

RUNNING HEAD: MODALITY & INTENSITY EFFECTS ON TIME REPRODUCTION

Combined effects of motor response, sensory modality,
and stimulus intensity on temporal reproduction

Allegra Indraccolo^{1,2,†}, Charles Spence¹, Argiro Vatakis³, & Vanessa Harrar^{1,4,*,†}

¹Department of Experimental Psychology, University of Oxford, GB

²Department of Human Science, Università Europea di Roma, Italy

³Cognitive Systems Research Institute, Athens, Greece

⁴School of Optometry, Université de Montréal, Canada

† A.I. and V.H. contributed equally to this work

(*) Correspondence should be addressed to:

vanessa.harrar@umontreal.ca

School of Optometry, University of Montreal

3744 Jean-Brillant, Montréal, QC, H3T 1P1, Canada

Tel: +1 (514) 343-6111 x 31551

Fax: +1 (514) 343-2382

Number of figures 4

Number of tables 2

Number of words 3627

+ Supplementary section (RM-ANOVA analysis results)

Abstract

The ability to estimate a filled interval of time is affected by numerous non-temporal factors, such as the sensory modality, duration, and the intensity of the stimulus. Here we explore the role of modality (auditory or visual), stimulus intensity (low vs. high), and motor response speed on the ability to reproduce the duration of short (<1s) filled intervals. In accordance with the literature, the reproduced duration was affected both by the modality and intensity of the stimulus; longer reproduction times were generally observed for visual as compared to auditory stimuli, and for low as compared to high intensity stimuli. We used general estimating equations in order to determine whether these factors independently affected participants' ability to reproduce a given duration, after eliminating the variability associated with reaction time, since it covaries with the reproduced durations. This analysis revealed that stimulus duration, modality, and intensity were all significant independent predictors of the reproduced durations. Additionally, duration interacted with intensity when reproducing auditory intervals. That is, after taking into account the general speeding-up effect that high intensity stimuli have on responses, they seem to have an additional effect on the rate of the internal clock. These results support previous evidence suggesting that auditory and visual clocks run at different speeds.

Keywords: time estimation, stimulus magnitude, auditory, visual, processing speed

1. Introduction

Time is an integral part of our daily life, and the perception of duration is an area of particular interest to researchers in the field of cognitive neuroscience. While “duration has no existence in and of itself” (Fraisse, 1984), every stimulus has a duration, and accurate perception of time and duration is essential to adaptive behaviour (Belin et al., 2002).

The perception of duration is affected by a variety of non-temporal factors. A duration that is filled is perceived as longer than one that is unfilled (Allan, 1979), but this is limited to very short durations (Rammsayer, 2014). The duration of a higher intensity stimulus is perceived as longer than the duration of a less intense stimulus (Matthews et al., 2011). Auditory and visual stimuli of equal duration are rarely perceived as such (e.g., Goldstone & Lhamon, 1974; Penney et al., 2000). Duration perception is also affected by one’s cognitive load (Allan, 1992, 1998; Tse et al., 2004; see Eagleman & Pariyadath, 2009, for a review), by the presentation of large or small numbers during the interval (see numerosity studies, such as Dormal & Pesenti, 2007; Javadi & Aichelburg, 2012), and can also depend upon whether the stimuli are presented on the left or right side of space (e.g., Cappelletti, Freeman, & Cipolotti, 2009).

While many tasks have been used to investigate temporal perception, the temporal reproduction task is one of the most commonly used (e.g., Fraisse, 1964; Ulbrich et al., 2006; Woodrow, 1930). In this task, participants are presented with a stimulus of a specific duration (sample stimulus) and, subsequently, with a second stimulus (comparison stimulus). Their task is to produce a motor action in order to terminate the comparison stimulus when they think that its duration is equal to that of the sample stimulus.

Reproduced durations using the reproduction task appear to be more stable because the task requires fewer cognitive resources (e.g., memory) for the processing of time (Gil & Droit-Volet, 2011). We therefore chose this task in order to investigate simultaneous effects of modality and intensity on duration perception. However, reproduced durations using this task vary between participants in a way that can be partially predicted by the individual's reaction times (RTs), since preparing and executing motor responses take time. There are individual differences in the time taken to plan, prepare, and execute motor commands and press a button, causing RT to be highly correlated with temporal reproduction times (Droit-Volet, 2010). Thus, in the present study, we factored out the variation in reproduced durations that can be attributed to the variability in RTs, and then assessed the variability due to modality and intensity.

Previous reports have repeatedly demonstrated that auditory and visual stimuli of similar duration aren't perceived as such (see Penney 2003, for a review). However, multiple methodological differences among studies (see Table 1) make it difficult to interpret this difference. For example, the perceived duration of auditory stimuli might depend on how they are presented; auditory stimuli are sometimes presented over headphones, at other times via external loudspeakers, sometimes they are co-localized with the visual stimuli while at other times they are presented spatially offset. Spatial separation between stimuli is known to affect multisensory binding and processing speeds (Spence & Driver, 1997; though see also Spence, 2013), and could thus have contributed to the differences in time perception between studies. Similarly, the relative intensity of the stimuli that were presented in different modalities has largely been overlooked, especially with respect to intensities of the background stimuli (Matthews, Wearden, & Stewart, 2011). We suggest

that the difference in relative intensity between modalities might partially explain previous differences in results (see Table 1). One of the goals of the present study was therefore to determine whether the effects of modality and intensity directly affect duration estimation, or whether the effects might be mediated by the same process that causes variations in RTs to different stimuli (e.g., processing speeds, threshold criterion).

Table 1. Selective summary of studies on duration perception.

Task	Authors	Auditory	Visual	Duration (ms)	Results
Duration bisection	Penney et al. (2000)**	880 Hz, ~ 70dB	Black squares	3000-6000	A>V
Duration bisection & verbal estimation	Wearden et al. (2006)**	500 Hz	Blue squares	150-865	A>V
Temporal reproduction	Brown & Hitchcock (1965)**	1000Hz ~ 60 dB	9 or 22 ft-c	1000-17000	A=V
	Hirsh et al. (1956) [†]	250 Hz ~ 80dB Noise or quiet background	Flash Dark or light background	1000-16000	Depends on background intensity
	Walker & Scott (1981) [†]	600 Hz ~ 75dB	Neon light	500-1500	1500 ms: A>V 500 ms: V>A
	Goldstone (1968)**	1000 Hz ~ 84dB	Blue-white light	1000-4000	V>A
	Ulbrich et al. (2006) [‡]	300 & 600 Hz, ~ 70dB	White and yellow square	1000-5000	V>A
	Szelag et al. (2002)**	200 Hz ~40-60dB	Light 7cd/m ²	1000-5500	A=V
Temporal generalization & verbal estimation	Wearden et al. (1998)**	500 Hz	Light-blue squares	400-600	A>V
Temporal judgment	Goldstone & Goldfarb (1964) [†]	725 Hz ~ 70 db	Light	150-1950	A>V
	Matthews et al. (2011) [‡]	Stimulus: 46dB & 68dB Background: 42dB & 72dB	Stimulus: 1.8 & 98 cd/m ² Background 0.5 & 128 cd/m ²	600 & 800	Depends on relative intensity - signal to noise ratio

V>A: visual stimulus perceived as longer than auditory stimulus (vice versa for A>V).

