Brown, Heathcote, & Marley, 2009) have demonstrated is not always straightforward.

When total stimulus time was controlled, additional stimulus presentations did provide some benefit in the distance identification task, supporting Nosofsky's (1983) conclusion that an increase in duration is not the same as a stimulus repetition. In Nosofsky's interpretation, separated repetitions cause more precise representations than a mere increase in duration because separation in time leads to unrelated (rather than related) samples of noise. If this were true, the decrease in separation in time might account for the effect of reducing interstimulus interval in Experiments 5 and 6. However, Experiment 6 showed that discrimination can be improved by increasing the amount of non-perceptual processing time after a single stimulus presentation. This suggests the effect of increasing the interstimulus interval in Experiments 5 and 6 was mostly due to increased time for non-perceptual processes and not increased separation. Whilst separation may have played a role, presenting an additional

stimulus during a trial had only a limited effect on performance, and so any effect of separation would have been relatively small.

The improvement in absolute identification performance as the time before a response may be made increases indicates the relative importance of non-perceptual processes in absolute identification. Relevant non-perceptual processes are: retrieval from memory, decision making, and response selection. In both contemporary and older models that attribute variation in response time to processes other than stimulus sampling (including SAMBA, S. D. Brown et al., 2008; the leaky competing accumulator model, Lacouture & Marley, 2004; the EBRW, Nosofsky, 1997; and the ballistic accumulator version of the RJM, Matthews & Stewart, 2009) response selection is implemented as an accumulation processes with either sampling variability or variability in starting point (or both). All accumulator-based models can predict that absolute identification performance improves when response selection processing time is increased as these sources of variability are surmounted over time (for example by shifting the threshold for selecting a winning accumulator).

Whilst models that detail the time course of response selection processes are able to account for the improved performance when non-perceptual processing time is increased, none of them currently account for the (albeit rapid) stimulus sampling process. Only one model currently considers both stimulus sampling and response selection, the EBRW-PE (Cohen & Nosofsky, 2003) which is a hybrid of both the EBRW (Nosofsky & Palmeri, 1997) and the EGCM (Lamberts, 2000). So far this model has not been applied to absolute identification, although individually both constituent models have (Kent & Lamberts, 2005; Nosofsky, 1997), and so the EBRW-PE could potentially be extended to absolute identification. Such an extension may also increase the viability of the EBRW as a model of absolute

identification, as in its current format, the EBRW explicitly assumes a linear relation between the variances of the memory representations and the distance from the nearest edge of the stimulus range, essentially forcing the model to produce bow effects. In the EBRW-PE, the need for this assumption would be decreased as bow effects in RT could also be determined by the time required for stimulus sampling (as in the EGCM). However, further work will be required to determine whether the EBRW-PE is a viable model of absolute identification.

Although all the major current models of absolute identification can probably be modified to allow for the data presented in the experiments here, we have shown that response selection (including retrieval of memory representations) and not stimulus sampling, is the crucial limiting process in the majority of absolute identification studies. Response selection processes are therefore likely to constitute the majority of the time required to identify a stimulus.

How do additional stimulus presentations affect processing?

Finally, we discuss the specific effects of additional stimulus presentations on processing of the trial as a whole.

Quite apart from the processing of the stimulus itself, it is likely that the expectation of a stimulus leads to a different mode of processing. If no further information is expected (e.g., with a delayed response deadline, but no further stimulus) then response selection may complete, response preparation may proceed and only execution need be delayed. By contrast, if further information is expected (i.e., in the gap between two stimuli) it would seem sensible to delay the completion of response selection until this information (the further stimulus) has been presented.

Such strategies may be immune to the absence of any actual benefit from the expected further information. Indeed, such a benefit is not always seen, as when three stimuli are equivalent to two in Experiment 4a. We now go on to address the modes of processing the additional stimulus may receive despite its lack of influence on discrimination.

The first possibility to consider is that the additional presentation is ignored, either because of the instruction to participants that each presentation is identical, or the ability to detect that the additional stimulus is identical, or because the identification decision has already been made on the basis of the previous presentation(s). If the additional presentation is ignored, this would explain the absence of an effect on discrimination in Experiment 4a, but if stimuli are completely ignored, then the RT difference in Experiment 4a is not explained.

The second possibility is that the additional presentation affects response criteria only. For example, the response threshold (the amount of accumulated evidence needed in favor of one response) might be influenced by the number of stimulus presentations. However, this explanation is somewhat less favorable when it is considered that Experiments 5 and 6 seemed to indicate that the number of presentations was acting as a proxy for extending the amount of non-perceptual processing time between stimulus onset and response onset (i.e., improvements were seen in the absence of additional stimulus presentations). More generally, it seems necessary that there should be a limit on the effectiveness of changing response criteria; otherwise, there is nothing to prevent a suitably motivated participant increasing his or her criteria arbitrarily far to obtain perfect accuracy. Critically, this limit cannot be due to forgetting, as the additional stimulus presentation prevents this. Overall, it seems that the locus of the limit on information transmission is at an earlier

stage, which is well justified as it seems a limit that depends on the stimulus dimension should not occur due to decision parameters.

The third possible explanation for the lack of the additional stimulus presentation affecting accuracy is that each additional presentation starts afresh the response selection process with new evidence. Thus, essentially the whole process is repeated with no memory for each stimulus presentation. In principle, starting again with the second (or third) stimulus presentation would produce no change in discrimination, but would imply an increase in RT, which is inconsistent with the evidence for all the experiments. One would have to suppose that there is a local speed-up of response selection processing after each stimulus presentation, in order to predict the decrease in RT with additional stimulus presentations.

A fourth explanation is that the additional stimulus explanation evokes a new independent representation of the stimulus that is integrated with evidence from previous presentations. If the evidence is integrated then the evidence, on the whole, should better support the correct response (Nosofsky, 1983). However, Experiment 4a is clear evidence against such an explanation.

The final possibility we consider, is that the additional presentation produces a representation that supports the same (possibly erroneous) response. Such a biased process would lead to faster responding, with no concurrent increase in discrimination. In SAMBA, for instance, there is non-psychophysical variability due to the allocation of limited selective attention resources during the mapping process. If the allocation of these resources were to move very slowly (much slower than in the parameter sets that have previously been used in prior applications of the model) the magnitude estimation process will have the same error (and hence the same error would be propagated into the response selection mechanism). The ballistic

accumulators would receive the same inputs, and added to the existing values, this would speed the response selection process, without a concurrent increase in discrimination. This, however, runs counter to the usual understanding of selective attention as a resource that is rapidly moved to relevant information. An alternative version of this possibility is that the attention limit does not lie in the stimulus representation, but in its allocation to the response. Specifically, if on a particular trial, the mapping of stimulus to responses is erroneous, the representation of the stimulus can be perfect (and therefore not improved by additional representations or sampling) but the error in response selection occurs because the mapping between stimulus and response is incorrect. Within this framework, the RT advantage for longer trials (Experiments 5 and 6) is due to slow memory sampling, with the possibility of using poorer quality memory representations reducing over time.

Conclusion

The evidence presented here suggests: a) the presentation of additional stimuli within a trial can have an artefactual effect from the duration of response selection processes; b) that there are situations where the cognitive system is able to obtain and integrate multiple independent perceptual representations from additional presentations to improve discrimination; but c) that there are situations where the cognitive system is unable to obtain an independent representation, but the representation is integrated in the same way to obtain an improvement in latency but not accuracy. This implicates, in either selective attention or memory, a strong influence on performance in absolute identification that varies slowly, which forms the limit on information transmission.

References

Adelman, J. S., & Stewart, N. (2006). Absolute identification is surprisingly faster with more closely spaced stimuli. In R. Sun & N. Miyake (Eds.), *Proceedings of the Twenty-Eighth Annual Conference of the Cognitive Science Society*, 943–948.

Ashby, F. G. (2000). A stochastic version of general recognition theory. *Journal of Mathematical Psychology, 44*, 310-329.

Ashby, F. G., & Townsend, J. T. (1986). Varieties of perceptual independence. *Psychological Review, 93*, 154-179.

