# CONTEXTUAL MODULATION OF TIME PERCEPTION: EFFECTS OF MOTION COHERENCE, BIOLOGICAL MOTION SPEED, AND NUMERALS ON TIME PERCEPTION

by

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# ABSTRACT OF THE DISSERTATION

# CONTEXTUAL MODULATION OF SUBJECTIVE TIME: EFFECTS OF MOTION COHERENCE, BIOLOGICAL MOTION SPEED, AND NUMERALS ON TIME PERCEPTION

by HAKAN KARŞILAR

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This thesis investigates how perception of time is affected by systematic manipulations of stimulus properties, with the overarching aim of contributing to the understanding of (non-temporal) contextual modulation of time perception. Over three studies, systematic effects on subjective time were observed in response to the experimental manipulations of 1) motion coherence, 2) biological motion speed, and 3) symbolic vs. non-symbolic magnitudes with the aim to understand the factors that lead to the warping of mental time line.

Chapter I aimed to investigate the effect of signal-to-noise ratio (SNR) in the motion direction of non-biological motion (a random dot motion patch) on subjective time using the temporal reproduction task. Given the previous literature, we predicted that increased SNR would result in dilation (i.e. lengthening) of perceived time. Our results on the other hand, showed constriction of perceived time with increasing (from encoding to testing) SNR with no apparent effects of decreasing SNR.

Chapter II aimed to investigate the effect of quantitative (i.e., speed) and qualitative (i.e., natural vs. unnatural) features of biological motion (i.e., walking) on subjective time using the temporal bisection task. The speed of biological motion lengthened perceived time whereas qualitative differences in the form of direction of walking did not have an effect on subjective time.

Chapter III aimed to investigate how numerosity signalled in symbolic form and stimulus size interact in terms of their effects on subjective time. Two properties of timing stimuli (i.e. numerical value and size) were manipulated simultaneously, both of which have previously been shown to have isolated directional effects on perceived time (larger magnitudes lengthening perceived time) when they were the sole sources of experimental manipulation. Our results showed that numerals as symbolic representations of numerosities had an effect on subjective time (smallest numeral leading to shortening of perceived time) and overshadowed the effect of stimulus size.

Overall, our results show that subjective time is amenable to a series of stimulus manipulations including motion coherence, motion speed, and numerical magnitude providing an empirical basis for the elaboration of timing models to accommodate interactions with non-temporal forms of information. Taken together, these results provide a fertile ground for future studies on interval timing.

# ÖZET

Bu tez, zaman algısının zamansal olmayan koşullara göre nasıl bir değişkenlik gösterdiğini anlamak amacıyla, uyaran özelliklerinin sistematik olarak değiştirilmelerinin algılanan süre üzerindeki etkilerini araştırmaktadır. Bu bağlamda, zihinsel zaman çizgisinin bükülmesine sebep olan unsurların anlaşılması amacıyla, 1) hareket eşevreliliği, 2) biyolojik hareket hızı, ve 3) simgesel ve simgesel olmayan miktar göstergeleri deneysel ortamda değiştirilerek öznel zaman algısındaki sistematik değişimler gözlenmiştir.

Birinci bölümde, zamansal tekrar-üretme görevi kullanılarak biyolojik olmayan hareket eşevreliliğindeki Sinyal-Gürültü Oranı'nın (SGO) öznel zaman üzerindeki etkisi incelenmiştir. Mevcut literatür göz önünde bulundurulduğunda, yüksek SGO'nun algılanan sürenin esnemesine (uzamasına) sebep olacağı öngörülmüştür. Halbuki elde edilen sonuçlar, verilen süreden tekrar üretilen süreye SGO'nun artış gösterdiği koşullarda algılanan sürenin daraldığını (kısaldığını), öte yandan aynı koşullarda azalan SGO'nun ise zaman algısı üzerinde herhangi bir etkisinin olmadığını göstermiştir.

İkinci bölümde, zamansal ayrıştırma (ikili kategorizasyon) görevi kullanılarak biyolojik hareketin (yürüme) kantitatif (hız) ve kalitatif (doğal ve doğal olmayan) özelliklerinin öznel zaman üzerindeki etkisi incelenmiştir. Sonuçlar incelendiğinde, artan biyolojik hareket hızının algılanan süreyi uzattığı, öte yandan aynı uyaranın "yürüyüş yönü" olarak tanımlanan kalitatif değişkenlerin öznel zaman algısı üzerinde bir etkisinin olmadığı gözlenmiştir.

Üçüncü bölümde, sembolik olarak ifade edilen sayısal nicelik ve uyaran büyüklüğünün nasıl bir etkileşim içinde öznel zaman algısını değiştirdiği araştırılmıştır. Algılanan süre üzerinde tek başlarına yönsel etkisi olduğu daha önceden bilinen iki uyaran özelliği (sayısal değer ve fiziksel büyüklük) eşzamanlı olarak değiştirilerek öznel zaman

algısındaki değişiklikler incelenmiştir. Sonuç olarak, sayısal niceliğin sembolik temsilinin algılanan süreyi değiştirdiği (en küçük sayısal değerin en kısa algılanan süreye denk geleceği şekilde) ve buna ek olarak uyaran büyüklüğünün normal koşullarda beklenen etkisini de gölgelediği gözlenmiştir.

Genel anlamda çalışmalarımız hareket eşevreliliği, hareket hızı ve sayısal büyüklük dahil olmak üzere bir dizi uyaran özelliğinin öznel zamanı etkileyebildiğini göstermiştir. Öte yandan bu sonuçlar, zamansal olmayan bilgi türlerinin öznel zaman algısıyla etkileşiminin zamanlama modelleriyle açıklanabilmesi için deneysel bir temel oluşturmaktadır. Tezin bütünü ele alındığında ortaya konulan sonuçlar, ileride aralık zamanlama üzerine gerçekleştirilebilecek çalışmalar için verimli bir zemin sağlamaktadır.

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# INTRODUCTION

Despite the importance of the veridicality of subjective time for effectively organizing behavior in accordance with the temporal regularities in the environment (Gallistel, 1990), it is not uncommon to observe systematic biases in our time perception. For instance, people often feel like time is dragging when they are bored whereas like it is passing too quickly when they were having fun. It is likely the ubiquity of these gross biases in time perceptions that has led to the amenability of time perception to the sensory properties of the timed stimuli or external events to become a popular research topic that has received public as well as scientific interest (Eagleman, 2008). This line of research not only highlights the relativity of subjective time, but also provides valuable information regarding how temporal information is generated/processed by the brain (Merchant, Harrington & Meck, 2013).

Within the scope of this thesis, participants have been shown to have the tendency to report longer experienced durations –both in the sub-second and the supra-second interval ranges-- if the corresponding duration was signalled by a larger, compared to a smaller magnitude in a given physical domain. For instance, faster dynamic stimuli lengthen perceived time compared to slower ones (Brown, 1995). Furthermore, static physical properties such as stimulus size, brightness, loudness or numerosity (Xuan, Zhang, He, & Chen, 2007) as well as implied actions in static images can also modulate perceived time; larger magnitudes or implied motions with more apparent effort lead to lengthened perceived time (Nather & Bueno, 2011). Finally, embedded cognition of time perception seems to include a “module” for biological plausibility of the observed action, where such plausibility can increase the accuracy with which durations are timed (Blake & Shiffrar, 2007).

Within the timing literature, the pacemaker-accumulator family of interval timing models has proven to be useful in accounting for the contextual modulation of time perception

(Allman, Teki, Griffiths, & Meck, 2014). Based on the evaluation of temporal judgments within the framework of an information-processing theoretic approach to interval timing, these models allow researchers to make testable predictions regarding which component of the hypothetical internal clock mechanism might have been modified as a result of external manipulation. For instance, stimuli that induce a higher level of physiological arousal (e.g. a click-train prior to encoding) are hypothesized to speed up the pacemaker of the internal clock thereby leading to longer perceived durations (Matthews, 2011), whereas decreased attention to temporal properties of timed stimuli have been assumed to lead to some of the signals generated by the pacemaker to get lost before being accumulated, leading to shorter perceived durations (e.g. Droit-Volet, Clement & Wearden, 2001).

On the other hand, the formal properties of these models do not necessarily explicate these relations in an *a priori* fashion through a mechanism formulated in relation to a network of stimulus and magnitude representations. As an alternative to such mechanistic models, representational (i.e. metaphorical) models of time perception have also been proposed, suggesting that magnitude information from abstract domains such as space, time and number can interact with each other since they are represented by a common neural code within a noisy and generalized system of magnitude representation (Walsh, 2003). While these models are able to account for and encompass a larger range of data on contextual regulation of time perception, they nonetheless lack the predictive and explanatory power of the aforementioned information-theoretic models. In this thesis, the predictions of both classes of models contributed to the formulation of research questions with the hope to contribute to their further development.

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# CHAPTER I

## Asymmetrical Modulation of Time Perception by Increase vs. Decrease in Coherence of Motion

## Abstract

Stimulus properties are known to affect the duration judgments. In this study, we tested the effect of motion coherence level in randomly moving dots on the perceived duration of these stimuli. To this end, in Experiments 1 and 2 we tested participants on a temporal reproduction task, using stimuli with varying degrees of motion coherence as the to-be-timed stimuli. Our results in both experiments showed that increasing motion coherence from the encoded (i.e. the first) to the reproduced (i.e. the second) stimulus leads to longer reproduction times. These effects were primarily additive in nature and their magnitude increased with the difference between the coherence levels in the encoding vs. reproduction (decoding) phases. Interestingly, this effect was not mirrored when there was a decrease in motion coherence. Experiment 3 tested if the differential number of exploratory saccadic eye-movements during encoding and reproduction predicted these effects. The behavioral findings of Experiment 1 and 2 were replicated in the third experiment and the change in the number of eye movements from encoding to reproduction predicted the reproduction time when there was an increase in motion coherence. These results are explained by the effect of attention on the the latency to initiate temporal integration that is only manifested when there is an increase in the level of motion coherence.

Keywords: Time perception, Signal-to-noise ratio, Random Dot Motion, Temporal Reproduction, Saccadic Eye Movements

## Introduction

Accurate timing ability is essential to many daily cognitive tasks (Allan 1979; Buhusi & Meck 2005). However, a constantly growing body of literature shows that the subjective experience of time is highly susceptible to subtle changes in non-temporal stimulus properties (Eagleman, 2008; Eagleman & Pariyadath, 2009). For instance, Xuan, Zhang, He and Chen (2007) have shown that an increase in the magnitude of various properties of the to-be-timed stimulus (e.g., its size, luminance, numeric value etc.) lead to longer temporal judgments (also see for Berglund, Berglund, Ekman, & Frankenhaeuser, 1969;  Rammsayer & Verner, 2014 for similar effects in other domains). These so called "temporal illusions" are thought to be mediated by different arousal and attentional levels induced by the respective stimuli, with implications regarding the neural mechanisms that underlie time perception (see Merchant, Harrington, & Meck, 2013 for a review).

Although majority of the abovementioned studies systematically tested the effect of the *magnitude* of stimulus properties on the subjective experience of duration, to our knowledge, no study so far has investigated the effect of motion coherence levels (SNR; signal-to-noise ratio of motion direction) on time perception. To this end, by employing a temporal reproduction paradigm and utilizing random dot motion (RDM) stimuli as the to-be-timed stimulus (see Gold & Shadlen, 2001), the current study aimed to elucidate the effect of the level of coherent motion on the perception of supra-second intervals. In order to further explicate any potential relationship between the perceived durations and the differential number of eye movements elicited by various levels of motion coherence from encoding to reproduction (e.g. Burr, Ross, Binda & Morrone, 2011; Suzuki & Yamazaki, 2010; Penney et al. 2016), we conducted an additional experiment where the eye movements of participants were recorded while being tested in identical task conditions.