A=V: visual and auditory stimuli of the same duration were perceived as such.

**Crossmodal study; † Multisensory study; *Separate experiments for each modality, not necessarily compared in the paper.

The speed with which stimuli are processed, and responded to, might be related to the clock speed. While processing speed is measured with responses to an event that occurs at a single point in time (e.g., onset or offset), clock speed is measured with responses to the duration of an event. A higher intensity stimulus has been repeatedly shown to have a longer perceived duration (Allan, 1979; Fraisse, 1984; Wearden et al., 1998). Louder auditory stimuli are perceived as longer than quieter sounds (e.g., Berglund et al., 1969; Goldstone et al., 1978; Zelkind, 1973), and brighter (or larger) visual stimuli are perceived as having a longer duration than dimmer or smaller ones (e.g., Goldstone & Goldfarb, 1964; Xuan et al., 2007, respectively). Similarly, sensory and perceptual processes proceed more rapidly for more intense stimuli (e.g., Jaśkowski et al., 1990; Levick, 1973; Rutschmann & Link, 1964). This is true for visual, auditory, and tactile stimuli (Angel, 1973; Jaśkowski et al., 2007; Kohfeld, 1971; van der Molen & Keuss, 1979). Attention might be at the root of the effects; More arousing stimuli would attract more attention and cause the organism to speed up (Eagleman & Pariyadath, 2009). Indeed, more intense stimuli appear to dominate the clock speed (Walker & Scott, 1981). Of course, processing speed also vary across modalities because stimulus transduction follows a different process, which take varying amounts of time (e.g., transduction in vision is a chemical reaction, which is slower than the mechanical transduction in touch, see Spence & Squire, 2003). Processing speed could therefore account for some of the differences between clock speeds across modalities.

In order to determine if the differences in processing speed between modalities (and between stimulus intensities) can account for the differences in duration perception, we measured RTs (that vary with processing speed and attention) and reproduced durations for stimuli in different modalities and at multiple intensity levels.

Using generalized estimating equations, we estimated the parameters of a general linear model with the possible correlation between reproduced duration and RT (Droit-Volet, 2010). If modality and intensity do not have a direct impact on the internal clock, then we would not expect these two factors to be significant predictors of the reproduced duration (Figure 1b), since the effect they have on processing speed will already be taken into account by using RTs as covariates in the model. If, on the other hand, these factors have an additional impact on reproduced durations, there are 3 possible scenarios: It might be that only modality affects the rate of the internal clock directly (Figure 1c). Alternatively, we could see an additional effect of the intensity (model d). Or, intensity and modality might affect the speed of the clock (Figure 1e). While previous studies have focused on the effects of these non-temporal factors on duration perception mostly in isolation, the present study is the first to elucidate any interaction among modality, duration, and intensity.

2. Methods

2.1. Participants

Twenty-one (14 female; M=25.6 years of age) students from the University of Oxford took part in the study. All had normal or corrected-to-normal vision and normal hearing (by self-report). Each participant gave their informed consent prior to the experiment and was paid £10 for one-hour. The experiment was reviewed by the University of Oxford Central

University Research Ethics Committee and was conducted according to the ethical standards laid down in the Declaration of Helsinki (Version Seoul, 2008).

2.2. Stimuli

The visual stimuli measured 3x3 cm ($\sim 3.07^\circ$ visual angle) and were displayed in the centre of a CRT computer screen (1280 x 960 pixels; 75Hz). The squares were displayed with one of two brightness levels: dark-grey (2.45cd/m^2) and white (87.50cd/m^2) presented against a black background (0.66cd/m^2 ; ColorCAL-Cambridge research systems colormeter).

The auditory stimuli were white noise bursts with one of two loudness levels: quiet ($40\pm 3\text{dB}$) and loud ($70\pm 3\text{dB}$) presented with background noise ($30\pm 3\text{dB}$) generated from the fans in the soundproof booth. The sounds were played from stereo loudspeakers placed on either side of the monitor – their perceived source was co-localised with the visual stimulus.

2.3. Procedure

The participants were seated in a dimly-lit anechoic chamber, facing a monitor placed at a distance of approximately 56 cm from their chin placed in a chin-rest. The experiment started with a short instruction and a few practice trials (which included feedback) prior to the main experiment.

To avoid response delays due to shifting attention between modalities (Spence et al., 2001), auditory and visual trials were presented in separate blocks (4 for each modality, ~ 5 min each). To distribute fatigue, memory mixing (Penney, 2003), and other potential confounds equally across blocks, the modality blocks were tested in an alternating fashion.

After four temporal reproduction blocks (two auditory and two visual alternating blocks), RTs to the two modalities were measured separately in alternating blocks (see Figure 2).

2.4. Temporal reproduction task

After the participant pressed the space bar to initiate the trial, there was a random delay (1500 ± 250 ms) before the presentation of the first (sample) stimulus. The duration of the sample stimulus was 600, 800 or 1000 ms. Then there was another variable blank interval (1500 ± 250 ms) followed by the second signal (the comparison stimulus). The participants were asked to 'turn off' the comparison stimulus (by pressing a button) when they thought that the comparison had been presented for the same duration as the sample stimulus (see Figure 2).

Within each block of trials, there were four stimulus intensity combinations: sample high/comparison high, sample high/comparison low, sample low/comparison high, and sample low/comparison low. Each intensity combination was presented four times at each of the three durations, plus an additional eight trials with random durations¹, giving rise to a total of 56 trials per block. While the order of stimulus presentation was randomised, they were clustered so that intensity combinations were presented together. Just before each sub-block of four trials, the participants were primed with the to-be-presented intensity combination.