Breitmeyer, B. G., & Öğmen, H. (2006). *Visual masking: Time slices through conscious and unconscious vision (2nd Ed.)*. New York: Oxford University Press.

Brockdorff, N., & Lamberts, K. (2000). A feature-sampling account of the time course of old-new recognition judgements. *Journal of Experimental Psychology: Learning Memory and Cognition, 26*, 77-102.

Brown, S. D., Marley, A. A. J., Donkin, C., & Heathcote, A. (2008). An integrated model of choices and response times in absolute identification. *Psychological Review, 115*, 396-425.

Busey, T. A., & Loftus, G. R. (1994). Sensory and cognitive components of visual information acquisition. *Psychological Review, 101*, 446-469.

Cohen, A. L., & Nosofsky, R. M. (2003). An extension of the exemplar-based random-walk model to separable-dimension stimuli. *Journal of Mathematical Psychology, 47*, 150-165.

Donkin, C., Brown, S., D, Heathcote, A. J., & Marley, A. A. J. (2009). Dissociating speed and accuracy in absolute identification: The effect of unequal stimulus

spacing. *Psychological Research*, *37,* 308-316.

Garner, W. R., & Creelman, C. D. (1964). Effect of redundancy and duration on absolute judgments of visual stimuli. *Journal of Experimental Psychology, 67*, 168-172.

Hsieh, I. H., & Saberi, K. (2007). Temporal integration in absolute identification of musical pitch. *Hearing Research, 233*, 108-116.

Kent, C., & Lamberts, K. (2005). An exemplar account of the bow and set-size effects in absolute identification. *Journal of Experimental Psychology: Learning Memory and Cognition, 31*, 289-305.

Kent, C., & Lamberts, K. (2006a). Modeling the time course of feature perception and feature information retrieval. *Journal of Memory and Language, 55*, 553-571.

Kent, C., & Lamberts, K. (2006b). The time course of perception and retrieval in matching and recognition. *Journal of Experimental Psychology-Human Perception and Performance, 32*, 920-931.

Kent, C., & Lamberts, K. (2008). The encoding-retrieval relationship: retrieval as mental simulation. *Trends in Cognitive Sciences, 12*, 92-98.

Lacouture, Y. (1997). Bow, range, and sequential effects in absolute identification: A response-time analysis. *Psychological Research, 60*, 121-133.

Lacouture, Y., Li, S.-C., & Marley, A., A, J. (1998). The roles of stimulus and response set size in the identification and categorization of unidimensional stimuli. *Australian Journal of Psychology, 50*, 165-174.

Lacouture, Y., & Marley, A. A. J. (2004). Choice and response time processes in the identification and categorization of unidimensional stimuli. *Perception & Psychophysics, 66*, 1206-1226.

Lamberts, K. (1995). Categorization under time pressure. *Journal of Experimental*

Psychology: General, 124, 161-180.

Lamberts, K. (1998). The time course of categorization. *Journal of Experimental Psychology: Learning Memory and Cognition, 24*, 695-711.

Lamberts, K. (2000). Information accumulation theory of speeded categorization. *Psychological Review, 107*, 227-260.

Lamberts, K., & Freeman, R. P. J. (1999). Building object representations from parts: Tests of a stochastic sampling model. *Journal of Experimental Psychology: Human Perception and Performance, 25*, 904-926.

Lamberts, K., & Kent, C. (2008). The time course of object-feature retrieval in recognition. *Journal of Experimental Psychology-Learning Memory and Cognition, 34*, 688-695.

Loftus, G. R., Duncan, J., & Gehrig, P. (1992). On the time course of perceptual information that results from a brief visual presentation. *Journal of Experimental Psychology-Human Perception and Performance, 18*, 530-549.

Loftus, G. R., & McLean, J. (1999). A front end to a theory of picture recognition. *Psychonomic Bulletin and Review, 6*, 394-411.

Luce, R. D., Nosofsky, R. M., Green, D. M., & Smith, A. F. (1982). The bow and sequential effects in absolute identification. *Perception & Psychophysics, 32,* 397-408.

Massaro, D. W. (1972a). Preperceptual images, Processing time, and perceptual units in auditory perception. *Psychological Review, 79*, 124-&.

Massaro, D. W. (1972b). Stimulus information Vs processing time in auditory pattern-recognition. *Perception & Psychophysics, 12*, 50-56.

Matthews, W. J., & Stewart, N. (2009). A relative judgment model of response times in absolute identification. *Manuscript submitted for publication*.

Meyer, D. E., Irwin, D. E., Osman, A. M., & Kounios, J. (1988). The dynamics of cognition and action - Mental processes inferred from speed accuracy decomposition. *Psychological Review, 95*, 183-237.

Miller, G. A. (1956). The magical number seven plus or minus two: some limits on our capacity for processing information. *Psychological Review, 63*, 81-97.

Nosofsky, R. M. (1983). Information integration and the identification of stimulus noise and criterial noise in absolute judgment. *Journal of Experimental Psychology-Human Perception and Performance, 9*, 299-309.

Nosofsky R.M. (1997). An exemplar based random-walk model of speeded categorization and absolute judgement. In A. J. Marley (Ed.), *Choice, decision, and measurement; Essays in honour of R. Duncan Luce* (pp. 347-365.) Mahwah, NJ: Erlbaum.

Petrov, A. A., & Anderson, J. R. (2005). The dynamics of scaling: A memory-based anchor model of category rating and absolute identification. *Psychological Review, 112*, 383-416.

Rouder, J. N., Morey, R. D., Cowan, N., & Pfaltz, M. (2004). Learning in a unidimensional absolute identification task. *Psychonomic Bulletin & Review, 11*, 938-944.

Rumelhart, D. E. (1970). A multicomponent theory of perception of briefly exposed visual displays. *Journal of Mathematical Psychology, 7*, 191-218.

Schwarz, W., & Kühn, S. (2008). Better to take one long or two quick looks? Independent processing of evidence from discrete visual presentations. *Journal of Experimental Psychology-Human Perception and Performance, 34*, 1337-1352.

Shiffrin, R. M., & Nosofsky, R. M. (1994). Seven plus or minus two - a commentary

on capacity limitations. *Psychological Review, 101*, 357-361.

Sperling, G. (1963). A model for visual memory tasks. *Human Factors, 5*, 19-31.

Stewart, N. (2007). Absolute identification is relative: A reply to Brown, Marley, and Lacouture (2007). *Psychological Review, 114*, 533-538.

Stewart, N., Brown, G. D. A., & Chater, N. (2005). Absolute identification by relative judgment. *Psychological Review, 112*, 881-911.

Ward, L. M. (1991). Informational and neural adaptation curves are asynchronous. *Perception & Psychophysics, 50*, 117-128.

Wever, E. G., & Zener, K. E. (1928). The method of absolute judgment in psychophysics. *Psychological Review, 35*, 466-493.

Author notes

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Footnotes

[1] We used intermixing here to avoid long-term strategy use by participants. That is, the state of the participant going into a trial was not confounded with the type of the trial, which would occur in a blocked design.

[2] For the visual stimuli this refresh rate meant we actually had exposure times of 253, 173, and 120 ms for the different stimulus presentation times in Experiments 1-6, and the inter-presentations gaps and masks were rounded up to the nearest multiplier of 13.333 ms.

[3] Following Luce, Nosofsky, Green, and Smith (1982), $d'_{i\,i+1}$ was used as a measure of discriminability between the stimulus$_i$ and stimulus$_{i+1}$ (lower $d'_{i\,i+1}$ scores indicate less discriminability). The following definition of $d'_{i,\,i+1}$ is with respect to a stimulus pair $(i, i+1)$. A response of $i + 1$ or greater to Stimulus $i + 1$ is considered a 'hit', whereas a response of i or less is considered a 'miss'. Similarly a response of $i + 1$ or greater to Stimulus i is considered a 'false alarm' whereas a response of i or less is a 'correct rejection' (Nosofsky, 1983b). $d'_{i,\,i+1}$ is then calculated in the normal way (see Green & Swets, 1966 or Macmillan & Creelman, 2006). The RT analysis was conducted on both correct and incorrect RT, but in all cases the main effect of Condition was the same as that for correct RT and so only analysis on correct RT is presented.