The typical result from research on the effect of motion on perceived duration suggests that moving stimuli are perceived to last longer compared to stationary ones (Brown, 1995) and this distortion (i.e., dilation) in the perception of time intervals increases as a function of the speed of movement (e.g., Beckmann & Young, 2009; Kaneko & Murakami, 2009; Tomassini, Gori, Burr, Sandini, & Morrone, 2011). For instance Matthews (2011) has shown that a constantly moving stimulus is perceived to last longer than a decelerating one, which in turn seems to last longer than an accelerating stimulus. Kanai, Paffen, Hogendoorn and Verstraten (2006) on the other hand, have used flickering stimuli to show that temporal frequency is more critical to the lengthening of the perceived duration than speed or spatial frequency (but see Kaneko & Murakami, 2009), while coherence was found to have no effect at all on the perceived durations. However, Yamamoto and Miura (2016) have recently shown that, depending on stimulus configurations, the perceived speed and the coherence of motion in line segments affects perceived time, further demonstrating the role of motion processing on interval timing. Thus, while the debate as to how motion is related to time perception is not settled, no study so far has utilized RDM (or related) stimuli in order to formally define and systematically manipulate the amount of coherent motion (i.e. SNR) in a timed stimulus while simultaneously keeping such confounding variables as size, speed, and direction of motion constant.

Studies linking stimulus magnitudes (e.g. size, luminosity, speed etc.) with distortions in the perception of their durations generally make use of information-processing models as the theoretical basis for the interpretation of their findings (see Grondin 2010 for a tutorial review). Amongst these, the Scalar Timing Theory (STT; Gibbon, Church & Meck, 1984), the information processing variant of the Scalar Expectancy Theory (Gibbon, 1977; see Allman, Teki, Griffiths, & Meck, 2014 for a review), allows researchers to make testable predictions based on modulations in its components as a result of manipulations made in external stimuli (i.e. the input component). For instance, an increase in pacemaker rate (i.e. due to arousal) is thought to underlie time dilation (Zelkind, 1973; Kaneko & Murakami, 2009; Matthews, 2011; see Wearden, Edwards, Fakhri & Percival, 1998 for a discussion). Modulations of the attentional gating of pacemaker outputs to the working memory system or memory processes also have clear predictions regarding timing behavior (Droit-Volet, Clement & Wearden, 2001; Wearden et al., 1998). More specifically, it has been suggested that, more attention paid to time should lead to more pulses being integrated in the clock stage (Zakay & Block, 1995), which in turn code for a longer duration (i.e. dilation of perceived time; Yarrow, Haggard, & Rothwell, 2004). Thus, models such as the STT have consistently proven useful in explaining variations in timing behavior in response to experimental manipulations.

Although current models of interval timing do not make clear predictions regarding SNR (motion coherence in our case) and perceived time, certain hypotheses can be formulated with regard to the cited literature on the effect of motion direction SNR on different components of temporal information processing. Principally, if the amount of coherent motion (i.e. SNR) in an RDM stimulus is taken as an indicator of the *magnitude* of the motion, an RDM stimulus with higher coherence would be expected to increase the rate of the pacemaker, leading to overestimations of durations coded by these stimuli, and vice versa. If on the other hand, higher SNR grabs more attention at the expense of attention paid to the duration of the stimulus (Thomas & Cantor, 1978; Thomas & Weaver, 1975; Tse et al., 2004), an RDM stimulus with higher coherence should decrease the rate of temporal integration, leading to underestimations of durations coded by these stimuli. Both of these effects would be multiplicative, and therefore would be expected to be proportional to the target duration. If the presence of motion in the RDM stimulus introduces an additive effect (e.g., due to the delay in switch closure) however, its time normalized effect would decrease with longer target durations. In any case, the slope and intercept of regression lines relating reproduced durations to target durations can be used for capturing the effect of various types of experimental manipulations on disparate STT components (e.g., Wearden, Edwards, Fakhri, & Percival, 1998).

Finally, in addition to being a viable tool for representing various levels of SNR, the nature of the to-be-timed stimulus used in this study (i.e. the RDM stimulus) is also unique in the sense that the perception of different levels of SNR might correlate with the emergence of subtly different visual responses. More specifically, it can be assumed that various levels of embedded coherent motion might elicit different patterns of eye movements (Beutter & Stone, 2000; Schütz, Braun, Movshon, & Gegenfurtner, 2010; see Schütz, Braun & Gegenfurtner, 2011 for a review). These patterns in turn can be quantified by the number of exploratory saccades in response to (i.e. while observing) an RDM stimulus. This assumption has crucial implications for the current study, since in addition to being classically related to distortions in the perception of space (Lappe, Awater & Krekelberg, 2000; Ross, Morrone & Burr, 1997), saccadic eye movements have recently been shown to compress perceived durations (see Burr, Ross, Binda, & Morrone, 2010; Eagleman, 2005). This, in turn, suggests that different patterns/numbers of eye movements in response to different levels of motion coherence may also mediate systematic distortions of perceived durations (e.g., Cheng & Penney, 2015; Penney et al. 2016).

Studies investigating the relationship between eye movements and time perception have tended to use highly controlled single trial paradigms, where the perceived duration between two eye movements was shown to be compressed as a result of single voluntary saccades (Morrone, Ross, & Burr, 2005; Suzuki & Yamazaki, 2010). In contrast, by employing an RDM stimulus as the to-be-timed stimulus, the current paradigm allows the participants to make multiple voluntary/exploratory saccades throughout a trial, thereby making it possible to observe the cumulative effect of a series of saccadic eye movements on perceived durations. In light of the cited literature, it was predicted that a duration timed concurrent with a higher number of saccades should be perceived to be shorter, compared to a duration in which a lower number of saccades were elicited by the stimulus. Thus, if the higher motion coherence elicits a larger number of eye movements, then it can be hypothesized, that within the temporal reproduction paradigm (Eisler, 1976), timed stimuli should be over-reproduced if that duration has been encoded with lower coherence stimulus and reproduced with higher coherence stimulus. An inverse behavioral output (i.e., under reproduction of durations) is predicted when higher coherence stimulus during encoding is followed by a lower coherence stimulus during reproduction.

## Experiment 1

### Methods

#### *Participants*

41 students of Koç University (18 male, $M_{age}$ = 20.7, $Range_{age}$ = 18 - 26 years) participated in Experiment 1 for course credit. 39 participants were tested in two identical sessions, whereas the remaining two participants were tested in a single session. Around 11 % of all participants were left-handed. All experiments were approved by the Institutional Review Panel for Human Subjects of Koç University and was in accordance with the principles of the Declaration of Helsinki. All participants provided written consent for their participation for all three experiments.

### *Stimuli and apparatus*

Stimuli used were circular RDM patches, with a diameter of approximately 7.6 cm, consisting of a percentage of randomly moving white dots (3 X 3 pixels) complemented by a coherent motion of the remaining dots (i.e. signal) in rightward or leftward direction (0 or 180 degrees respectively). All stimuli were presented on a black background, on a 21” LCD screen (60 Hz refresh-rate) on an Apple iMac G4 computer, generated in Matlab using the Psychtoolbox Extension (Brainard, 1997; Kleiner et al., 2007; Pelli, 1997) on the SnowDots framework developed by Joshua Gold at the University of Pennsylvania. Participants sat at a distance of 58-63 cm from the screen, in a dimly lit room and provided their responses using a standard Apple iMac keyboard. In addition to three different coherences in the RDM stimuli (0%, 8% & 64%; see below), an additional static stimulus was also used, which consisted of a snapshot image of a sample RDM patch, where none of the dots moved. No feedback was given in any of the experimental trials.

### *Procedure*

Participants’ task was to reproduce a given (i.e. encoded) duration by holding down the space button as close to the target duration as possible. At the start of the first session, 9 practice trials were completed, in which visual feedback was given as the normalized distance between a central red line representing the encoded duration, and a white line to the right or left of this central line representing the amount of over- or under-reproduction, respectively. Each trial began with the press of the space key, triggering the presentation of an RDM stimulus with 0%, 8% or 64% coherent motion, or the static image, for a duration of 2.1, 3.7 or 5.4 seconds. Our main objectives in selecting these target durations were to (1) span a large enough supra-second duration range and, (2) not present durations that can be sectioned into full seconds in order to prevent the use of any chronometric methods. After an inter-stimulus interval sampled from a truncated exponential distribution with a mean of 2 s (with a lower bound of 1 s and an upper bound of 5.6 s), a short verbal instruction appeared on the screen, prompting participants to hold down the space key for reproducing the encoded duration. At the onset of this button press, another RDM stimulus was presented on the screen with one of the coherence levels until the space key was released. The presentation of the encoded RDM stimulus and its subsequent reproduction constituted a single trial. All coherence pairs – encoded and reproduced- and all durations were counter-balanced. Each session lasted 50 - 60 minutes. In order to further make sure that participants were looking at the screen and thereby paying attention to the task, in approximately 20% of the trials a small triangle or a square with a height of 10 pixels was flashed for 10 ms in the center of the screen following the encoded stimulus. The participants' additional task in these trials was to report which shape was the one that was flashed. These trials were automatically replaced by others with identical settings (without flashing shape) at a random order within the session. Data from these replacement trials were used in the analyses instead. Each session consisted of a total of 230 trials, 192 of which were used in the analysis.

### *Data Analysis*

Trials in which the reproduced durations were larger than three times, or less than one third of the target duration were treated as outliers and excluded from the analysis (Average percentage of cases: Short Duration: *M* = 2.87%; Mid Duration: *M* = 2.52%; Long Duration: *M* = 2.35%). Participants with mean reproductions above and below two standard deviations of the sample mean in any of the target duration conditions were excluded from further analyses (amounting to 4 participants in this experiment).

A two-way repeated measures ANOVA with same coherence pairs (4 levels; 0 vs. 0; 8 vs. 8; 64 vs. 64 & Static vs. Static), and target duration (3 levels; 2.1 s, 3.7 s & 5.4 s) as within subject factors, and mean normalized reproduction times as the dependent variable was conducted. Additionally, a three-factor repeated measures ANOVA was conducted with duration (3 levels; 2.1 s, 3.7 s & 5.4 s), unequal coherence pairs (3 levels; 0 vs. 8; 8 vs. 64 & 0 vs. 64), and the order of lower coherence stimulus (2 levels; lower coherence stimulus encoded & lower coherence stimulus reproduced) as the within subject factors, and normalized reproduction time as the dependent variable was conducted. If an interaction was observed between target duration and any of the within subjects factors, follow-up two-way repeated measures ANOVAs with coherence pairs (3 levels), and the order of lower coherence stimulus (2 levels) as the two factors were conducted separately for the three target durations. Greenhouse-Geisser correction was applied for comparisons where sphericity was violated in all three experiments.

Finally, the change in normalized reproduction times of each participant were calculated and ordered as a function of the absolute difference between the coherence of the encoded and reproduced RDM stimulus, separately for the different orders of the lower coherence conditions and durations, and the gathered slopes were compared to a slope of 0 (i.e., slope expected if there was no effect of coherence difference) using one-sample t-tests.

By design, all three experiments in the current study employed a variety of SNR levels. Namely, the coherence used in either the encoded or the reproduced stimulus order is of directly relevant to how it should be interpreted. We will use an order-specific parenthetical notation to refer to the coherence level of the encoded (i.e. first) and the reproduced (i.e. second) stimuli pairs within a trial. For instance, “(8,64)” will mean that “*an RDM stimulus with 8 percent coherence was encoded and an RDM stimulus with 64 percent coherence was reproduced”.*

## Results

Although comparisons regarding differing encoded and reproduced coherence pairs were our main interest in this experiment, we first analyzed mean normalized reproduced durations (i.e. reproduced duration divided by target duration) in same coherence pairs across target durations in order to detect any systematic over-/under-reproduction between durations (Figure 1.1). Visual inspection of Figure 1.1A suggests an over-reproduction of the 2.1 s duration, close-to-target reproduction of the 3.7 s duration, and an under-reproduction of the 5.4 s duration (in all same-coherence pairs). Our analysis showed a main effect of target duration ($F(1.089,39.202) = 108.57$, $p < .001$, $\eta_p^2 = .75$), as well as a significant main effect of same coherence pairs ($F(3,108) = 35.65$, $p < .001$, $\eta_p^2 = .50$), and no interaction between target duration and same coherence pairs ($F(4.05,145.75) = 2.36$, $p = .055$). Post-hoc analyses showed that the difference between all three durations reached significance (all *p*s < .001). Additionally, post-hoc analyses of the effect of coherence pairs showed that the static dot array stimuli were reproduced significantly longer ($M = 1.08$) compared to all of the remaining stimuli with embedded coherent motion (i.e. 0%, 8% & 64% coherence stimuli, see Figure 1.1A). Further analyses with unequal coherence pairs showed that, regardless of the order in which it was presented (i.e. during encoding; $M = 1.07$ , $SD = 0.15$, or reproduction $M = 1.06$, $SD = 0.15$), the trials in which the static stimulus was presented were always over-reproduced compared to trials in which both stimuli had embedded motion in them ($M = 1$, $SD = 0.14$). Hence, although the static dot array stimulus was included in our study as a representative condition for an "absolute lack of motion", altogether these results preclude us from making further comparisons using the static dot array stimulus as a parametric level of SNR in combination with the three dynamic RDM stimuli. Therefore the remaining analyses were conducted by using those trials where both given and reproduced durations were represented by dynamic RDM stimuli only.