2.5. RT task

¹ To minimize any learning effects, for 1/7th of the trials, the sample duration was random (500-1100 ms); the trials containing random durations were not analysed since there were usually no repetitions.

Each trial started with a random delay (1500 ± 500 ms). Then, the stimulus was presented and the participants were instructed to press a button as soon as they saw (or heard) the stimulus (i.e., at stimulus onset).

As with the temporal reproduction task, auditory and visual stimuli were presented in separate, alternating blocks – counterbalanced among participants. In each block, low-intensity stimuli (dark-grey square or 40dB white noise) and high-intensity (white square or 70dB white noise) were randomly presented.

2.6. Analysis

The data were inspected for outliers. One participant was removed due to exceedingly slow RTs (medians >1 sec).

Kolmogorov-Smirnov tests revealed that both RTs and reproduction data were positively skewed and significantly different from normal [RT task: $D(1521)=.225$; $p<.001$; temporal reproduction task: $D(8073)=.020$; $p<.001$]. Thus, we used medians as measures of central tendency. Median RTs were calculated for each participant for each of the four stimulus types, and median reproduced durations were calculated for each participant for each of the 24 stimulus types. The medians were normally distributed [RT task: $D(76)=.059$; $p=.20$; temporal reproduction task: $D(240)=.054$; $p=.09$] and thus further analysis was conducted using parametric tests.

The results of a repeated measures analysis of variance (RM-ANOVA) for RT data is presented in the Supplementary Materials. Similarly, several RM-ANOVAs were conducted for the data obtained from the temporal reproduction tasks (central tendency, precision, and accuracy) and are presented in the Supplementary Materials. These results replicate

previous studies by demonstrating effects of intensity and modality on duration reproduction. However, the majority of previous studies have looked at modality, duration, and intensity in isolation (or, at most, at two factors simultaneously, e.g., Walker & Scott, 1981; Rammsayer, 2014). More important than the replication of previously reported effects, the novel question in the present study is whether the factors tested affect duration reproduction *independently* from the effect these factors have on processing/RTs (applied in the model with RTs as covariates). Figure 1 describes several different models of how the factors might be related. To best determine the nature of the any interactions, and the strength that each factor exerts on the reproduced duration, we have used an altogether novel analysis of the temporal reproduction results.

We used a generalized estimating equation (GEE) model to investigate the effect of the factors and the covariate on the reproduced duration (see Equation 1 for the general form of the model). The reproduced duration was the outcome of the equation. The modality, the intensity of the sample stimulus, the intensity of the comparison, and the duration of the sample stimulus were factors – as such, interactions between these factors were directly assessed. Since the intensity of the sample and comparison stimuli varied independently (sample stimulus/comparison stimulus: high/high; high/low; low/high; low/low), it was important to consider RTs to sample and comparison stimuli as independent factors. RTs were set as covariates in the model. This analysis technique takes into account the dependency between the multiple measures of each participant, while building a model (equation) that includes only significant factors (and their interactions) and estimates the beta values associated with each.

3. Results

To test for dark adaptation, we compared reproduced duration of the visual stimuli in the first and last block. There was no significant difference [$F(1,19) < 1$] suggesting that any effects of dark adaptation over the course of the experiment were negligible.

Modality had a significant main effect on the reproduced duration ($p < .001$) and significant interactions with duration ($p < .001$) and intensity (Modality*Intensity of comparison stimulus: $p = .029$). This significant interaction means that the effect of modality is not the same across durations or across intensities. The effect of modality is larger when the sample stimulus is low intensity – compared to the negligible effect of modality when the sample stimuli are high intensity (Figure 3a); The effect of modality is larger when the comparison stimulus is high intensity – compared to the negligible effect of modality when the comparison stimulus is low intensity (Figure 3b); The effect of modality is largest at short durations, and negligible at the longest duration tested – 1 sec (Figure 3c). There was also a significant 3-way interaction (Modality*Duration*Intensity, $p = .022$). To follow this interaction and gain a better understanding of how RT, stimulus intensity, and duration affect reproduction in each modality, auditory and visual models were estimated independently.

The final model predicting auditory reproduced duration included more significant factors than the final model for predicting visual reproduced durations ($QIC_{\text{auditory}}: 3242957$; $QIC_{\text{visual}}: 6502364$). While all main effects (duration and intensity of both the sample and the comparison stimulus) and interaction effects were significant predictors of the reproduced durations of auditory stimuli (at least one level of “duration” was significantly different from baseline), fewer factors affected visual reproduced durations (see Table 2). Equations 2 and

3 indicate only the significant factors for models of auditory and visual reproduction times, respectively.

The output from the GEE analysis revealed that the RT to the comparison stimulus was a significant predictor of the reproduced duration, which is apt since the participants' response requires a button press to the comparison stimulus when it has reached a certain duration. The negative beta value suggests that longer RTs (e.g., for dim or quiet stimuli) resulted in shorter reproduced durations.

Intensity and duration of the stimuli affect the reproduced duration. As the duration of the sample stimulus increased (from 600 to 800 or 1000 ms) the duration of the reproduced stimulus also increased. The intensity of the sample stimulus, the stimulus whose duration the participants are attempting to replicate, has a positive beta value meaning that higher intensity (bright or loud) stimuli are replicated with longer durations than lower intensity sample stimuli (see Figure 3). However, since significant interactions are present, the main effects should be considered with caution.

For both auditory and visual stimuli, the interaction of the intensity of the sample and the comparison stimuli was a significant predictor when modelling the reproduced duration ($p < .001$, see Table 2). Figure 4 demonstrates that when the intensity of the sample stimulus matches the intensity of the comparison stimulus (either both high or both low intensity) reproduced durations are similar for visual and auditory, both slightly overestimate the actual duration (~830 ms across all durations and modalities). However, when the intensity of the sample stimulus is high, and the intensity of the comparison stimulus is low, then the reproduced duration greatly exceeds the actual duration. In contrast, when the intensity of the auditory sample stimulus is low, and the intensity of the

auditory comparison stimulus is high, the duration that is reproduced is an underestimation. Other interactions between these factors that significantly predicted the auditory (but not visual) reproduced duration include the interaction of intensity with duration (see Table 2 for beta and p-values, and see Figure 4 for estimated means).

Table 2. Factors (intensity and duration) and covariates (RT) significantly affecting reproduced duration for auditory and visual stimuli. See mean values in Figures 3 and 4.