[4] The hazard must be decreasing in the tail because accuracy asymptotes before 1.

[5] Decreasing or peaked hazard for stimulus sampling would be required to fit Experiment 4b. This could perhaps be achieved rather trivially by a small probability that stimulus sampling never proceeds on any given presentation.

[6] Note that, if the proportion false alarms or hits in a cell is either 0 or 1, then $d'_{i,i+1}$ will tend to infinity. For this reason whenever either proportion was 0 or 1 it was replaced with .05 and .95 respectively. Given that the maximum number of cells per condition in the 200 trial blocks was 16 this replacement is adequate in that the difference between 1/20 (the shift used for the replacement of ceiling and floor proportions) and 1/16 is greater than that of 1/16 and 1/15. Thus $d'_{i,i+1}$ scores would change more for more extreme responding. Replacing proportions of 0 or 1 by .025 or .975 had little effect on the outcome of the $d'_{i,i+1}$ analyses. Note that using replacements with much smaller differences is problematic as $d'_{i,i+1}$ scores become very large or very small, increasing the variance in $d'_{i,i+1}$ scores.

Table 1.

	Participant				
	1	2	3	4	5
Stimulus	** ^^	** ^^	** ^	** ^^	** ^^
Trial length	** ^^	** ^^	^^	** ^^	** ^^
Number of presentations		^			*
Stimulus x Length		*		^^	^^
Stimulus x Number	^^		*		
Length x Number				*	
Stimulus x Length x Number					

Note. ANOVA results for d'$_{i,i+1}$ (*) and RT (^) analysis of individual participant data from Experiment 6. Single symbols (* or ^) indicate p<.05 and two symbols (** or ^^) indicates p<.01.

Figure list

Figure 1. A temporal schematic of Experiments 1-3. S = stimulus; M = mask; numbers refer to milliseconds; ??? is the response prompt.

Figure 2. Discrimination (top row) and response times (bottom row) for the absolute identification of tone frequency task (Experiment 1a, left column) and the absolute identification of line length task (Experiment 1b, right column). Each graph shows data for the 1-stimulus (○) and 2-stimulus (□) conditions and for each stimulus (or stimulus pair $d'_{i, i+1}$). $d'_{i, i+1}$ = discriminability; RT = mean correct response time. Large symbols represent grand condition means. Errors bars represent within subject 95% confidence intervals.

Figure 3. Discrimination (top row) and response times (bottom row) for the absolute identification of tone frequency task (Experiment 2a, left column) and the absolute identification of line length task (Experiment 2b, right column). Each graph shows data for the masked ISI (○) and unmasked ISI (□) conditions for each stimulus (or stimulus pair $d'_{i, i+1}$). $d'_{i, i+1}$ = discriminability; RT = mean correct response time. Large symbols represent grand condition means. Errors bars represent within subject 95% confidence intervals.

Figure 4. Discrimination (top row) and response times (bottom row) for the absolute identification of tone frequency task (Experiment 3a, left column) and the absolute identification of line length task (Experiment 3b, right column). Each graph shows data for the short exposure (○) and long exposure (□) duration conditions for each

stimulus (or stimulus pair $d'_{i, i+1}$). $d'_{i, i+1}$ = discriminability; RT = mean correct response time. Large symbols represent grand condition means. Errors bars represent within subject 95% confidence intervals.

Figure 5. Discrimination (top row) and response times (bottom row) for the absolute identification of tone frequency task (Experiment 4a, left column) and the absolute identification of line length task (Experiment 4b, right column). Each graph shows data for the 2-stimulus (○) and 3-stimulus (□) conditions for each stimulus (or stimulus pair $d'_{i, i+1}$). $d'_{i, i+1}$ = discriminability; RT = mean correct response time. Large symbols represent grand condition means. Errors bars represent within subject 95% confidence intervals.

Figure 6. A temporal schematic of Experiment 5. S = stimulus; M = mask; numbers refer to milliseconds; ??? is the response prompt.

Figure 7. Discrimination (top row) and response times (bottom row) for the absolute identification of tone frequency task (Experiment 5a, left column) and the absolute identification of line length task (Experiment 5b, right column). Each graph shows data for the short ISI (50 ms; ○) and long ISI (2000 ms; □) conditions for each stimulus (or stimulus pair $d'_{i, i+1}$). $d'_{i, i+1}$ = discriminability; RT = mean correct response time. Large symbols represent grand condition means. Errors bars represent within subject 95% confidence intervals.

Figure 8. A temporal schematic of Experiment 6. S = stimulus; M = mask; numbers refer to milliseconds; ??? is the response prompt.

*Figure 9*. Discrimination for the absolute identification of tone frequency task (Experiment 6). Each graph shows data for the conditions crossing short response delay (250 ms; ○) and long response delay (2150 ms; □) with one-presentation (+) and two-presentation (×) conditions for each adjacent stimulus pair. $d'_{i, i+1} =$ discriminability. Panels 1-5 show results for Participants 1-5 respectively and panel 6 shows the average results. Large symbols represent grand means for the main effects. Errors bars represent repeated measures 95% confidence intervals on the basis of trial blocks (see text). Panel AVG shows averaged data.

Figure 10. Mean correct response times for the absolute identification of tone frequency task (Experiment 6). Each graph shows data for the conditions crossing short response delay (250 ms; ○) and long response delay (2150 ms; □) with one-presentation (+) and two-presentation (×) conditions for each stimulus. Panels 1-5 show results for Participants 1-5 respectively and panel 6 shows the average results. Large symbols represent grand means for the main effects. Errors bars represent repeated measures 95% confidence intervals on the basis of trial blocks (see text). Panel AVG shows averaged data.

a) Experiment 1

1–stimulus

| S | ??? |

250

2–stimulus

| S |

| S | ??? |

250   2000   250
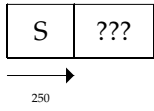
b) Experiment 2

Unmasked

| M | S |

| S | M | ??? |

250 250   2000   250 250

Masked

| M | S | M |

| S | M | ??? |

250 250   2000   250 250
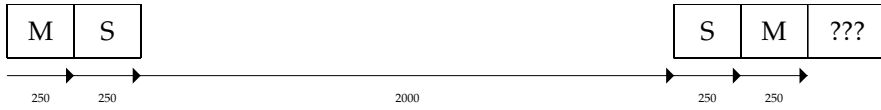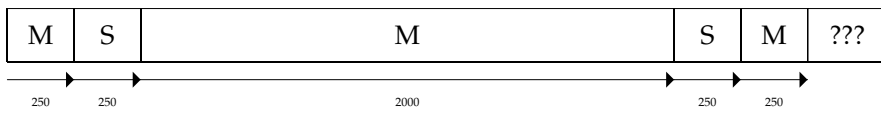
c) Experiment 3

Long exposure

| M | S | M |

| S | M | ??? |

250 250   2000   250 250

Short exposure

| M | S | M |

| S | M | ??? |

250 125   2250   125 250
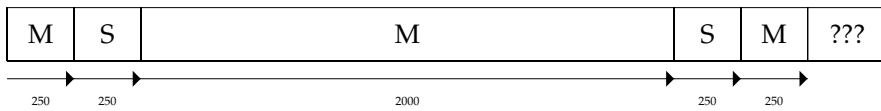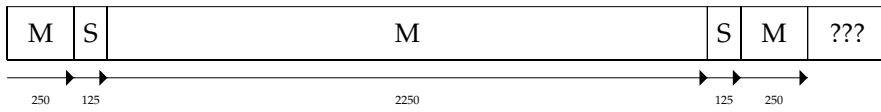
d) Experiment 4