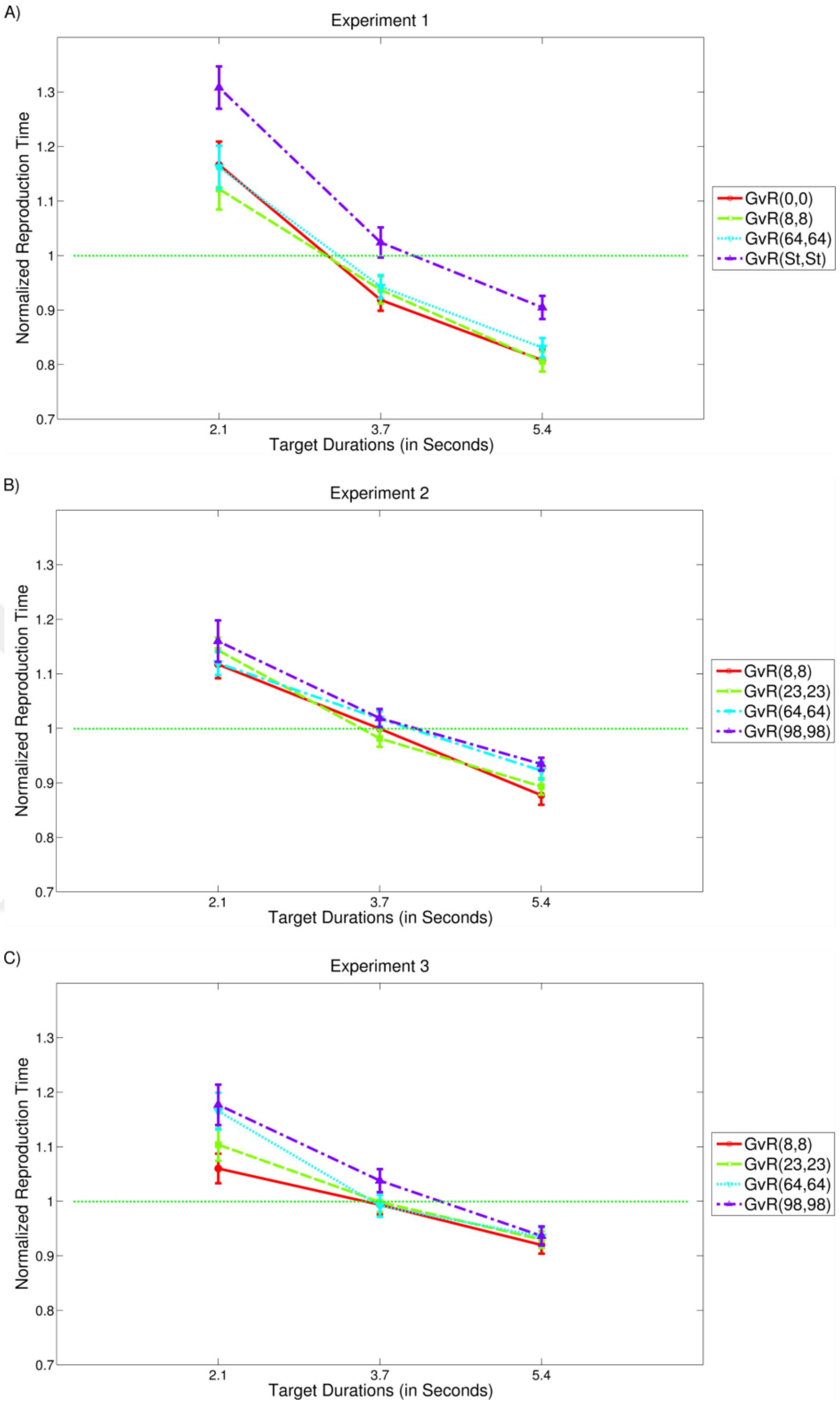

Figure 1.1 Mean normalized reproduction time as a function of same coherence pairs and target duration in (A) Experiment 1, (B) Experiment 2 and (C) Experiment 3. Dashed, green horizontal lines denote hypothetical perfect performance Error bars denote standard errors of the mean.

Next we compared the data from unequal coherence pairs. The three-way repeated measures ANOVA with data from unequal coherence pair conditions showed that all three main effects were significant (Duration: $F(1.08, 38.69) = 107.05, p < .001, \eta_p^2 = .75$; Coherence Pairs: $F(2, 72) = 20.31, p < .001, \eta_p^2 = .36$; Order of lower coherence stimulus: $F(1, 36) = 17.29, p < .001, \eta_p^2 = .32$). There was also a significant interaction between duration and order of lower coherence ($F(1.43, 51.52) = 4.55, p = .025, \eta_p^2 = .11$) as well as order of lower coherence and coherence pairs ($F(1.6, 57.8) = 8.77, p = .001, \eta_p^2 = .20$). For easier tractability, these results necessitated separate two-way ANOVAs to be conducted for the three target durations (Table 1.1).

Table 1.1

*Order of Lower Coherence Stimulus X Unequal Coherence Pairs Repeated Measure Analyses of Variance for Normalized Reproduced Duration, for three target duration conditions (2.1, 3.7 & 5.4 seconds), in Experiment 1.*

| Target Duration | Source | *df* | *F* | $\eta_p^2$ | *p* |
|---|---|---|---|---|---|
| 2.1 Seconds | (A) Order of Lower Coherence | 1 | 11.56 | .24 | .002 |
| | (B) Unequal Coherence Pairs | 2 | 10.24 | .22 | .001 |
| | A X B (interaction) | 2 | 2.35 | .06 | .1 |
| | Error (within subjects) | 72 | | | |
| 3.7 Seconds | (A) Order of Lower Coherence | 1 | 13.21 | .27 | .001 |
| | (B) Unequal Coherence Pairs | 1.63 | 8.53 | .19 | .001[a] |
| | A X B (interaction) | 2 | 7.71 | .18 | .001 |
| | Error (within subjects) | 72 | | | |
| 5.4 Seconds | (A) Order of Lower Coherence | 1 | 5.15 | .13 | .03 |
| | (B) Unequal Coherence Pairs | 2 | 7.9 | .18 | .001 |
| | A X B (interaction) | 2 | 4.16 | .1 | .02 |
| | Error (within subjects) | 72 | | | |

*Note: [a] Greenhouse-Geisser correction.*

Note that if the SNR of the stimuli (or the difference between them) had no effect on the reproduced durations, we would expect no significant differences between the unequal encoded and reproduced coherence pairs when the order of stimuli is switched. Our analyses opposed this prediction, showing that the reproduced durations were significantly longer when the lower coherence is encoded compared to when it is reproduced for all target durations (Table 1.1). There was also a significant effect of unequal coherence pairs for all durations, as well as an interaction between the coherence pairs and low coherence order for the 3.7 and 5.4 s duration conditions (Table 1.1). The simple effects analyses of this interaction effect showed that, for both target duration conditions, there was an effect of lower coherence order in the (8,64) and (0,64) pairs (all *p*s < .05), and no significant difference in the (0,8) pair was observed (both *ps* ≥ .27), which suggests that mean reproduced durations were longer for "lower encoded" coherence pairs when the difference between the coherences was large for the longer durations. (see Figure 1.2B-C). Results depicted in Table 1.1 suggest an effect of coherence pairs for all reproduced durations.

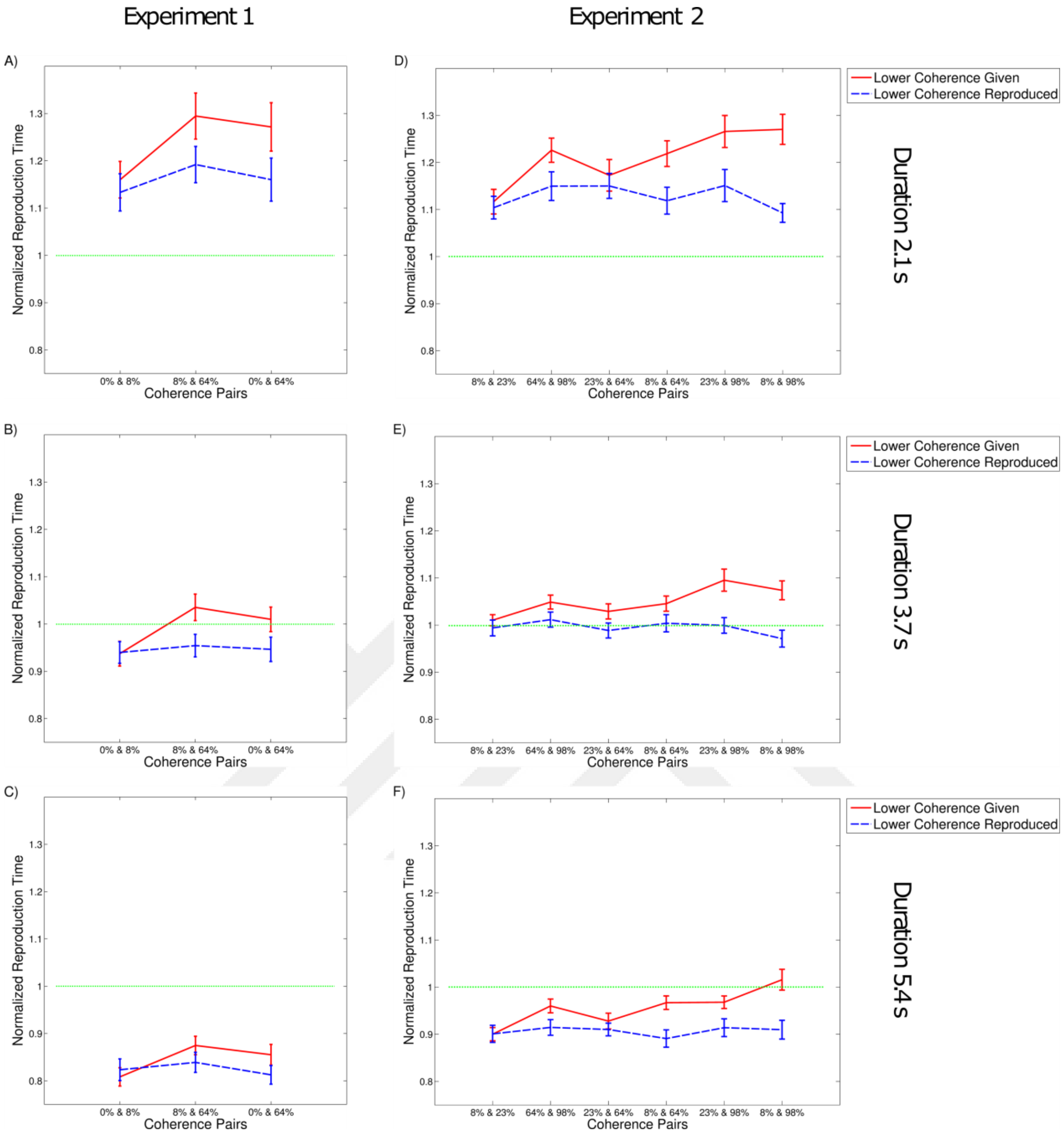

Figure 1.2 Mean normalized reproduced durations as a function of coherence pair and the order of lower coherence in Experiment 1 (A-B-C) and Experiment 2 (D-E-F) in 2.1 second (A & D), 3.7 second (B & E), and 5.4 second (C & F) conditions. Coherence pairs are ordered in ascending order according to their difference. Dashed, green horizontal lines denote hypothetical perfect performance. Error bars denote standard errors of the mean.