Predictors	Auditory		Visual	
	Beta	p-value	beta	p-value
Intercept	749.7	p< .001	899.2	p< .001
RT to the comparison	-2.1	p= .001	-0.8	p= .002
RT to the sample	1.6	p= .015	0.2	p= .460
Intensity of the sample	99.0	p< .001	62.7	p< .001
Intensity of the comparison	-44.5	p= .067	-2.8	p= .903
Duration	198.5	p< .001	139.8	p< .001
	359.8		246.4	
Intensity of the sample* Intensity of the comparison	-88.9	p< .001	-88.1	p< .001
Intensity of the sample* Duration	47.2	p= .005	12.7	p= .413
	16.8	p= .512	-0.5	p= .985
Intensity of the comparison* Duration	-49.9	p= .079	-3.8	p= .862
	-83.5	p= .003	-13.4	p= .566
Intensity of the sample* Intensity of the comparison* Duration	10.6	p= .736	13.9	p= .543
	84.5	p= .031	48.1	p= .154

N.B. Factors were treated as categorical variables: Intensity was coded with 0 or 1 (low or high intensity, respectively), and duration was coded as 0, 1, or 2 (600, 800, or 1000 ms, respectively). Beta values are only relevant when the factor is not set to zero (i.e., factor=1: high intensity or 800 ms duration) or 2 (1000 ms duration). Only Duration has three levels, therefore there are two rows for effects related to Duration. The upper beta value for duration represents the 800 ms duration, and the lower value represents the 1000 ms duration.

Equation 1.

$$\text{Reproduction}_{\text{general}} = \text{Intercept} + \text{RT}_c + \text{RT}_s + \text{Intensity}_s + \text{Intensity}_c + \text{Duration}_{800} + \text{Duration}_{1000} + \text{Intensity}_s * \text{Intensity}_c + \text{Intensity}_s * \text{Duration}_{800} + \text{Intensity}_s * \text{Duration}_{1000} + \text{Intensity}_c * \text{Duration}_{800} + \text{Intensity}_c * \text{Duration}_{1000} + \text{Intensity}_s * \text{Intensity}_c * \text{Duration}_{800} + \text{Intensity}_s * \text{Intensity}_c * \text{Duration}_{1000}$$

Equation 2.

$$\text{Reproduction}_{\text{Auditory}} = \text{Intercept} + \text{RT}_C + \text{RT}_S + \text{Intensity}_S + \text{Duration}_{800} + \text{Duration}_{1000} + \text{Intensity}_S * \text{Intensity}_C + \text{Intensity}_S * \text{Duration}_{800} + \text{Intensity}_C * \text{Duration}_{1000} + \text{Intensity}_S * \text{Intensity}_C * \text{Duration}_{1000}$$

Equation 3.

$$\text{Reproduction}_{\text{Visual}} = \text{Intercept} + \text{RT}_C + \text{Intensity}_S + \text{Duration}_{800} + \text{Duration}_{1000} + \text{Intensity}_S * \text{Intensity}_C$$

These results reveal that each of these factors significantly and independently affected the reproduction response, as well as some interactions between these factors. We found that the reproduced duration increased as the duration of the sample stimulus increased. The reproduced duration also increased as the intensity of the sample stimulus decreased, but decreased with increased motor response speed. Finally, the reproduced duration was generally longer for the visual stimuli used here compared to the auditory stimuli.

4. Discussion

Overall, the results of the present study demonstrate that multiple factors affect the ability of people to reproduce durations and these factors interact in complex ways. The analysis we provide, estimating the equation that best predicts the reproduced durations, suggests that while modality and intensity affect response latency (a general speeding-up of the organism's response) they have additional effects on duration perception, thus supporting the hypothesis that these factors directly mediate the speed of an internal clock.

The schematic image depicted in Figure 1e, where modality and intensity affect processing speed and the speed at which the internal clock ticks, is the model that is best supported by the results reported here. More evidence is required to determine the range of stimulus intensities and durations where these results hold true.

The internal clock is an important element of the **scalar timing theory** framework (Gibbon et al., 1984). This theory has been proposed as an explanation for how we perceive time. In this theory, timing is accounted for by three basic processing stages. The first one (clock stage) is described as a pacemaker-accumulator linked to an accumulator by a switch. When a stimulus begins, the switch opens and pulses flow into the accumulator; at stimulus offset, the switch closes and the flow of pulses supposedly stops. The second stage is the memory stage in which the representation of the duration is transferred to short-term memory. The number of pulses stored in the accumulator provides the basis for judgment of stimulus duration if required at the decision state (third stage). According to such a framework, modality and intensity likely influence the speed of the clock (i.e., stage one) by impacting the rate of the pacemaker-accumulator, or the latency with which the switch is opened and closed, or the variance of the switch latencies (Matthews et al., 2011; **Meck, 1984**; Penney, 2003; Penney et al., 2000; Ulbrich et al., 2006).

In the clock model, stimulus modality, intensity, and duration could affect different components of the clock. The effect of modality on duration reproduction has previously been attributed to differences in the pacemaker-accumulator speed (Penney et al., 2000; Wearden, 2003; Wearden et al., 1998). There are at least two possible accounts to explain the clock speed differences between modalities. First, the pacemaker-accumulator might run at a different (usually faster) rate for auditory stimuli than for visual ones, so that within the same duration more pulses will have accumulated for auditory stimuli than for visual stimuli. It has been suggested that the visual pacemaker-accumulator needs more time to accumulate the pulses for a specific duration (Zelkind, 1973). In the temporal reproduction task, participants reproducing a specific duration of an auditory stimulus will stop the

presentation earlier as compared to if the stimulus had been visual. Second, since visual stimuli are usually reproduced with longer durations than auditory ones, it has been proposed that visual stimuli might be less efficient at holding the switch in an open state causing greater oscillations between a closed and an open state, which would produce a greater loss of pulses in the visual than in the auditory modality (Penney, 2003). A similar reasoning could also be used to explain the effect of intensity on duration estimation. That is, more pulses might accumulate for the high intensity stimuli than for the low intensity ones; on the other hand, duration may be affected by changes at the memory stage (second stage).