2–stimulus

| M | S | M |

| S | M | ??? |

250 250   4000   250 250

3–stimulus

| M | S | M | S | M |

| S | M | ??? |

250 167   2000   167   2000   167 250
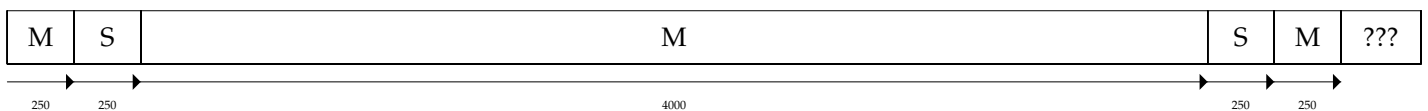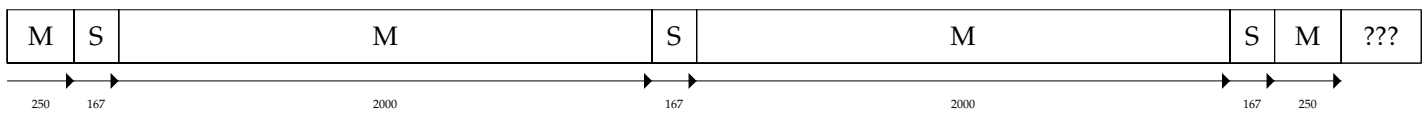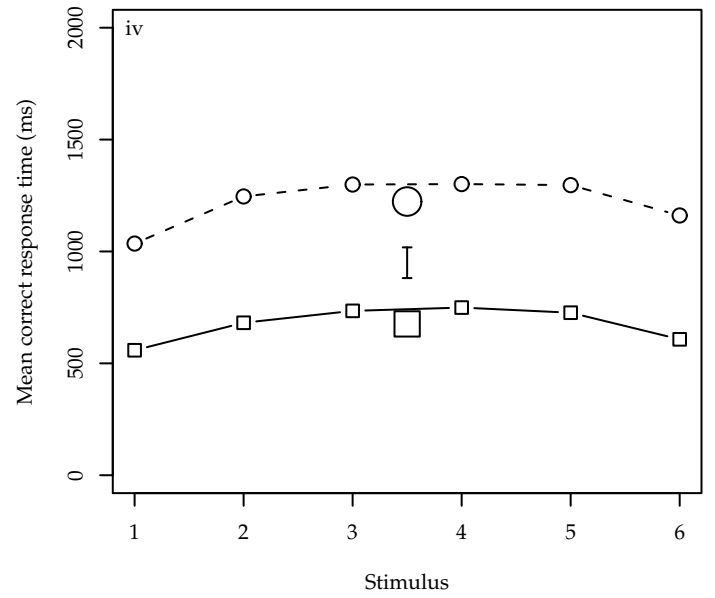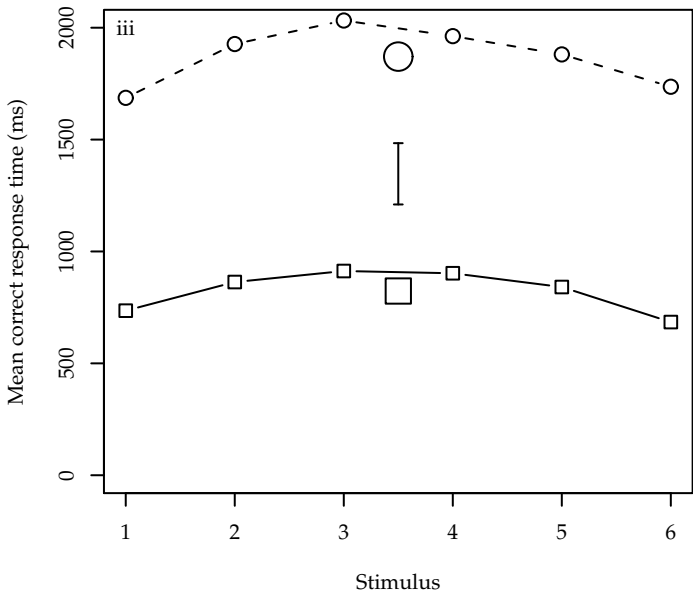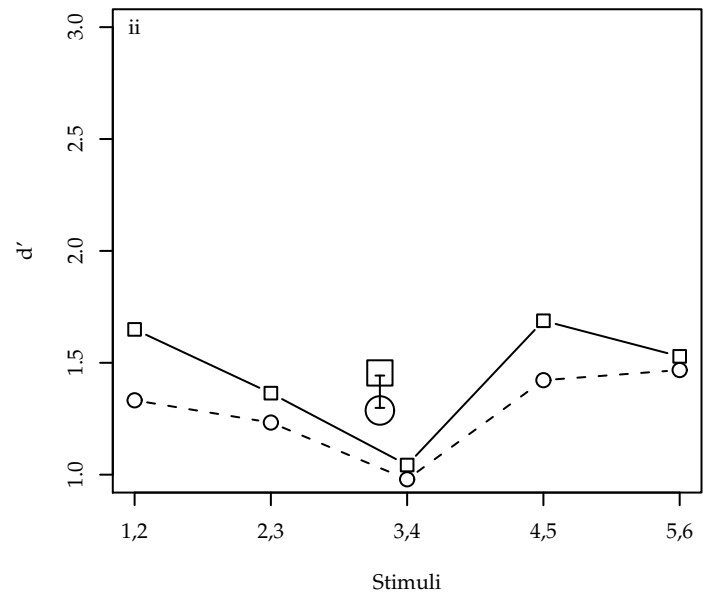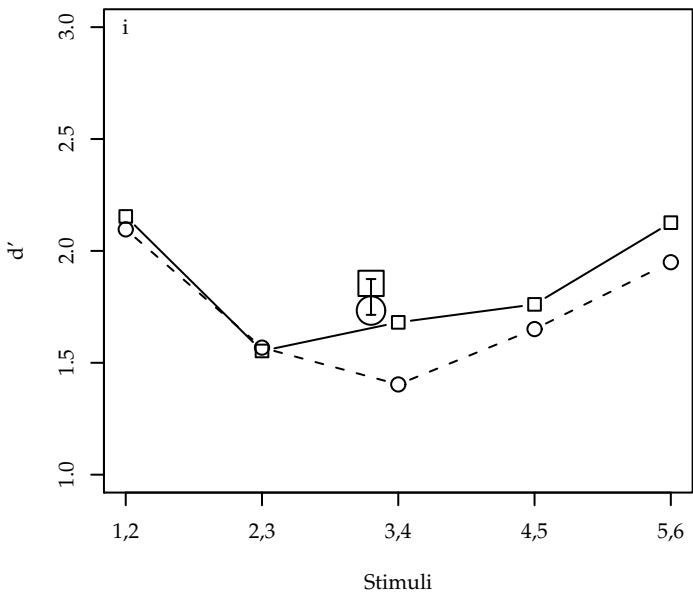
FIGURE 1