In order to better characterize the relationship between the direct *index of change* in reproduced durations and the difference between encoded and reproduced coherence pairs, we conducted a regression analysis. To this end, the change in reproduction with increasing difference in coherence was quantified as the slope of the lines (i.e. the regression equation) that relate the reproduced durations to the “lower coherence encoded ” and “lower coherence reproduced” trial conditions of these coherence pairs (see Figure 1.2, solid red and dashed blue lines, respectively). Our comparisons of participants’ slopes to a value of 0 for the low coherence (i.e. SNR) encoded / high coherence reproduced, and the high coherence encoded / low coherence reproduced conditions (see Figure 1.2A-B-C) showed that in the *lower coherence encoded* condition, the slopes differed significantly from 0 for all test durations; 2.1 s ($M$ = 0.06, $SD$ = 0.12, $t$(36) = 2.93, $p$ = .006), 3.7 s ($M$ = 0.04, $SD$ = 0.06, $t$(36) = 3.68, $p$ < .001) and 5.4 ($M$ = 0.02, $SD$ = 0.04, $t$(36) = 3.45, $p$ = .001) target durations, whereas the slopes of the *lower coherence second* condition in the 2.1 s ($M$ = 0.01, $SD$ = 0.09), 3.7 s ($M$ = 0.003, $SD$ = 0.05) or the 5.4 s ($M$ = -0.005, $SD$ = 0.05) target duration conditions were not significantly different from the slope of 0 (all $p$s ≥ .36).

The same analyses were conducted for participants’ coefficient of variation (CV) values. CVs were calculated by dividing each participant’s standard deviation of reproduction durations by their mean. Results showed that target duration had a significant effect on CVs ($F$(1.56, 55.99) = 30.54, $p$ < .001, $\eta_p^2$ = .46), where CVs in the 2.1 s condition ($M$ = .251) were significantly higher compared to the 3.7 s ($M$ = .193) and 5.4 s ($M$ = .196) conditions (both $p$s < .001), whereas the difference between the latter two conditions did not reach significance ($p$ = .58). Coherence pairs or the order of lower coherence stimulus had no effect on CVs (both $p$s ≥.44). Identical results were obtained with analyses conducted using same coherence pairs.

In order to see if the above-observed effect of SNR on reproduced durations is multiplicative (i.e. proportional to the target duration) or additive, or potentially a mixture of the two, we have calculated the mean absolute differences in raw (i.e. non-normalized) reproduced durations between low coherence encoded and low coherence reproduced conditions for each participant, separately for each target duration (i.e. mean difference between solid red and dashed blue lines in Figures 1.2A, B & C). The differences in reproduced durations were *M* = 0.258 for the short duration, *M* = 0.259 for the mid duration, and *M* = 0.243 for the long duration. One-way repeated measures ANOVA did not reveal a significant effect of target duration on the coherence order-based difference in reproduced durations (*p* = .89). These results point at the additive nature of the observed effects. In order to further elucidate the question of proportionality and additivity of the effects, we have also calculated the slope and intercept of the regression lines relating these difference scores to target durations for each participant. Next, one-sample t-tests were conducted in order to compare these two parameter values to a value of 0. A slope value significantly higher than 0 was hypothesized to capture the multiplicative portion of the effect of the SNR, whereas a non-zero intercept value would capture the additive portion of the effect of the SNR, which applies equally to all durations. Results suggest that the while the intercept of the regression line was significantly higher than 0 (*M* = 0.27, *SD* = 0.338, *t*(36) = 4.87, *p* < .001), the slope (M = -0.005) was not (*p* = .14).

## Experiment 2

We modified the experimental design in Experiment 2 to test the generality and robustness of the findings in Experiment 1 by testing a different group of participants with a different set of SNRs (i.e., motion coherences).

### Methods

### *Participants*

The inclusion criteria for participants in Experiment 2 were the same as those in Experiment 1. 36 participants were tested in Experiment 2 (12 male, $M_{age} = 19.8$, $Range_{age} = 18 - 23$ years), 29 of which participated for course credit in two identical sessions, whereas the remaining 7 participated in a single session.

### *Procedure*

The procedure of Experiment 2 was identical to Experiment 1, except for the replacement of the 0% coherence stimulus and the static stimulus with 23% and 98% coherence stimuli. This change was implemented for three reasons; (1) The 0% and 8% coherence stimuli were generally reported to be perceptually very similar by the participants in Experiment 1, (2) the static stimulus was systematically overestimated and therefore could not be included as a parametric level of SNR to analyses, and (3) we aimed to explore the effect of a wider range of coherence levels for completeness.

### *Data Analysis*

As with Experiment 1, trials in which reproduced durations were larger than three times, or less than one third of the target duration were excluded as outliers (Average percentage of cases: Short Duration: $M = 2.1\%$; Mid Duration: $M = 2.55\%$; Long Duration: $M = 2.45\%$) Additionally, five participants' data were excluded from analyses in line with the exclusion criterion described earlier (see Experiment 1 *data analysis* section). The same analyses described for Experiment 1 were also applied to the data gathered from this experiment.

## Results

Consistent with the results of Experiment 1, our analysis of the mean normalized reproduced durations (i.e., reproduced duration divided by target duration) in same coherence pairs across target durations in Experiment 2 revealed a main effect of target duration ($F(1.177, 35.312) = 60.3, p < .001, \eta_p^2 = .67$), as well as a significant main effect of same coherence pairs ($F(2.1, 62) = 3.326, p = .041, \eta_p^2 = .10$), and no interaction between target duration and same coherence pairs ($p = .24$). Post-hoc analyses based on the normalized reproduction times showed that the difference between all three durations reached significance (all *p*s < .001; Figure 1.1B). Additionally, post-hoc analyses of the effect of coherence pairs showed that the (8,8) coherence pair ($M = 1$) was reproduced significantly shorter than the (98,98) coherence pair ($M = 1.04$, $p = .012$). None of the remaining comparisons reached significance (all *p*s ≥.071; see Figure 1.1B).

The three-way repeated measures ANOVA conducted with unequal coherence pairs in Experiment 2 showed the identical pattern as that conducted in Experiment 1. Namely, all three main effect were significant (Duration: $F(1.15, 33.44) = 78.13, p < .001, \eta_p^2 = .73$; Coherence Pairs: $F(5, 145) = 8.22, p < .001\eta_p^2, = .22$; Order of lower coherence stimulus: $F(1, 29) = 34.78, p < .001, \eta_p^2 = .55$). There was also a significant interaction between duration and order of lower coherence ($F(2, 58) = 7.07, p = .002, \eta_p^2 = .20$) as well as order of lower coherence and coherence pairs ($F(2.99, 86.86) = 10.59, p < .001, \eta_p^2 = .27$).

Results of Experiment 2 regarding unequal coherence pairs for different duration conditions also closely resembled those obtained in Experiment 1 (see Table 1.2), where an increase in SNR from an encoded to a reproduced stimulus led to an over-reproduction, and this effect was magnified with increasing difference between the encoded and the reproduced coherences. On the other hand, a decrease in SNR from a encoded to a reproduced stimulus did not result in an under-reproduction of the target durations by the same amount (see Figure 1.2D-E-F).

Table 1.2

*Order of Lower Coherence Stimulus X Unequal Coherence Pairs Repeated Measure Analyses of Variance for Normalized Reproduced Duration, for three target duration conditions (2.1, 3.7 & 5.4 seconds), in Experiment 2.*

| Target Duration | Source | *df* | *F* | $\eta_p^2$ | *p* |
|---|---|---|---|---|---|
| 2.1 Seconds | (A) Order of Lower Coherence | 1 | 42.36 | .59 | .001 |
| | (B) Unequal Coherence Pairs | 3.57 | 4.28 | .13 | .004[a] |
| | A X B (interaction) | 5 | 7.43 | .2 | .001 |
| | Error (within subjects) | 145 | | | |
| 3.7 Seconds | (A) Order of Lower Coherence | 1 | 21.8 | .42 | .001 |
| | (B) Unequal Coherence Pairs | 5 | 3.4 | .1 | .006 |
| | A X B (interaction) | 2.77 | 3.23 | .1 | .03[a] |
| | Error (within subjects) | 145 | | | |
| 5.4 Seconds | (A) Order of Lower Coherence | 1 | 16.89 | .36 | .001 |
| | (B) Unequal Coherence Pairs | 5 | 7.69 | .2 | .001 |
| | A X B (interaction) | 2.94 | 5.76 | .16 | .001[a] |
| | Error (within subjects) | 145 | | | |

*Note:* [a] *Greenhouse-Geisser correction.*

Table 1.2 shows that for all duration conditions there was a significant effect of coherence pairs, as well as a significant effect of the order of lower coherence stimulus, in addition to an interaction effect of the two factors. Simple effects analyses of the significant interaction in 2.1 s duration condition showed an effect of lower coherence order in the (64,98), (8,64), (23,98) and (8,98) pairs (all *p*s < .001), in all of which the normalized reproduced durations were longer when the participants encoded the duration with the lower coherence (Note that one participant's data in the (23,8) pair were not included in the analysis due to exclusion criteria). Simple effect analyses in the 3.7 s duration condition showed an effect of lower coherence order in the (64, 98), (23, 64), (23, 98) and (8, 98) pairs (all *p*s < .05), where the normalized reproduced durations were longer when lower coherence was encoded compared to when it was reproduced. Finally, in the post-hoc comparisons of the interaction effect in the 5.4 s condition, the effect of order of lower coherence reached significance in the (64,98), (8,64), (23,98) and (8,98) pairs (all *p*s < .05), where the normalized reproduced durations were longer when the lower coherence was encoded compared to when it was reproduced.

Our comparisons of participants' slopes of the lines that relate the reproduced durations to the low SNR encoded / high SNR reproduced, and the high SNR encoded / low SNR reproduced conditions (see Figure 1.2D-E-F) showed the exact pattern as the one seen in Experiment 1. Namely, in the *lower coherence encoded* condition, the slopes differed significantly from a value of 0 in the 2.1 s (*M* = 0.03, *SD* = 0.03, *t*(30) = 5.57, *p* < .001), 3.7 s (*M* = 0.01, *SD* = 0.02, *t*(30) = 4.26, *p* < .001) and 5.4 s (*M* = 0.02, *SD* = 0.02, *t*(30) = 5.08, *p* < .001) target durations, whereas the slopes of the *lower coherence second* condition in the 2.1 s (*M* = -0.004, *SD* = 0.02), 3.7 s (*M* = -0.004, *SD* = 0.02) or the 5.4 s (*M* = 0, *SD* = 0.01) target durations were not significantly different from the slope of 0 (all *p*s ≥ .35). (Note that the data of the same participant excluded from the analysis).