Given the data, it seems unlikely that memory contributed to the effect of modality. Stimuli with longer durations would need to be kept in memory for longer periods of time (in particular, in a reproduction task). Thus, a stimulus with a long duration will have larger memory components than a shorter stimulus. If memory contributed to the modality effect, then there should be a larger difference between modalities at longer durations. However, the data show the opposite effect: The difference in reproduced durations between modalities was nearly absent at longer durations (see Figure 3c) while reproduction times were significantly shorter for auditory than visual stimuli at shorter durations (see similar results in Rammsayer, 2014). Therefore, memory load does not appear to contribute to the difference in modalities, for duration up to 1000 ms (Fraisse 1984; Ulbrich et al., 2006; see the difference between perception and estimation of duration). Instead, the interaction effects that we found, especially the interaction effects of modality and duration, might be related to the decision stage of the internal clock model, which produces a specific judgment and the subsequent motor response of the participants.

Overall, these results fit with the hypothesis of an internal clock, with different components, that are affected by the modality, duration, and intensity of the stimuli. It is possible that there are two modality specific clocks (Penney, 2003; Rousseau & Rousseau, 1996; this could explain the different interactions that we found for the auditory and visual modality), or a single clock with the possibility of running at different speeds (the latter view supported by Walker and Scott's, 1981, early suggestion of "auditory dominance"). Perhaps the Bayesian approach, recently proposed as a tool to investigate temporal perception (Shi et al., 2013), can be used to distinguish between the hypotheses.

5. Conclusion

In conclusion, the results of the present study demonstrate the complicated relationship between modality, intensity, and processing speed. While the effects of modality and intensity are known, as well as the effect of motor speed, we present novel interactions between these three factors. More importantly, these factors appear to contribute to the perception of duration independently from the general effects they have on the speed of the organism's response. Our results support the view that modality and intensity affect motor speed and duration perception. Importantly, these data negate the possibility that the difference in duration perception across modalities and intensities is solely due to the difference with which the stimuli are processed. For example, while auditory stimuli were consistently responded to more quickly than visual stimuli (faster processing speed), auditory stimuli were not consistently reproduced with shorter durations than visual stimuli (see Figure 4a). Although we process high intensity stimuli more quickly than low intensity stimuli, this is not the sole explanation for high intensity stimuli appearing

to last for shorter periods of time. While processing speed appears to play some role in the variation in duration reproduction, on the basis of the GEE analysis, we show that there appear to be additional mechanisms (such as the rate of the internal clock) that are directly influenced by changes in modality, duration, and intensity – in a manner that cannot be predicted from the effects of these factors on processing speed. Temporal perception and reproduction appear to be the result of an interaction between the speed of processing, the speed of responding, and the speed at which the internal clock is ticking.

Acknowledgments: VH was supported by the Mary Somerville Junior Research Fellowship from Somerville College, Oxford University; and is currently supported by a Banting Fellowship. VH & AV were supported by the European COST Action ISCH TD0904 “TIMELY” (www.timely-cost.eu). CS would like to acknowledge the AHRC Rethinking the Senses grant (AH/L007053/1).

References

- Allan, L. G. (1979). The perception of time. *Perception & Psychophysics*, **26**, 340–354.
- Allan, L. G. (1992). The internal clock revisited. In F. Macar, V. Pouthas, & W. Freidman (Eds.), *Time, action and cognition: Towards bridging the gap* (pp. 191–202). London: Kluwer Academic.
- Allan, L. G. (1998). The influence of the scalar timing model on human timing research. *Behavioural Processes*, **44**, 101–117.
- Angel, A. (1973). Input-output relations in simple reaction time experiments. *Quarterly Journal of Experimental Psychology*, **25**, 193–200.
- Belin, P., McAdams, S., Thivard, L., Smith, B., Savel, S., Zilbovicius, M., Samson, S., & Samson, Y. (2002). The neuroanatomical substrate of sound duration discrimination. *Neuropsychologia*, **40**, 1956–1964.
- Berglund, B., Berglund, U., Ekman, G., & Frankenhaeuser, M. (1969). The influence of auditory stimulus intensity on apparent duration. *Scandinavian Journal of Psychology*, **10**, 21–26.
- Brown, D. R., & Hitchcock, L. (1965). Time estimation: Dependence and independence of modality-specific effect. *Perceptual and Motor Skills*, **21**, 727–734.
- Cappelletti, M., Freeman, E. D., & Cipolotti, L. (2009). Dissociations and interactions between time, numerosity and space processing. *Neuropsychologia*, **47**, 2732–2748.
- Dormal, V., & Pesenti, M. (2007). Numerosity-length interference: A Stroop experiment. *Experimental Psychology*, **54**, 289–297.
- Droit-Volet, S. (2010). Stop using time reproduction tasks in a comparative perspective without further analyses of the role of the motor response on the temporal performance. The case of children. *European Journal of Cognitive Psychology*, **22**, 130–148.
- Eagleman, D. M., & Pariyadath, V. (2009). Is subjective duration a signature of coding efficiency? *Philosophical Transactions of the Royal Society B*, **364**, 1841–1851.
- Fraisse, P. (1964). *The psychology of time*. London: Eyre & Spottiswoode.
- Fraisse, P. (1984). Perception and estimation of time. *Annual Review of Psychology*, **35**, 1–36.