FIGURE 2 / EXPT 1
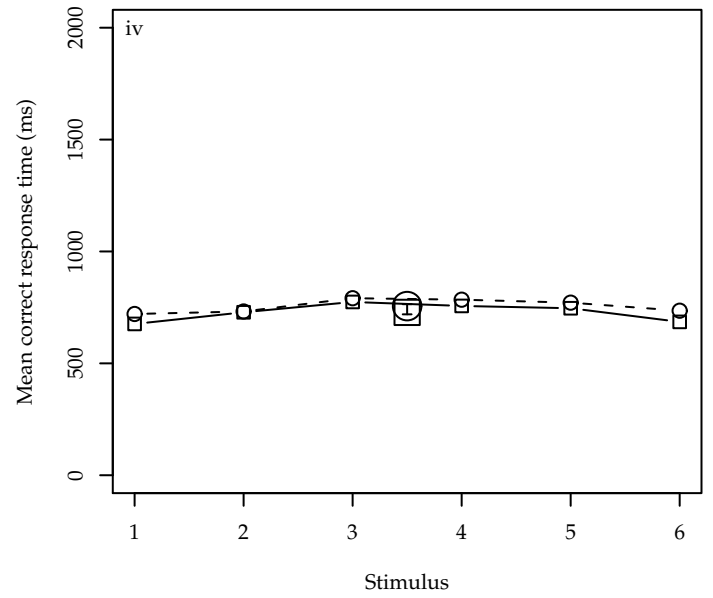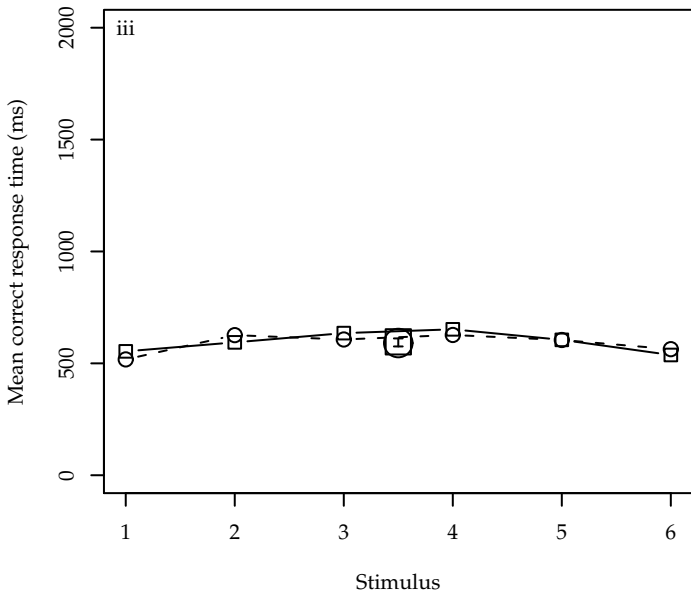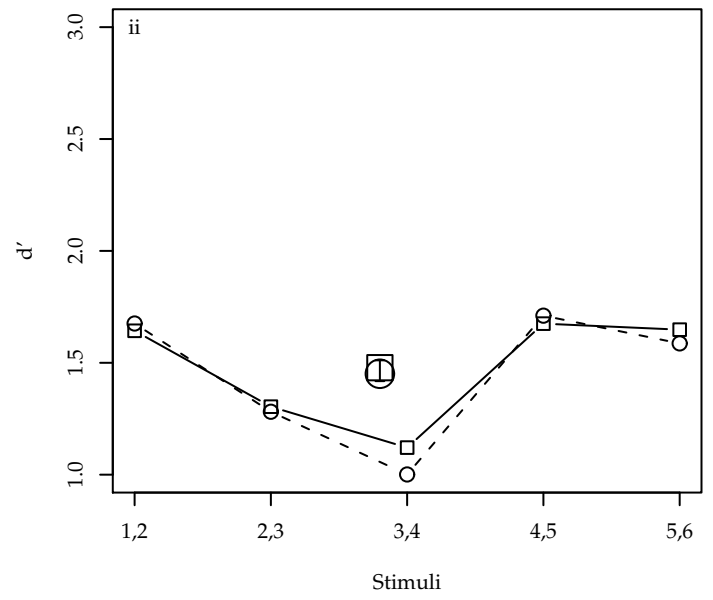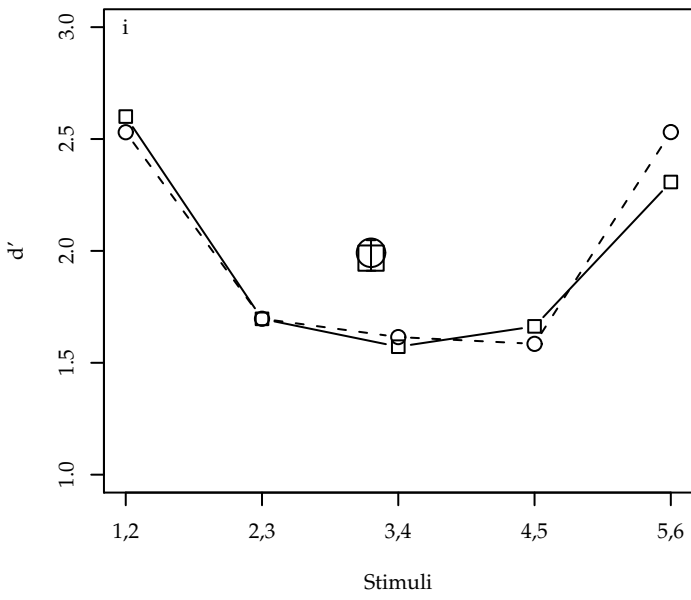
FIGURE 3 / EXPT 2
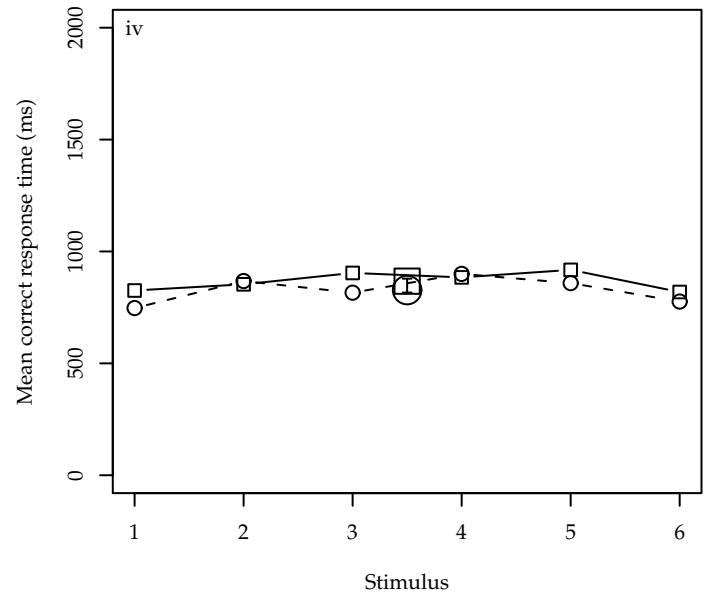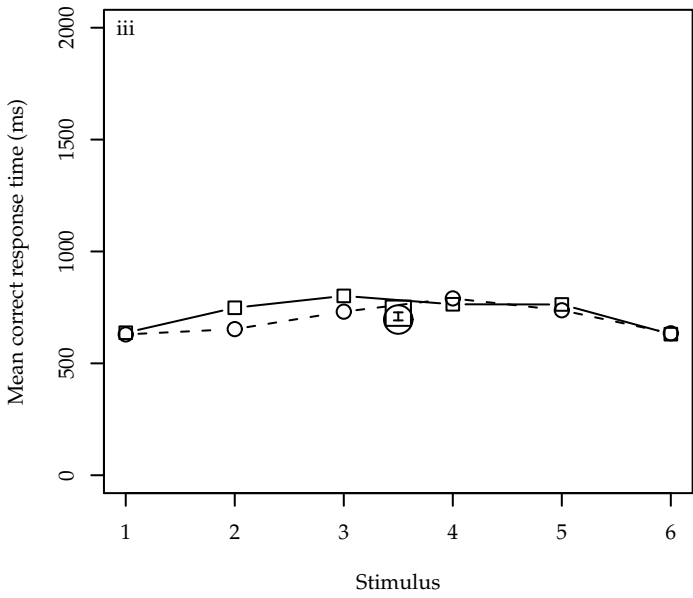