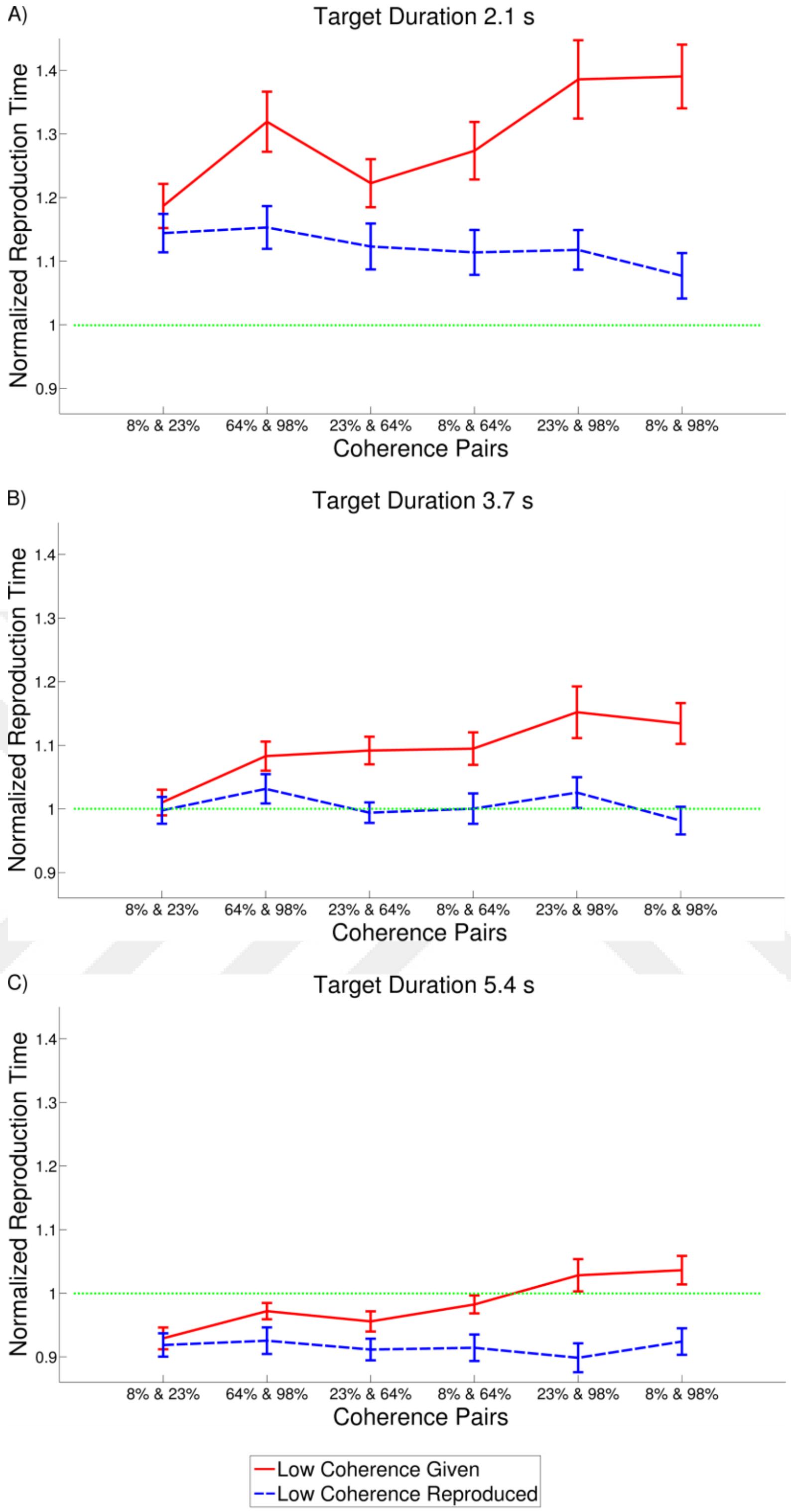

Figure 1.3 Mean normalized reproduced durations as a function of coherence pair and the order of lower coherence in Experiment 3. Coherence pairs are ordered in ascending order according to their difference. Dashed, green horizontal lines denote hypothetical perfect performance. Error bars denote standard errors of the mean.

As with Experiment 1, a three-way ANOVA was performed to see if mean CV values changed as a function of target duration, coherence pairs or the order of lower coherence stimulus. Results showed that target duration had a significant effect on CVs ($F(2, 60) = 39.57$, $p < .001$, $\eta_p^2 = .57$). Post-hoc pairwise comparisons showed that all duration pairs differed significantly from each other (all *p*s < .01), with CVs being highest in the 2.1 s condition ($M = .19$), followed by the 3.7 s ($M = .154$), and the 5.4 s conditions ($M = .137$). Additionally, there was a main effect of the order of lower coherence stimulus on CV ($F(1,30) = 4.58$, $p = .04$, $\eta_p^2 = .13$), where CVs were higher when lower coherence was reproduced (M = .165), compared to when it was encoded ($M = .155$). There was no main effect of coherence pairs, or a significant interaction between any of the factors on CV (all *p*s $\geq .13$). (Results obtained with analyses using same coherence pairs were the same except that they showed that CVs in the 3.7 and 5.4 s conditions did not differ significantly.)

Also identical with Experiment 1, the mean absolute differences in raw reproductions between low encoded and low reproduced conditions (i.e. mean difference between solid red and dashed blue lines in Figures 1.2D, E & F) were calculated for each participant, separately for each target duration. A one-way repeated measures ANOVA with this difference value as the dependent, and target duration as the independent variable was conducted in order to see if the above observed effect of SNR on reproduced durations is multiplicative or additive (or potentially a mixture of the two). Results revealed a significant effect of target duration on the coherence order-based difference in reproduced durations ($F(2,60) = 6.92$, $p = .002$, $\eta_p^2 = .19$). Post-hoc analyses revealed that the effect of SNR on reproduced durations tended to increase with longer target durations ($M_{Short} = 0.191$, $M_{Mid} = 0.23$, $M_{Long} = 0.332$). All comparisons, except for the one between the mid and long target duration conditions ($p = .21$) reached significance (all *p*s < 0.05). Additionally, we calculated the slope and intercept parameters of the regression lines relating these absolute difference scores to target durations for each participant. One-sample t-tests suggest that, both the slope (*M* = 0.043, *SD* = 0.075, *t*(30) = 3.18, *p* = .003) and the intercept of the regression line were significantly higher than 0 (*M* = 0.09, *SD* = 0.221, *t*(30) = 2.28, *p* = .03).

## Experiment 3

Experiments 1 and 2 provided almost identical results regarding the behavioral effect of coherent motion of perceived time, where over-reproduction of durations is observed when durations are encoded and reproduced with lower and higher coherence stimuli, respectively. In Experiment 3, we specifically aimed to investigate the potential relationship between this robust behavioral effect and the change in the number of eye movements from encoding to reproduction. Accordingly, Experiment 3 was in effect identical to Experiment 2, except for the addition of the eye tracking methodology. A different group of participants were tested in this study.

### Methods

#### *Participants*

37 participants participated in a single session (16 male, $M_{age}$= 19.4, $Range_{age}$= 18 - 24 years), and were paid 15 Liras for participation (approx. $5).

#### *Procedure, Stimuli and Apparatus*

The experimental procedure as well as the stimulus properties used in Experiment 3 were identical to those in Experiment 2. Participants' eye movements were recorded by a

Tobii T120 eye tracker (Tobii Technology, AB, Danderyd, Sweden), at a constant frame rate of 120 Hz (at approximately 8 ms intervals) using five infrared lights. Stimuli were presented on the integrated 17 inch TFT screen of the T120 (1280 × 1024 pixel resolution). No head mount was used. Two 9-point calibrations were made; one in the beginning, and another one halfway through the session.

### *Data Analysis*

As with Experiment 1 and 2, trials in which the reproduced durations were larger than three times, or less than one third of the target duration were excluded as outliers (Average percentage of cases: Short Duration: $M = 2.21\%$; Mid Duration: $M = 2.45\%$; Long Duration: $M = 2.3\%$). Additionally, five participants' data were excluded from analyses in line with the exclusion criterion described above (see Experiment 1 *data analysis* section). The behavioral analyses conducted in Experiment 3 were identical with Experiment 2 (See Experiment 2 *data analysis* section).

Preprocessing of eye tracking data was done by replacing each bad value with the last good value before it, as described in Leppänen et al. (2014). Bad values were determined based on the most conservative (exclusive) measure of gaze data validity as suggested by Tobii, where the eye tracking system successfully recorded both eyes and was sure that the detected gaze data came from that particular eye (Invalid and Uncertain Frames During Encoding: $M = 25.01$ %, $SD = 19.28$ %, Invalid and Uncertain Frames During Reproduction: $M = 26.58$ %, $SD = 20.28$ %; see Nevalainen & Sajaniemi (2004) for reference values). Interpolated gaze data was then smoothed by applying a five-point running average, after which the number of saccadic eye movements in each trial was calculated by the *Microsaccade Toolbox for R* (Engbert, Sinn, Mergenthaler & Trukenbrod, 2015). Number of saccades in each trial, for both the encoded and the reproduced RDM stimuli, were then estimated by using the same toolbox. The velocity threshold for a saccade was set at three times the median of smoothed gaze data (see Engbert et al., 2015). Candidate saccade sequences had to pass this threshold for a minimum duration of 2 data samples (i.e. around 16.7 ms), which were then identified as binocular saccades from monocular candidate sequences in right and left eyes (Engbert et al., 2015).

## Results

Our analysis of the mean normalized reproduced durations in same coherence pairs across target durations in Experiment 3 revealed a main effect of target duration (*F*(1.213, 37,603) = 59.6, $p < .001$, $\eta_p^2 = .67$), as well as a significant main effect of same coherence pairs (*F*(2.104, 65.234) = 5.43, $p = .006$, $\eta_p^2 = .15$), and a significant interaction between target duration and same coherence pairs (*F*(3.92, 121.36) = 2.635, $p = .038$, $\eta_p^2 = .08$). Post-hoc analyses based on the normalized reproduction times showed that the difference between all three durations reached significance for all coherence pairs (all *p*s < .01; Figure 1.1C). Additionally, post-hoc analyses of the effect of coherence pairs showed that the (8,8) coherence pair (*M* = 1.06) was reproduced significantly shorter than the (64,64) and the (98,98) coherence pairs (*M* = 1.165, *M* = 1.177, respectively), in the 2.1 s duration (both *p*s < .01), and the (64,64) coherence pair (*M* = 0.992) was reproduced significantly shorter than the (98,98) coherence pair (*M* = 1.038, $p = .032$) in the 3.4 s duration conditions. None of the remaining comparisons reached significance (all *p*s ≥ .061; see Figure 1.1C).

The three-way repeated measures ANOVA conducted with unequal coherence pairs in Experiment 3 showed the identical pattern as that conducted in Experiment 1 and 2. Namely, all three main effects were significant (Duration: *F*(1.18, 36.52) = 87.59, $p < .001$, $\eta_p^2 = .74$;

Coherence Pairs: $F(3.13, 96.88) = 8.45$, $p < .001$, $\eta_p^2 = .21$; Order of lower coherence stimulus: $F(1, 31) = 32.48$, $p < .001$, $\eta_p^2 = .51$). There was also a significant interaction between duration and order of lower coherence ($F(1.35, 41.73) = 21.37$, $p < .001$, $\eta_p^2 = .41$) as well as order of lower coherence and coherence pairs ($F(2.94, 91.04) = 13.15$, $p < .001$, $\eta_p^2 = .30$).

Results of Experiment 3 regarding unequal coherence pairs for different duration conditions also closely resembled those obtained in Experiment 1 and 2, where an increase in SNR from an encoded to a reproduced stimulus lead to an over-reproduction, and this effect was magnified with increasing difference between the encoded and the reproduced coherences (Figure 1.3). The statistical outputs are presented in Table 1.3.

Table 1.3

*Order of Lower Coherence Stimulus X Unequal Coherence Pairs Repeated Measure Analyses of Variance for Normalized Reproduced Duration, for three target duration conditions (2.1, 3.7 & 5.4 seconds), in Experiment 3.*

| Target Duration | Source | *df* | *F* | $\eta_p^2$ | *p* |
|---|---|---|---|---|---|
| 2.1 Seconds | (A) Order of Lower Coherence | 1 | 33.89 | .52 | .001 |
| | (B) Unequal Coherence Pairs | 5 | 4.05 | .12 | .002 |
| | A X B (interaction) | 3.78 | 8.18 | .21 | .001[a] |
| | Error (within subjects) | 155 | | | |
| 3.7 Seconds | (A) Order of Lower Coherence | 1 | 27.34 | .46 | .001 |
| | (B) Unequal Coherence Pairs | 5 | 5.22 | .14 | .001 |
| | A X B (interaction) | 3.72 | 3.52 | .1 | .011[a] |
| | Error (within subjects) | 155 | | | |
| 5.4 Seconds | (A) Order of Lower Coherence | 1 | 19.57 | .39 | .001 |
| | (B) Unequal Coherence Pairs | 3.38 | 3.55 | .1 | .014 |
| | A X B (interaction) | 3.47 | 5.02 | .14 | .002 |
| | Error (within subjects) | 155 | | | |

*Note: [a] Greenhouse-Geisser correction.*

Table 1.3 shows that, as with Experiment 2, for all duration conditions there was a significant effect of coherence pairs, as well as a significant effect of the order of lower coherence stimulus, in addition to an interaction effect of the two factors. Simple effects analyses of the significant interaction in both 2.1 s and 3.7 s conditions showed an effect of lower coherence order in the all coherence pairs except for (8,23) (all *p*s < .05), in all of which the normalized reproduced durations were longer when the participants encoded the duration with the lower coherence. Finally, simple effects analyses of the significant interaction in the 5.4 s condition showed an effect of lower coherence order in the all coherence pairs except for the (8,23) and (64,98) (all *p*s < .05), in all of which the normalized reproduced durations were longer when the participants encoded the duration with the lower coherence.

Our comparisons of participants' slopes of the lines that relate the reproduced durations to the low SNR encoded / high SNR reproduced, and the high SNR encoded / low SNR reproduced conditions (see Figure 1.3A-B-C) showed the a similar pattern to the ones seen in Experiment 1 & 2. Namely, in the *lower coherence encoded* condition, the slopes differed significantly from a value of 0 in the 2.1 s ($M$ = 0.04, $SD$ = 0.04, $t$(31) = 4.88, $p$ < .001), 3.7 s ($M$ = 0.02, $SD$ = 0.04, $t$(31) = 3.81, $p$ = .001), and 5.4 s ($M$ = 0.02, $SD$ = 0.03, $t$(31) = 4.15, $p$ < .001) target duration conditions, whereas the slopes of the *lower coherence second* condition in the 3.7 s ($M$ = -0.003, $SD$ = 0.02) or the 5.4 s ($M$ = 0.001, $SD$ = 0.02) target duration conditions were not significantly different from the slope of 0 (both $p$s ≥.46). The slope of the *lower coherence reproduced* condition in the 2.1 s condition, did however significantly differ from 0 ($M$ = -0.013, $SD$ = 0.03, $t$(31) = -2.5, $p$ < .001).