- Gibbon, J., Church, R. M., & Meck, W. H. (1984). Scalar timing in memory. In J. Gibbon & L. Allan (Eds.), *Annals of the New York Academy of Sciences*, **423**: *Timing and time perception* (pp. 52–77). New York: New York Academy of Sciences.
- Gil, S., & Droit-Volet, S. (2011). Time flies in the presence of angry faces...*depending on the temporal task used*. *Acta Psychologica*, **136**, 354–362.
- Goldstone, S. (1968). Production and reproduction of duration: Intersensory comparisons. *Perceptual and Motor Skills*, **26**, 755–760.
- Goldstone, S., & Goldfarb, J. L. (1964) Auditory and visual time judgment. *Journal of General Psychology*, **70**, 369–387.
- Goldstone, S., & Lhamon, W. T. (1974). Studies of auditory-visual differences in human time judgment: 1. Sounds are judged longer than lights. *Perceptual and Motor Skills*, **39**, 63–82.
- Goldstone, S., Lhamon, W. T., & Sechzer, J. (1978). Light intensity and judged duration. *Bulletin of the Psychonomic Society*, **12**, 83–84.
- Hirsh, I. J., Bilger, R. C., & Deatherage, B. H. (1956). The effect of auditory and visual background on apparent duration. *American Journal of Psychology*, **69**, 561–574.
- Jaśkowski, P., Jaroszyk, F., & Hojan-lezierska, D. (1990). Temporal-order judgments and reaction time for stimuli of different modalities. *Psychological Research*, **52**, 35–38.
- Jaśkowski, P., Kurczewska, M., Nowik, A., Van Der Lubbe, R. H. J., & Verleger, R. (2007). Locus of the intensity effect in simple reaction time tasks. *Perception & Psychophysics*, **69**, 1334–1343.
- Javadi, A. H., & Aichelburg, C. (2012). When time and numerosity interfere: The longer the more, and the more the longer. *PLoS One*, **7**(7), e41496. doi: 10.1371/journal.pone.0041496.
- Kohfeld, D. L. (1971). Simple reaction time as a function of stimulus intensity in decibels of light and sound. *Journal of Experimental Psychology*, **88**, 251–257.
- Levick, W. R. (1973). Variation in the response latency of cat retinal ganglion cells. *Vision Research*, **13**, 837–853.
- Matthews, W. J., Stewart, N., & Wearden, J. H. (2011). Stimulus intensity and the perception of duration. *Journal of Experimental Psychology: Human Perception and Performance*, **37**, 303–313.
- Meck, W. H. (1984). Attentional bias between modalities: Effect on the internal clock, memory, and decision stages used in animal time discrimination. *Annals of The New York Academy of Sciences*, **423**, 528–541.
- Penney, T. B. (2003). Modality differences in interval timing: Attention, clock speed, and memory. In: *Functional and neural mechanisms of timing*, edited by W. H. Meck. Boca Raton, FL: CRC Press, 2003, pp. 209–234.
- Penney, T. B., Gibbon, J., & Meck, W. H. (2000). Differential effects of auditory and visual signals on clock speed and memory processes. *Journal of Experimental Psychology: Human Perception and Performance*, **26**, 1770–1787.

- Rammsayer, T. H. (2014). The effects of type of interval, sensory modality, base duration, and psychophysical task on the discrimination of brief time intervals. *Attention, Perception, & Psychophysics*, **76**, 1185-1196.
- Rousseau, L. and Rousseau, R. (1996). Stop-reaction time and the internal clock, *Perception & Psychophysics*, **58**, 434-448,.
- Rutschmann, J., & Link, R. (1964). Perception of temporal order of stimuli differing in sense mode and simple reaction time. *Perceptual & Motor Skills*, **18**, 345-352.
- Shi, Z., Church, R., & Meck, W. (2013). Bayesian optimization of time perception. *Trends in Cognitive Sciences*, **17**, 556-564.
- Spence, C. (2013). Just how important is spatial coincidence to multisensory integration? Evaluating the spatial rule. *Annals of the New York Academy of Sciences*, **1296**, 31-49.
- Spence, C., & Driver, J. (1997). On measuring selective attention to an expected sensory modality. *Perception & Psychophysics*, **59**, 389-403.
- Spence, C., Nicholls M., E., R., & Driver, J. (2001). The cost of expecting events in the wrong sensory modality. *Perception & Psychophysics*, **63**, 330-336.
- Spence, C., Shore, D. I., & Klein, R. M. (2001). Multisensory prior entry. *Journal of Experimental Psychology: General*, **130**, 799-832.
- Spence, C., & Squire, S. B. (2003). Multisensory integration: Maintaining the perception of synchrony. *Current Biology*, **13**, R519-R521.
- Szelag, E., Kowalska, J., Rymarczyk, K., & Pöppel, E. (2002). Duration processing in children as determined by time reproduction: Implications for a few seconds temporal window. *Acta Psychologica*, **110**, 1-19.
- Tse, P. U., Intriligator, J., Rivest, J., & Cavanagh, P. (2004). Attention and the subjective expansion of time. *Perception & Psychophysics*, **66**, 1171-1189.
- Ulbrich, P., Churan, J., Fink, M., & Wittmann, M. (2006). Temporal reproduction: Further evidence for two processes. *Acta Psychologica*, **125**, 51-65.
- Van der Molen, M. W., & Keuss, P. J. G. (1979). The relationship between reaction time and intensity in discrete auditory tasks. *Quarterly Journal of Experimental Psychology*, **31**, 95-102.
- Walker, J. T., & Scott, K. J. (1981). Auditory-visual conflicts in the perceived duration of lights, tones, and gaps. *Journal of Experimental Psychology: Human Perception and Performance*, **7**, 1327-1339.
- Wearden, J. H. (2003). Applying the scalar timing model to human time psychology: Progress and challenges. In H. Helfrich (Ed.), *Time and mind II*, pp. 21-39. Göttingen: Hogrefe & Huber
- Wearden, J. H., Edwards, H., Fakhri, M., & Percival, A. (1998). Why "sounds are judged longer than lights": Application of a model of the internal clock in humans. *Quarterly Journal of Experimental Psychology*, **51**, 97-120.
- Wearden, J. H., Todd, N. P. M., & Jones, L. A. (2006). When do auditory/visual differences in duration judgments occur? *Quarterly Journal of Experimental Psychology*, **59**, 1709-1724.

- Woodrow, H. (1930). The reproduction of temporal intervals. *Journal of Experimental Psychology*, **13**, 473–499.
- Zelkind, I. (1973). Factors in time estimation and a case for the internal clock. *Journal of General Psychology*, **88**, 295–301.

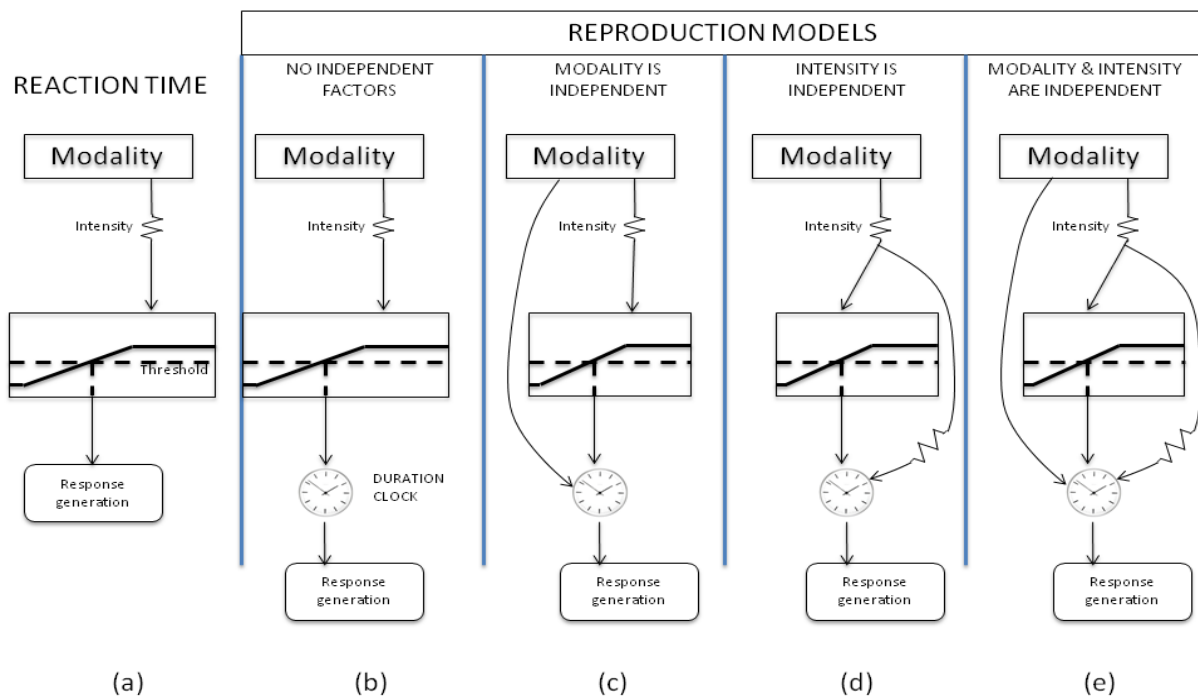
Figures:

Figure 1: Hypotheses concerning the factors affecting the internal clock. The intensity of a stimulus is depicted as a resistor, with low-intensity stimuli passing more slowly (i.e., high resistance) compared to high-intensity stimuli that pass more quickly through the system towards detection. a) For a RT task, the stimulus is transduced at the sensory organ represented by "MODALITY". Depending on the intensity of the stimulus, the action potential accumulates at different speeds until the "Threshold" is reached and then a signal is passed downstream. As soon as the threshold is reached, for the purpose of this overly simplified model, the organism becomes consciousness of the presence of the stimulus and a motor command to generate a response is initiated. b) The modality and intensity of the stimulus affect the rate at which it is detected. The "Duration Clock" accumulates pulses that are transmitted each time a stimulus reaches threshold. Since a low-intensity stimulus will take longer to reach threshold, it will send fewer pulses to the accumulator in any given period of time. c-d) The modality or intensity could independently affect the clock. For example, while the clock accumulates pulses as it did in model b, it might have a different gain for different modalities or different intensities. e) Depicts the model where intensity and modality independently affect the internal clock in addition to the effects that intensity and modality have on processing speed.

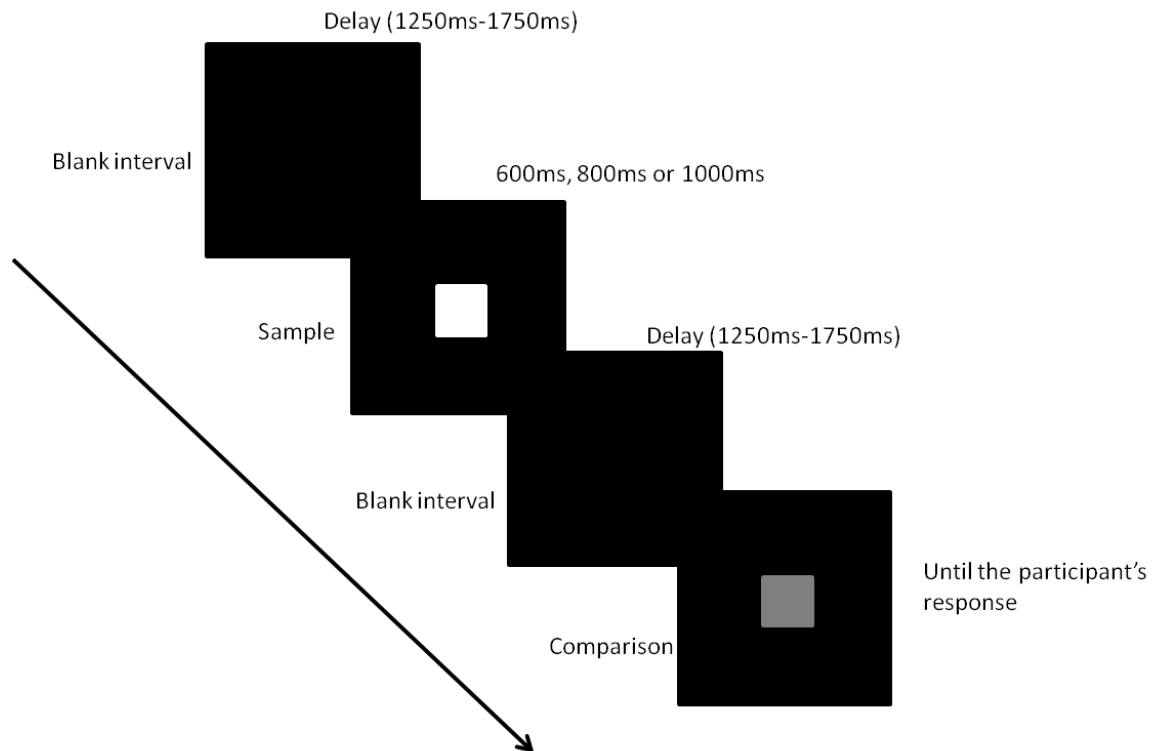


Figure 2. Trial structure for the temporal reproduction task. In the visual task, the sample and the comparison squares could either be white (87.50cd/m^2) or dark-grey (2.45cd/m^2). In the auditory task, the sample and the comparison sounds could either consist of a quiet (40dB) or a loud (70dB) burst of white noise. The sample stimulus lasted for one of three durations (600, 800 or 1000 ms). Following a blank interval (1250-1750 ms), a comparison stimulus was presented. The participants turned off the comparison stimulus when they perceived its duration to be the same as the sample duration.