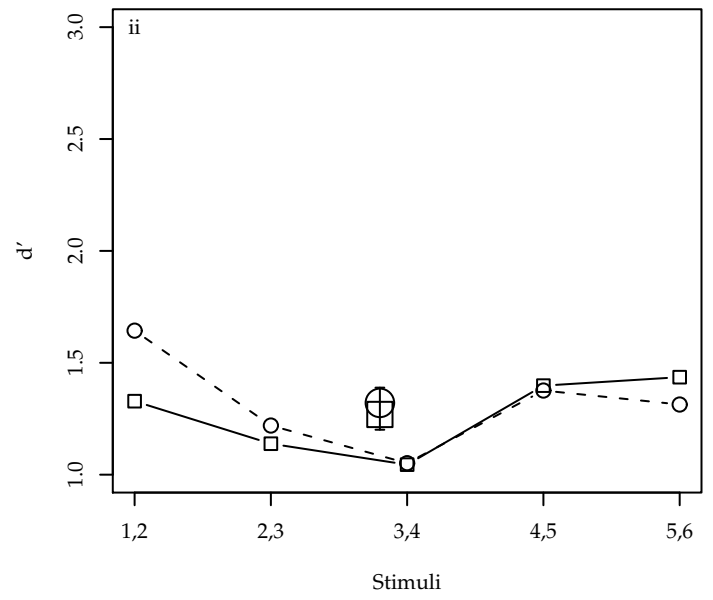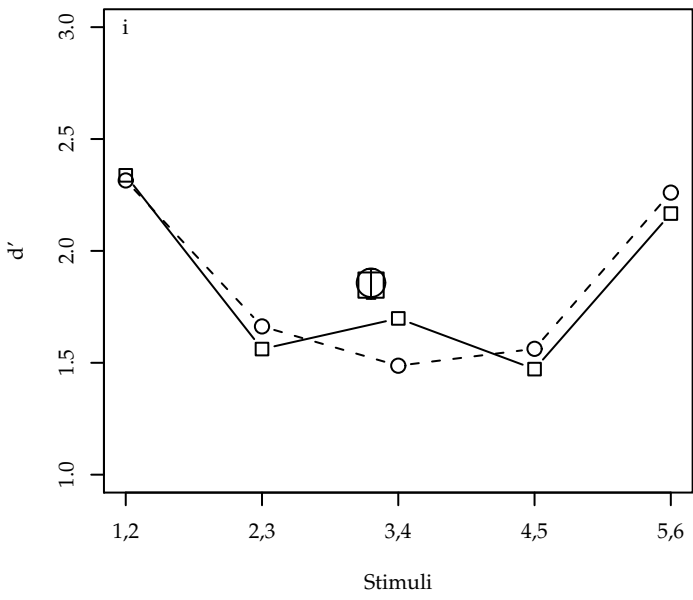
FIGURE 4 / EXPT 3
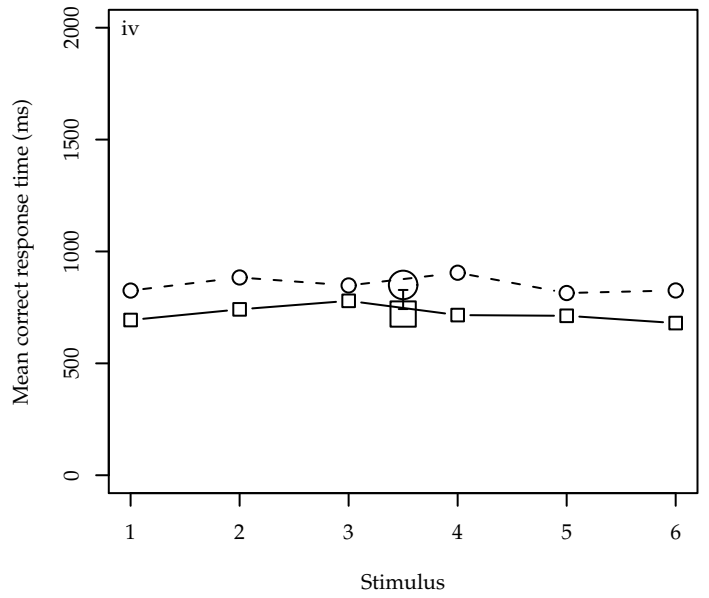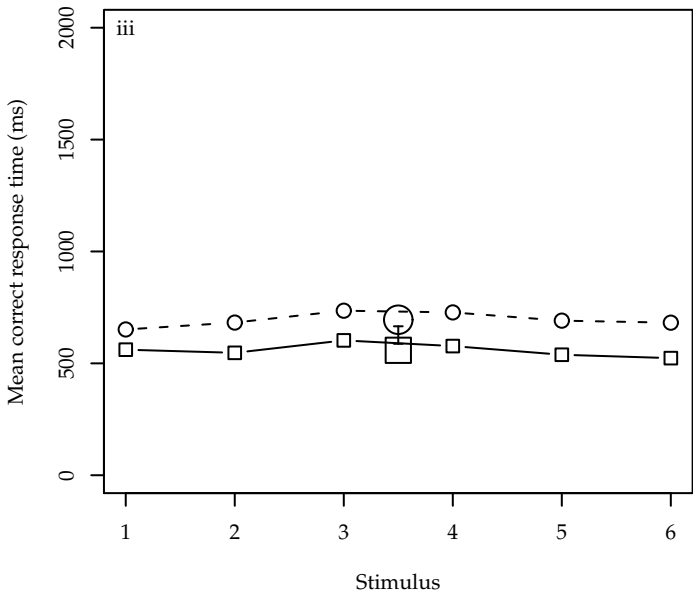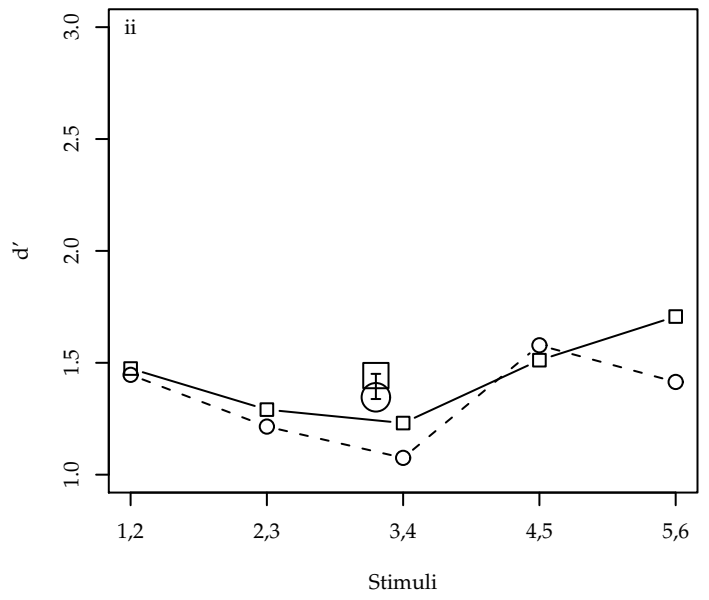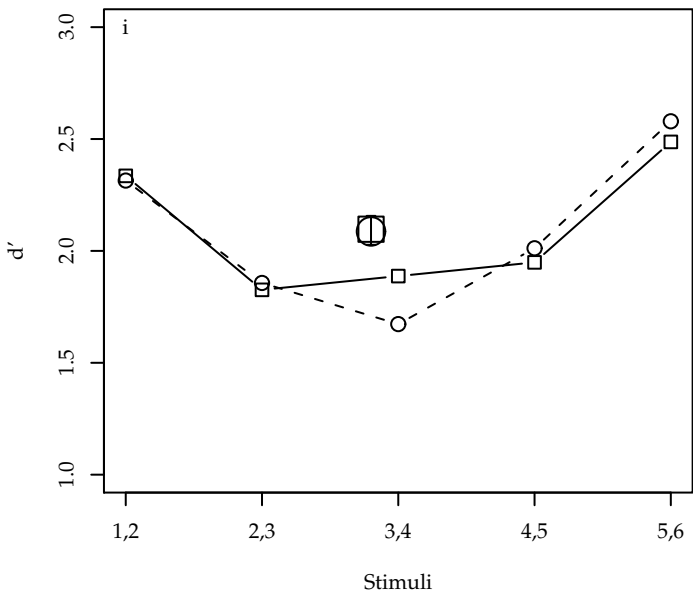
FIGURE 5 / EXPT 4