As with Experiments 1 and 2, a three-way ANOVA was conducted to see if CV values differed significantly depending on reproduced duration, unequal coherence pairs, or the order of lower coherence stimulus. Results suggest a significant effect of target duration on CV ($F$(2, 62) = 44.17, $p$ < .001, $\eta_p^2$ = .59). Post-hoc analyses parallel those in Experiment 2 with differences in all target duration pairs reaching significance (all $p$s < .001). Specifically, CVs decreased with increasing target duration, with highest CVs observed in the 2.1 s duration condition ($M$ = .19), followed by the 3.7 ($M$ = .138), and the 5.4 s duration conditions (M = .126), respectively. None of the other main or interaction effects reached significance (both $p$s ≥.64). Identical results were obtained with analyses conducted using same coherence pairs.

Finally, as with Experiments 1 & 2, in order to see if the above observed effect of SNR on reproduced durations is multiplicative or additive, a one-way repeated measures ANOVA was conducted with mean absolute raw differences in reproduced durations for the three target duration conditions as the dependent variable, and target duration as the independent variable.

The differences in reproduced durations were *M* = 0.384 for the short duration, *M* = 0.357 for the mid duration, and *M* = 0.418 for the long duration. A one-way repeated measures ANOVA failed to reveal a significant effect of target duration on the coherence order-based difference in reproduced durations ($p = .37$). Additionally, one-sample t-tests suggested that while the positive mean slope parameter of the regression lines relating these difference scores to target durations did not differ significantly from 0 ($M = 0.011$, $p = 0.51$), the intercept did (M = 0.347, SD = 0.404, $t(31) = 4.86$, $p < .001$).

### *Eye Tracking Data Analyses*

The change in the number of saccades from encoding to reproduction (henceforth referred to as the *saccadic differential*) in each target duration condition for each unequal coherence pair is presented in Figure 1.4. Visual inspection of Figure 1.4 suggests an overlap between the saccadic differential values and normalized reproduced durations, with increasing difference between encoded and reproduced stimulus coherences. This visual overlap suggests a predictive relationship between the saccadic differential and the reproduced duration. In order to test this assumption, we have conducted two orthogonal regression analyses separately for the “low coherence encoded ” and “low coherence reproduced” conditions (solid red and dashed blue lines in Figure 1.3, respectively). These analyses were conducted separately for each target duration condition (see Table 1.4).

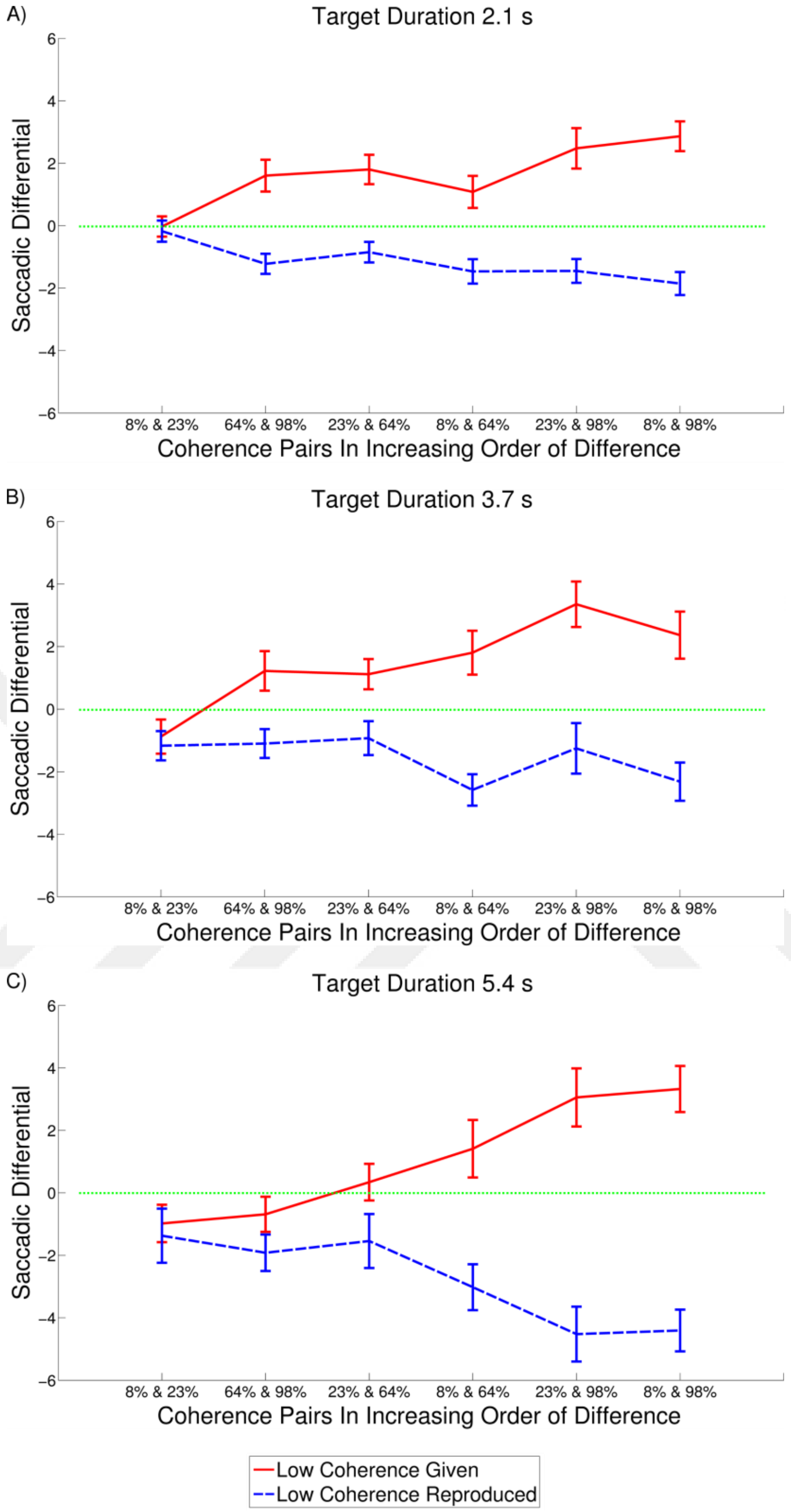

Figure 1.4 Change in the number of saccadic eye movements from training to reproduction in the low coherence given (red line) and low coherence reproduced (blue line) conditions, for the three target durations. Dashed, green horizontal lines denote hypothetical zero difference between number of eye movements. Error bars denote standard errors of the mean.

Table 1.4

*Coefficient variables resulting from Orthogonal Regression Analyses, for three target duration conditions (2.1, 3.7 & 5.4 seconds) with mean normalized reproduced duration.as the dependent variable in Experiment 3.*

| | | Unstandardized Coefficients | | | |
|---|---|---|---|---|---|
| Target Duration | Experimental Condition | *B* | *SE* | *Z* | *p* |
| 2.1 Seconds | Lower Coherence Given | 0.07 | 0.02 | 3.24 | .001 |
| | Lower Coherence Reproduced | 0.03 | 0.02 | 1.83 | .07 |
| 3.7 Seconds | Lower Coherence Given | 0.03 | 0 | 11.02 | .001 |
| | Lower Coherence Reproduced | 0.02 | 0.01 | 0.97 | .33 |
| 5.4 Seconds | Lower Coherence Given | 0.02 | 0 | 5.89 | .001 |
| | Lower Coherence Reproduced | 0 | 0 | 0.99 | .32 |

*Predictor: Saccadic Differential*

Each orthogonal regression analysis tested if the change in the number of eye movements from encoding to reproduction (i.e. the saccadic differential) significantly predicted normalized reproduced durations. Results depicted in Table 1.4 suggests that, in all three target duration conditions, saccadic differential significantly predicted the normalized reproduced durations when there was an increase in coherence from encoding to reproduction (i.e. “low coherence encoded ” condition). On the other hand, saccadic differentials did not predict reproduced durations when there was a decrease in coherence from encoding to reproduction, in any of the target duration conditions. Taken together, these results suggest that the change in the number of saccadic eye movements from encoding to reproduction is in fact able to index the reproduced duration when there is an accompanying increase in coherence. On the other hand, the predictive power of the saccadic differential disappears when there is an identical decrease in coherence from encoding to reproduction. Overall, these results point to a *conditional* predictive relation inherent to the change in saccadic eye movements, with regard to the perceived interval durations.

## General Discussion

Our results from all three experiments consistently showed that increasing the coherence of motion from encoding to reproduction resulted in over-reproduction of target intervals. This effect was also magnified with increasing difference between motion coherences of two consecutive stimuli and was not mirrored when motion coherence decreased from the encoded to the reproduced stimulus. The difference between encoded and reproduced coherences had virtually no effect on reproduced durations in this latter condition. Additionally, the difference between the number of saccadic eye movements during encoding and reproduction showed a very similar pattern to that seen with reproduced durations (i.e. when higher coherence was reproduced) with regard to unequal coherence pairs.

These results are more in line with the predictions of the effect of the motion coherence manipulation on attention to time, compared to its effects on the clock speed. If the effect of our manipulation was on the clock speed, with regard to the cited literature we would expect under-reproduction of the target durations when the coherence of the timed stimulus increased from the encoding to reproduction. This prediction is derived under the assumption that, if SNR is assumed to be an indicator of the *magnitude* of motion in an RDM stimulus, an increase in motion coherence would also increase the clock speed. Such an effect would result in multiplicative (proportional) modulation of the timing behavior. Our data directly oppose this prediction; First and foremost, durations were *over-reproduced* when there was an increase in coherence from encoding to reproduction. Secondly, the effect of change in motion coherence from encoding to reproduction on interval timing had a prominent *additive* component (in the opposite direction) in all three experiments.

In terms of the directionality of the observed effects, our findings are more in line with the attentional modulation of perceived durations. This conclusion is based on the finding that higher SNR attracts more attention to sensory stimulus properties (i.e. random motion, speed, directionality etc.) at the expense of attention paid to its temporal properties (Thomas & Cantor, 1978; Thomas & Weaver, 1975). This view of attention as being a limited cognitive resource that can be concurrently distributed among different qualities of perceived stimuli (e.g.its temporal and non-temporal properties) and thereby affect temporal perception is well grounded within the timing literature (Brown, 1985; Cantor & Thomas, 1977; Mattes & Ulrich, 1998; Thomas & Cantor, 1978; Thomas & Weaver, 1975; Tse et al., 2004). There are at least two forms in which attentional modulation can affect the timing behavior. First, the attention-based extension of the Scalar Timing Model (Gibbon, Church & Meck, 1984) suggests that the clock pulses are gated by a hypothetical *switch mechanism* to an accumulator, whose “letting through” function is probabilistic (Lejeune, 1998; Penney, 2003), and is thought to be modulated by the amount of attention paid to the temporal properties of an event, where higher attention to time codes for a higher probability of switch closure and vice versa (Lejeune, 1998; Penney, Gibbon, & Meck, 2000; Zakay & Block, 1995). Second, this switch mechanism is also characterized by alterations in its opening and closing latencies, on the onset and the offset of timing a duration, respectively (Gibbon & Church, 1998; Zakay & Block, 1995; Wearden et al., 1998). The second mechanism would lead to additive modulation of reproduced durations as it only affects the onset and/or offset of timing whereas the first mechanism would lead to proportional modulation of reproduced durations as it modulates timing throughout the entire stimulus presentation. In light of these models, our results can partially be explained by assuming that a higher SNR attracted more attention to the non-temporal properties of the timed stimulus and therefore was perceived to last shorter, by acting on either the switch closure probability, the switch opening-closing latencies, or both (see below). However, none of these accounts formulated within a “pacemaker-accumulator” framework predict an asymmetry between identical experimental manipulations made to the encoded and reproduced stimuli (i.e., increase vs. decrease in coherence from training to reproduction). This is due to the fact that, the encoding and decoding phases are typically assumed to adhere to identical pacemaker-accumulator contingencies. Consequently, further model specification is necessary to explain the asymmetry in our data, where an increase but not a decrease in SNR led to over-reproduction of intervals.