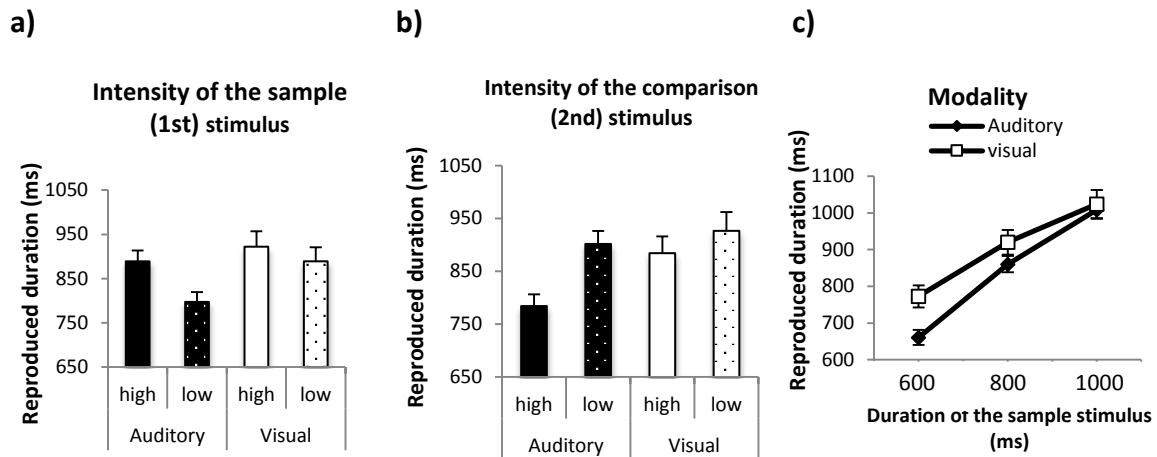


Figure 3. Main effects of stimulus intensity and duration on reproduced duration. a) Intensity of the sample stimulus significantly affects the reproduced duration. If the sample stimulus is low intensity (a quiet sound or a dim light), then the reproduced duration is shorter than when the sample stimulus is high intensity. b) Intensity of the comparison stimulus has the opposite effect (high intensity comparison stimuli are reproduced with shorter durations than low intensity comparison stimuli). c) As the duration of the sample stimulus increases, the reproduced duration also increases – but more so for auditory stimuli than visual stimuli. Covariates appearing in the model are fixed at the following values: RT_Auditory=179 ms; RT_Visual=215 ms. The error bars represent the standard error of the mean estimated in the GEE model.

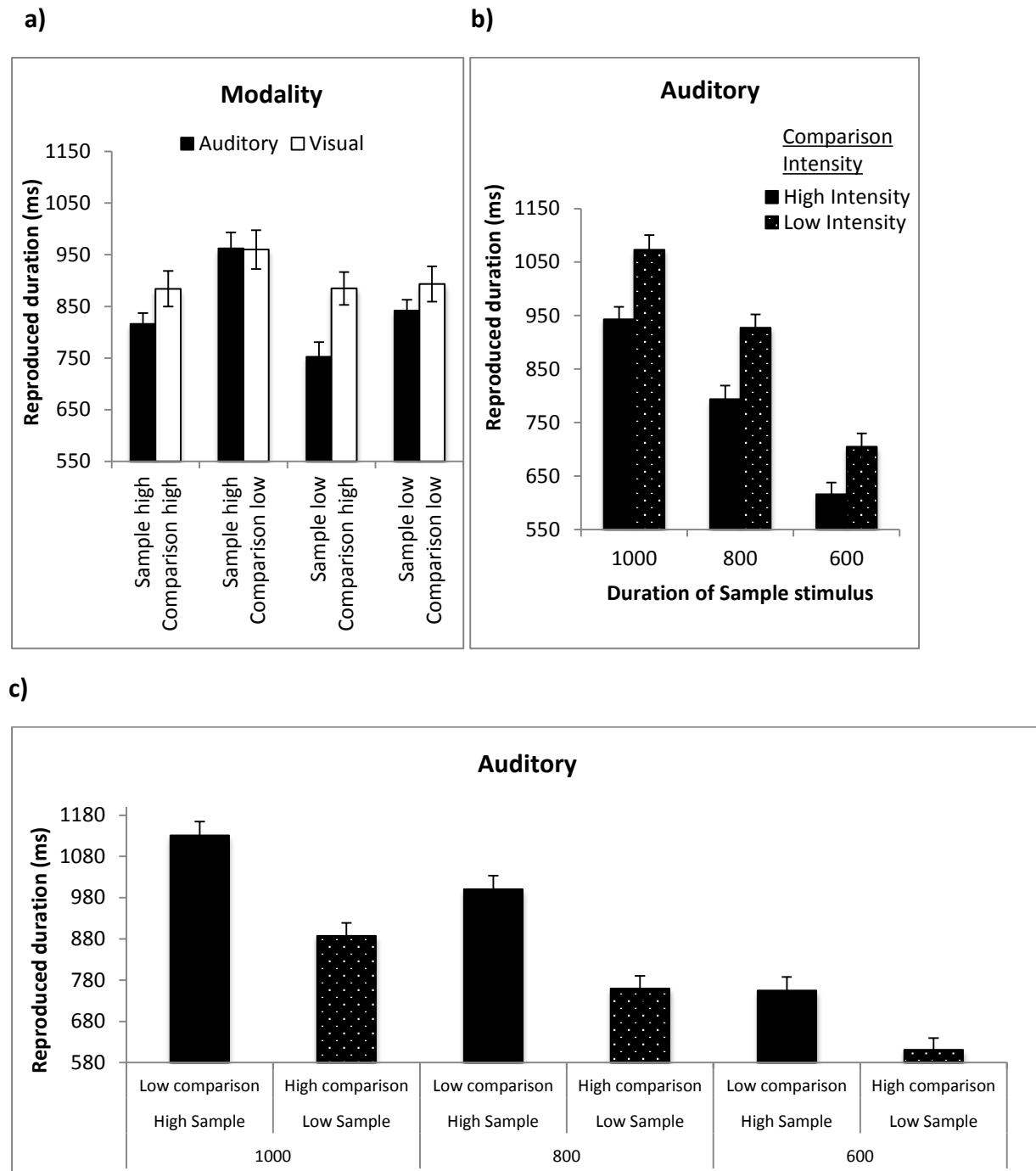


Figure 4. Interactions between stimulus intensity and duration that significantly predict the reproduced durations. a) demonstrates the interaction between the intensity of the sample and the comparison stimulus. b) demonstrates the interaction between the duration of the sample stimulus and the intensity of the comparison stimulus (only significant when predicting the reproduced duration for auditory stimuli). c) demonstrates the 3-way interaction between duration of the sample stimulus (1000, 800 or 600 ms), intensity of the sample stimulus (high or low), and the intensity of the comparison stimulus (high or low) – only significant when predicting auditory reproduced durations. Covariates appearing in the model are fixed at the following values: RT_Auditory=179 ms; RT_Visual=215 ms. The error bars represent the standard error of the mean estimated in the GEE model.