Experiment 5

Long trial

M	S	M	S

		M
		???

250   250   2000   250   250

Short trial

| M	S	M	S

		M
		???

250   250   50   250   250
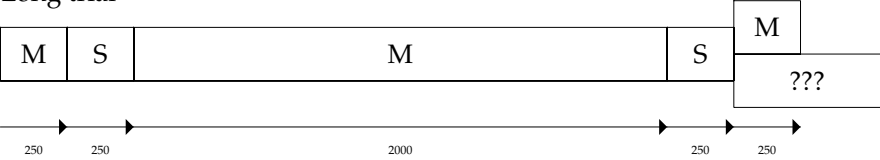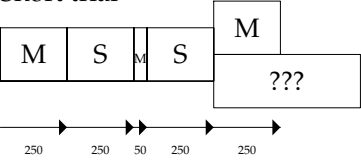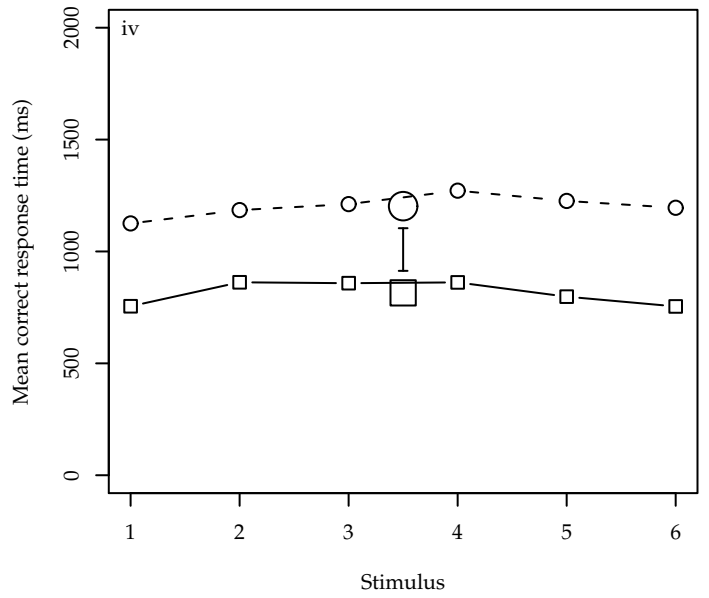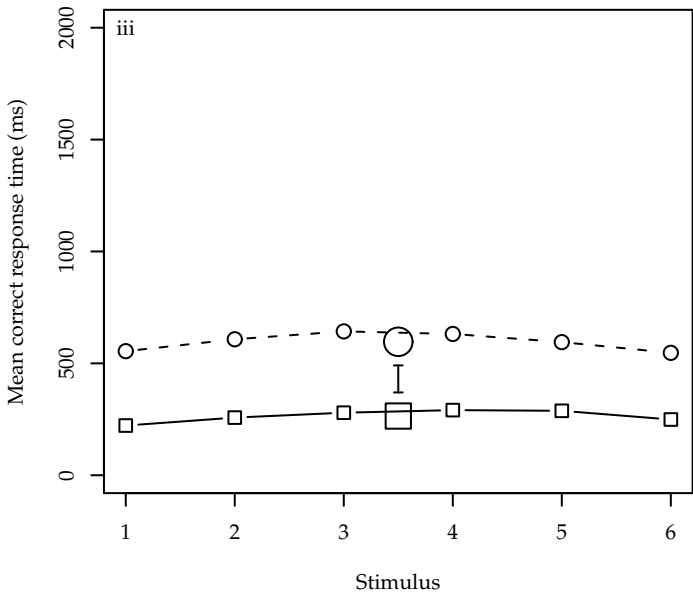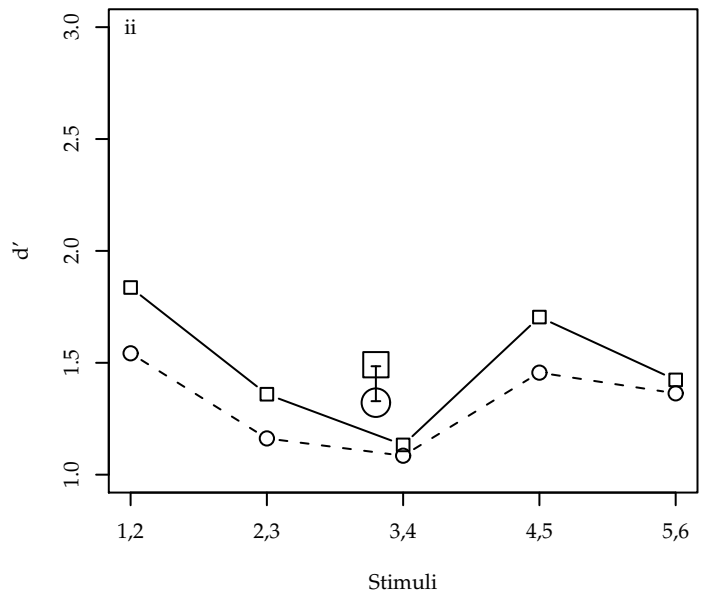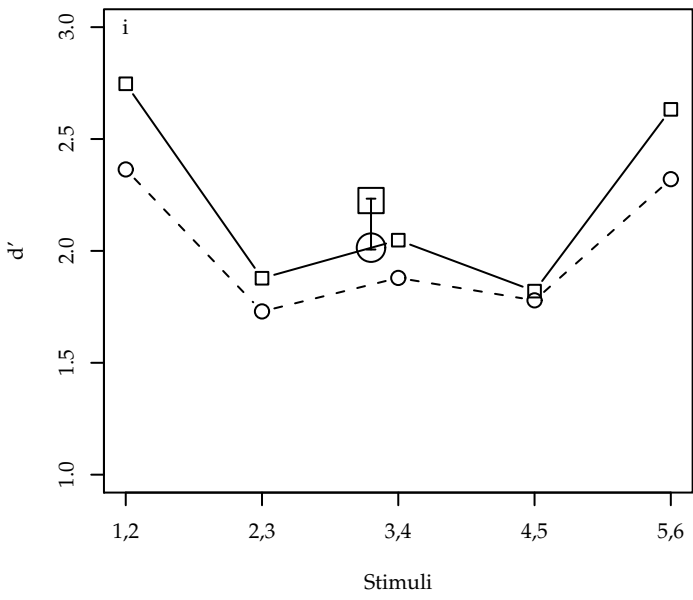
FIGURE 6