In order to explain the asymmetrical effects observed in our study, a speculative account of our the attention-based model can be formulated by assuming a one-directional “change detection” or attentional deployment process that is sensitive to an increase but not to a decrease in SNR by the same amount (a precondition for parametric attention-related effects). Within this conjecture, it can be assumed that an increase in SNR from encoding training to reproduction might universally attract attention to the stimulus quality that contains the corresponding signal but at the expense of attention given to its duration. As a result, such a model would predict over-reproduction of the target durations when the SNR increases from encoding to reproduction with no under-reproduction when the SNR decreases from encoding to reproduction. Thus, a combination of change detection with the attention-mediated switch mechanism (primarily latency to closure) can explain our findings including the prominent asymmetries (i.e., the lack of the expected negative slopes in Figures 1.2 & 1.3 discussed above).

Similar asymmetries have recently been observed in other studies testing for differences in the discrimination of temporal properties of stimuli using the temporal reproduction methodology (e.g. Cai & Wang, 2014; Rammsayer & Verner, 2014). For instance, a looming stimulus leads to time dilation, whereas the opposite effect is not observed for a receding stimulus. (e.g. Van Wassenhove et al., 2008; Van Wassenhove et al., 2011). These findings were hypothesized to result from potential modulations in both clock speed (multiplicative effects) and switch latency (additive effects), and therefore directly relate to and are complemented by the results presented here. Moreover, Raymond & Isaak (1998) have shown that, regardless of the interval between the two stimuli, the coherence threshold of a second RDM stimulus increases when the direction of motion is the same with the first stimulus. This predicts differential degrees of detectability of motion direction of the second stimulus between those cases in which the motion coherence was reduced vs. increased from the first to the second stimulus. This finding may also account for the asymmetry in our data. Further studies are necessary to confirm whether motion thresholds vary as such during temporal reproduction.

If an increase in the SNR leads to less attention paid to the temporal aspects throughout the trial (i.e., affect the switch closing probability), then one would expect the magnitude of over-reproduction to be proportional to the timed intervals. However, in all experiments the additive component of the effect was more prominent than the multiplicative component. In fact, there was no reliable multiplicative component of the effect in two out of three experiments. Thus, these unidirectional (high coherence → low coherence) additive alterations in timing behavior can be better explained by the effect of the increase in motion coherence on the switch closure latency during the reproduction phase (Block & Zakay 1995; Gibbon & Church, 1984; Gibbon et al., 1984; Zakay & Block, 1995; Zakay, & Block, 1996; Wearden et al., 1998), which would also lead to longer reproductions. Interestingly, this effect increased with the difference between the coherences, suggesting that the switch closure latency also increased as a function of the coherence difference when there was an increase motion coherence. This behavioral observation could be the manifestation of the surprisal/attentional lapse in the case of an increase in SNR during which the temporal aspects of the event are not processed.

To that end, although the task parameters were identical between Experiment 2 and 3, Experiment 2 revealed a slight multiplicative component to the effect of the increase in motion coherence from encoding to reproduction. Since this effect was in the direction of over-reproduction rather than the under-reproduction of the target intervals, it can also be attributed to the additional effect of the experimental manipulation on switch closure probability. Although participants were instructed not to pay attention to the properties of the RDM stimulus besides its duration (e.g., speed, direction, density etc.), given the close link between attention and the coherence of motion in the highly dynamic RDM stimulus (e.g. Baumann & Mattingley, 2014; Bolandnazar, Lennarz, Mirpour & Bisley, 2015; Liu, Fuller & Carrasco, 2006), it is indeed possible that the various levels of coherent motion attracted differential levels of attention paid to the non-temporal properties of the RDM stimulus between encoding and reproduction phases in this experiment.

Experiment 3 investigated the potential relationship between the change in the number of eye movements from encoding to reproduction, and the robust behavioral results observed in Experiments 1 and 2 (i.e., reproduced duration). As mentioned above, saccadic eye movements have been shown to compress (i.e. shorten) perceived durations (Burr, Ross, Binda, & Morrone, 2010; Eagleman, 2005). Our results from Experiment 3 mainly showed that the change in the saccadic eye movements from encoding to reproduction as a function of difference in related motion coherences exhibited a nearly identical pattern to the corresponding changes in the reproduced durations. More specifically the slope of the lines that relate the change in the number of saccadic eye movements from encoding to reproduction to the “lower coherence encoded” and “lower coherence reproduced” trial conditions of unequal coherence pairs correlated highly with the reproduced durations when there is an *increase* in coherence from encoding to reproduction. Additionally this effect was found to hold for all three target durations. On the other hand, there was no relation between eye movements and reproduced durations in conditions where there was a decrease in coherence from encoding to reproduction, which was expected given the lack of behavioral modulation in this particular condition. These results directly support the “one-directional change detection” variant of the Scalar Timing Model detailed above, and further complements the behavioral findings observed in Experiments 1 and 2. Given our findings, the change in the number of saccadic eye movements might correlate with the latency to start accumulating temporal information when there is an increase in coherence from encoding to reproduction.

Our analyses of CVs in Experiments 1, 2 and 3 suggest that CVs across durations were not constant. Interestingly, research contesting the constancy of CVs traditionally shows an increase in CV with longer/supra-second timed durations (also see Grondin, 2014 for a review); although higher CVs have been found for supra-second intervals as well (see Lewis & Miall, 2009). Our results in all three experiments contradict these findings, showing that CVs decrease with target durations (see above). Such effects can been accounted for by a generalized form of Weber’s Law (Getty, 1975; Killeen & Weiss, 1987), which assumes an additive (i.e. a constant noise) in addition to a scalar source of variability in perceived durations (Ekman, 1959). The additive source of effect would be expressed stronger in shorter durations. It is important to note, however, that the design of the current study is not ideal for coming to definitive conclusions regarding the “non-constancy” of CV.

Finally, over-reproduction of all same-coherence pairs in the 2.1 s condition, close-to-target reproduction in the 3.7 s condition, and an under-reproduction in the 5.4 s condition in all three experiments is in line with previous research on timing (see Figure 1.2). Specifically, these results point at a migration of reproduced durations (a.k.a. "memory-mixing") possibly due to the fact that the three durations were randomly assigned to each trial rather than being blocked (i.e. Vierordt's Law; Gu & Meck, 2011; Lejeune & Wearden, 2009). Additionally an unexpected result was found in Experiment 1, where reproductions in trials in which the static stimulus was encoded *or* decoded were longer than the target duration. This result cannot be readily explained by adhering to the effect of the static stimulus exclusively on the allocation of attentional resources (i.e. switch) or on the arousal level (i.e. pacemaker), since opposite behavioral outputs are expected for the two mechanisms. Further, more controlled experiments are necessary in order to elucidate the differential effect of a static stimulus among dynamic stimuli within the temporal reproduction paradigm.

Our findings point at the modulation of time perception by the complex statistics of the stimulus properties (e.g., increase vs. decrease in SNR) adding to the findings of similar studies that utilized other stimulus features. Moreover, a robust effect of motion coherence was found in all three experiments, opposing some of the previous work which found no effect of motion coherence on the perception of durations (e.g. Kanai et al., 2006), furthering the discussion on the subject. Based on our findings, specific predictions regarding other functions (e.g., signal detection) can be derived. For instance, the primarily additive nature of the effects of increase in motion coherence suggests that the behavioral effects are driven at the onset of the timed event. Consequently, the detection of other stimulus immediately after the onset (and maybe also at offset) of the timing stimulus might be less likely during the second presentation of the stimulus when there is an increase in SNR. Thus, the asymmetrical effects of our experimental manipulations on timing behavior might also generalize to other domains. Although our results primarily showed an additive effect on timing behavior, we also detected a multiplicative effect in the second experiment. In order to better estimate the relative contribution of multiplicative and additive effects, future studies can test a wider range of durations. Finally, future studies can test the generality of these findings to other stimulus dimensions such as size, speed, and brightness, in addition to using eye tracking methodologies with forced foveal fixation in order to distinguish between the effect of the perception of motion and the effect of saccadic eye movements induced by that motion.

# CHAPTER II

## Dilation and Constriction of Subjective Time Based on Speed of Biological Motion

## Abstract

Perceived time has been shown to be modulated by physical properties of the timed stimulus such as its intensity and saliency. This study tested the effect of different quantitative (i.e., three different walking speeds) and qualitative (i.e., walking forward vs. backward) features of biological motion on time perception using a within-subject design in two different experiments. The variance between walking speeds was larger for Experiment 2 compared to Experiment 1 but both experiments contained the same medium walking speed. Participants were tested in the temporal bisection task, where they were asked to categorize durations as short or long, and points of subjective equality (PSE) were estimated from individual subjects' choice proportions. We hypothesized subjective time to dilate (shorter PSEs) with faster and constrict (longer PSEs) with slower walking speed. Furthermore, we expected these effects to be more prominent in the forward compared to backward walking conditions due to higher biological plausibility of forward motion, as well as in Experiment 2 compared to Experiment 1 due to larger parametric differences in Experiment 2. Our results show that the speed of biological motion has a parametric effect (i.e., more prominent in Experiment 2) on perceived durations in the expected direction, irrespective of its qualitative features, namely the direction of motion.

Keywords**:** Biological Motion, Speed, Psychophysics, Temporal Bisection, Time Perception

## Introduction

Given that accurate timing is essential for the preparation and execution of most motor responses (e.g., Buhusi & Meck, 2005), the implicit assumption have been that perception of time is highly accurate across situations irrespective of what is being timed. However, it has been shown that changes in a stimulus' properties such as its size, brightness, numerosity or loudness modulate time perception (e.g., Eagleman & Pariyadath, 2009; Xuan, Zhang, He, & Chen, 2007). In line with theories that assume a shared mechanism for the perception of various magnitudes (e.g., time, numerosity, space) by adhering to a common representational basis (Walsh, 2003), perceived quantities change in the same direction with the change in other stimulus properties. In other words, as one perceptual dimension is experimentally increased (e.g. loudness) so does the perceived duration of that stimulus (e.g. Berglund, Berglund, Ekman, & Frankenhaeuser, 1969).

The relationship between motion (i.e., speed) and time perception has also been well documented (Brown, 1995; Kaneko & Murakami, 2009), where an increase in the speed (Matthews, 2011) or even the coherence (i.e., saliency) of motion (Karşılar & Balcı, 2016) can lead to overestimations of durations, and vice versa. Since motion is inherently tied to *change* per unit time which may be used as a proxy for the passage of time (Poynter, 1989), it has been theorized that the larger amount of change experienced by the observer at faster speeds or temporal/spatial frequencies may be what leads to the overestimation of durations (Brown, 1995; Kaneko & Murakami, 2009).

Information-theoretic approaches to modeling these variations in timing behavior generally assume an internal clock (Treisman, 1963) with three components: (1) a pacemaker-accumulator unit which generates and counts pulses, (2) a memory unit where the total number of pulses are encoded, and (3) a decision component which compares the current number of pulses in the pacemaker-accumulator unit to a random sample from the reference memory unit in order to arrive at a temporal judgment (Gibbon, Church, & Meck, 1984). Thus, depending on the task used, stimuli exhibiting higher speeds could speed up the pacemaker, thereby leading to longer perceived durations (Wearden, 1999; Zakay & Block, 1997), or it may lead to inadvertent attentional lapses which may lead to some of the pulses generated by the pacemaker to not get registered in the accumulator (e.g., Penney, 2003), thereby leading to shorter perceived durations.