FIGURE 7 / new EXPT 5

Experiment 6

Long trial, 2 presentations
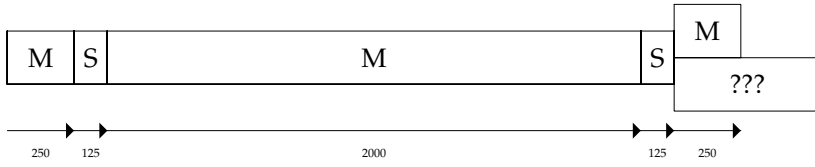
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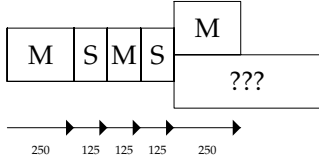
Long trial, 1 presentation
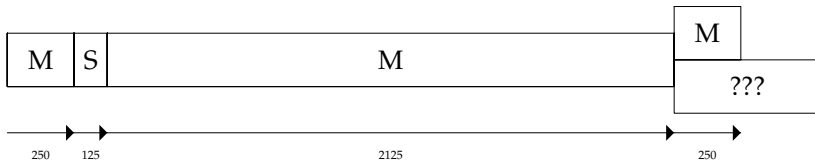
Short trial, 1 presentations
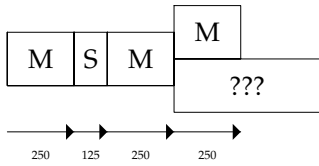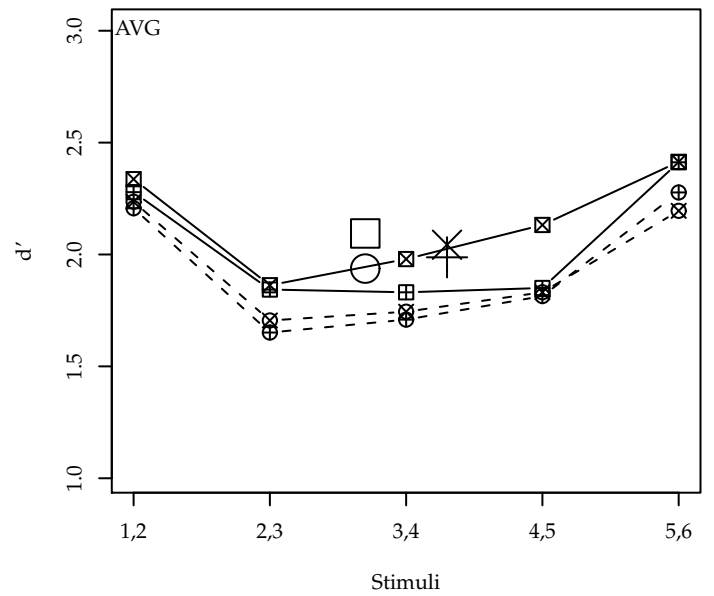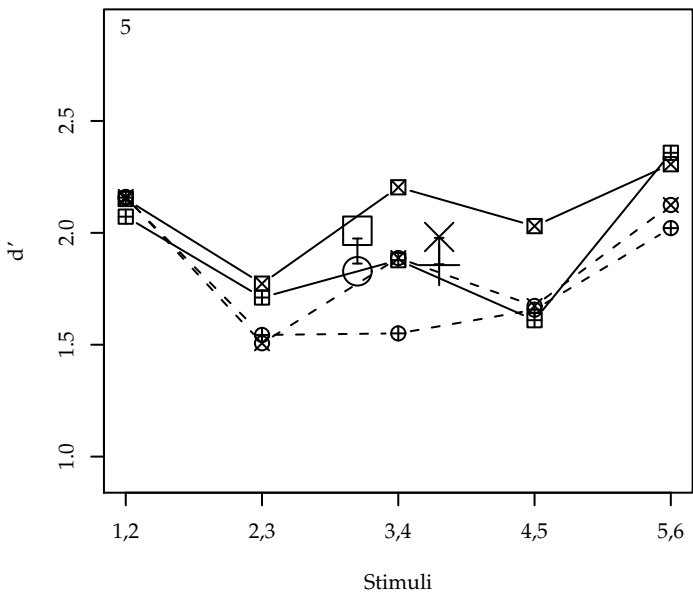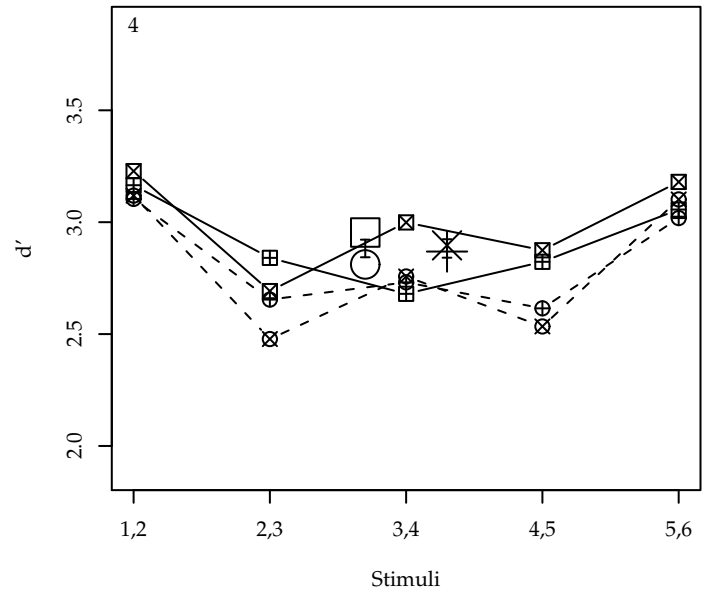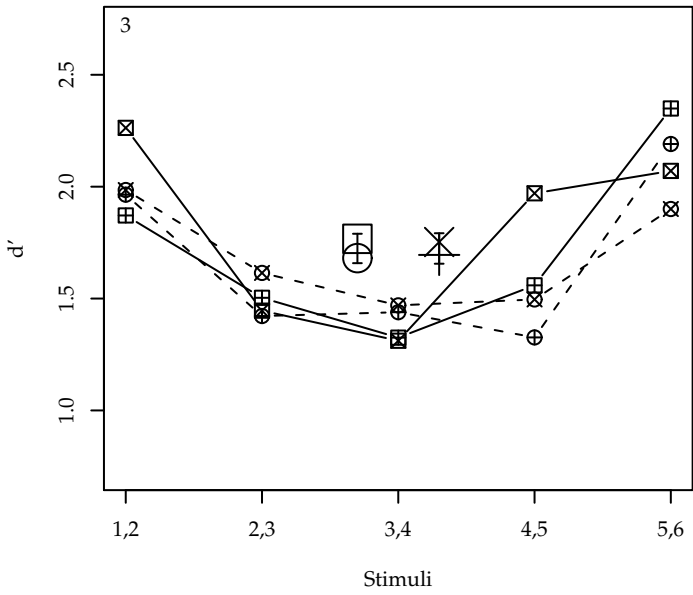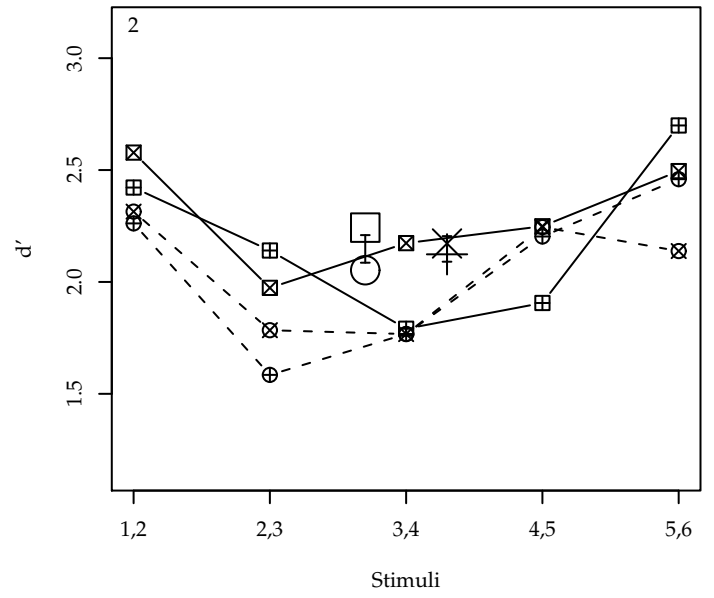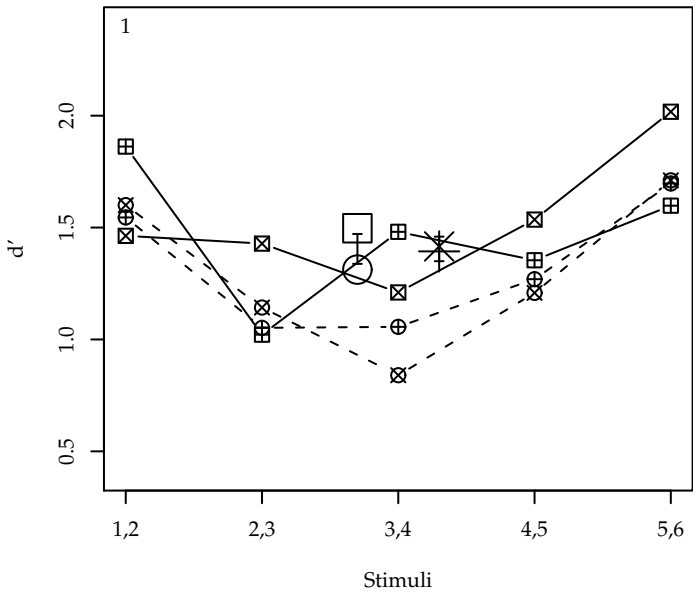
FIGURE 8

FIGURE 9 / EXPT 6 d'

FIGURE 10 / EXPT 6 RT