Given that disparate systems might be recruited with regard to the perception of animacy/inanimacy (Caramazza & Shelton, 1998; Zago, Carrozzo, Moscatelli, & Lacquaniti, 2011) as well as the biological plausibility vs. implausibility of the timed stimulus (Blake & Shiffrar, 2007; Shi, Weng, He, & Jiang, 2010), research on the relationship between the perception of time and motion has been further distinguished in relation to these variables. For instance, it has been found that still images of running postures are judged to have lasted longer compared to images of standing postures (Yamamoto & Miura, 2012), while timing of still images that imply human movement are more precise than those which do not (Moscatelli, Polito, & Lacquaniti, 2011). Relatedly, presentation durations of still images which show actions that imply having taken longer to complete (Nather & Bueno, 2011), sequential images that imply faster (Orgs, Bestmann, Schuur, & Haggard, 2011) or longer (Orgs & Haggard, 2011) apparent motion, or even words that imply a faster speed action (e.g. “gallop”; Zhang, Jia, & Ren, 2014) are generally judged to have lasted longer compared to identical conditions where shorter or slower actions are depicted. In addition to the information-processing model based “clock speeding up” account outlined above, discussion of such results have adhered to an effect of cognitive embodiment of perceived stimuli and durations (Droit-Volet, Fayolle, Lamotte, & Gil, 2013; Zhang et al., 2014), or cortical simulation of observed actions (Chen, Pizzolato, & Cesari, 2013; Nather & Bueno 2011), potentially underlain by structures that employ mirror neurons (Cattaneo & Rizzolatti, 2009) in addition to being mediated by higher order sensory-motor processing (e.g. Yamamoto & Miura, 2012).

On the other hand, based on the well-documented finding that perception of biological vs. non-biological objects utilize different neural structures (Downing, Jiang, Shuman, & Kanwisher, 2001; Giese & Poggio, 2003), still other researchers have shown that the modulation of perceived time induced by observing a moving stimulus is directly modulated by the biological nature/plausibility of the observed action as well (Watanabe, 2008; Wang & Jiang, 2012). Similar results have been obtained with stimuli showing animate (i.e., not implied) vs. inanimate motion in real time (e.g. Carrozzo & Lacquaniti, 2013; Carrozzo, Moscatelli, & Lacquaniti, 2010).

Overall, these studies further support a directional relationship between the perception of motion and the perception of time: Our timing mechanism is susceptible to the perceived speed of actual movement as well as that of an implied one embedded within still images which exert no physical change per unit time, and this timing system readily distinguishes between biological and non-biological actions, possibly applying different built-in statistical assumptions to the timing of two different types/sources of motion. Importantly, no study so far has explicitly tested the effect of different quantitative (e.g., speeds) and qualitative (e.g., forward vs. backward) features of biological motion on time perception. We hypothesized that the length of perceived durations would increase parametrically with increased walking speed. Moreover, we expected larger effect sizes when participants timed forward walking as opposed to backward walking motion, in addition to observing more precision with which participants timed durations in the former condition due to higher biological plausibility (Moscatelli, Polito, & Lacquaniti, 2011). Below we describe two experiments, both of which utilized the temporal bisection task, which entails categorizing durations as short or long. Our results show that the speed of biological motion has a parametric effect on perceived durations, irrespective of its qualitative features, namely the direction of motion (i.e., forward vs. backward), supporting the first of our hypotheses, and not the second.

## Methods

### *Participants*

34 participants (11 male, $M_{age}$ = 21.8) participated in *Experiment 1* and 32 participants participated in *Experiment 2* (10 male, $M_{age}$ = 21.2). Participants received 1 course credit in Experiment 1 and 12 liras (approx. 4 dollars) in Experiment 2. Both experiments were approved by the Institutional Review Panel for Human Subjects of Koç University. All participants provided written consent for their participation.

### *Stimuli and Apparatus*

Stimuli used in both experiments consisted of the animation of a walking stick-figure man (approx. height = 10 cm) composed of black lines for limbs and torso, as well as a black circle for the head (Figure 2.1; see Supplementary Materials). The animations consisted of the stick-figure man walking on a rectangular white background, which in turn was placed on a black canvas that encompassed the entire screen. All stimuli and instructions were presented on a 21” LCD screen (60 Hz refresh-rate) on an Apple iMac G4 computer, generated in Matlab using the PsychToolbox extension (Brainard, 1997). Participants sat at a distance of 58 - 63cm from the screen, in a dimly lit room and provided their responses using a mechanical keyboard.

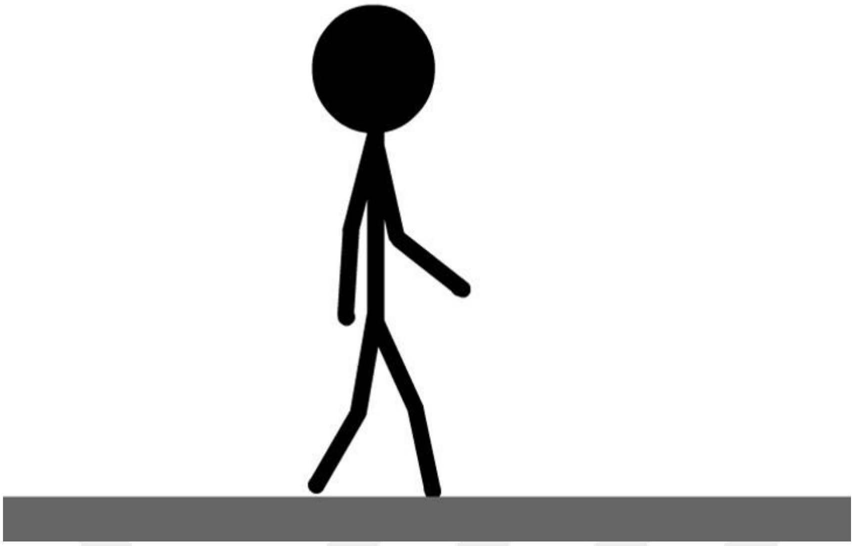

Figure 2.1 Sample frame taken from the animation loop.

One cycle of the walking animation consisted of two steps taken by the stick-figure, where the posture in the last frame was set so as to continue with the posture in the first frame, allowing us to form seemingly perfect and theoretically infinite loops. The center of the stick figure did not move on the x-axis, which gave the impression of a simultaneously moving camera at a right angle, while small movements of the body on the y-axis represented the characteristic bouncing motion as people walk. At 50 frames per second (fps), one cycle (i.e., two steps) lasted 1.5 seconds, which was considered to be the normal speed of walking. Five distinct walking speeds were then produced by modulating the fps of the walking animation (40, 50 & 63 fps in Experiment 1 and 25, 50, & 100 fps in Experiment 2) each of which lasted for one of 6 probe durations (1.0, 1.5, 2.0, 2.5, 3.0 & 3.5 seconds). Hence, lower fps values led to slower and higher fps values led to faster walking speeds. Finally, mirror animations were prepared by reversing the walking action in each video where the stick-figure walked backwards, serving as the “unnatural” walking condition.

### *Bisection Procedure*

***Training.*** Each session started with the presentation of two anchor durations at the offset of a space button press (short = 1 s, long = 3.5 s), represented by the presentation duration of a circular mottled texture (white, gray, black; approx. 8 cm in diameter). 10 training trials then pursued, in which the participants' task was to report if the duration of the automatically presented circular texture was the short or the long one (5 random trials each). A trial was repeated if an incorrect answer was given. The buttons denoting a "short" or a "long" response were randomly assigned in each session. Each participant attended a single session, which lasted 50-60 minutes. Participants were instructed not to count or use any other chronometric methods.

***Test.*** After 10 correct responses in the training trials, the experimental block commenced, in which the participants' task was to categorize the six probe durations of walking animations as closer to the "short" or "long" anchor durations. Three walking speeds were employed in each of the two experiments (Exp 1: 40, 50, 63 fps; Exp 2: 25, 50, 100 fps; see above). The videos started with the press of the space button. Once the video ended, the participant was allowed to respond after a stimulus-to-response interval sampled from an exponential distribution with a mean of 0.5 s and a lower bound of 0.2 s. All possible combinations of walking speeds (3 levels), probe durations (6 levels), and walking direction (2 levels) were randomly presented 12 times, leading to a total of 432 trials per session. No feedback was given after responding either for reference or intermediate durations.

## Results

Mean percentage of "long" responses were plotted as a function of the six probe durations for each combination of walking speed and walking direction conditions, thereby forming six sigmoidal psychometric functions per participant (see Figure 2.2). Standard two-parameter cumulative Weibull distribution functions were fit to these data. The parameters of fits with adjusted-R-squared values less than 0.70 (7 % and 4 % of the cases in Experiments 1 and 2, respectively) were substituted by a random value that was drawn from the sample distribution such that it did not alter the mean or the standard deviation. Two participants in Experiment 1 were excluded from further analyses due to more than two excluded fits.

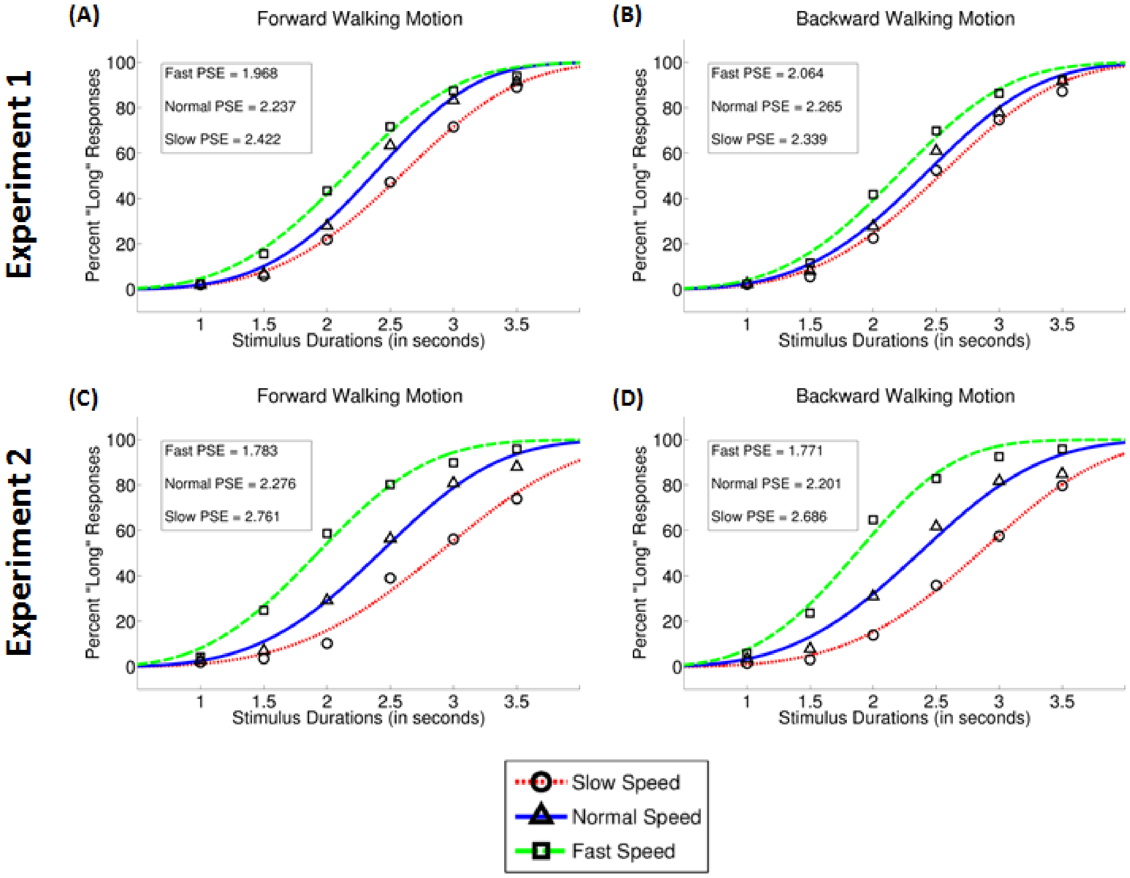

Figure 2.2 Average psychometric functions obtained by plotting the mean percentage of “long” responses as a function of probe duration in the forward (A & C) and the backward (B & D) walking conditions in Experiment 1 (A & B) and Experiment 2 (C & D). Solid blue (triangle) lines denote normal walking speed, whereas dotted red (circle) and dashed green (square) lines denote slow and fast walking speeds, respectively. Points of Subjective Equality (PSE) are provided for each condition.

Points of subjective equality (PSE; the duration at which a short and a long response was equally likely) were calculated as the median of the Weibull fits. We were primarily interested in potential leftward or rightward shifts of the PSE values as a function of experimental conditions, which would typically be interpreted in terms of an increase or a decrease in clock speed (i.e., perceived time), respectively. We have also calculated the Weber Ratios (WR), which is a measure of the steepness of the cumulative distribution function and refers to the sensitivity with which the probe durations are categorized. WR values were calculated by dividing the difference limen ([(*p*(long) = 0.75 – *p*(long) = 0.25)) / 2] ) by the PSE. A higher WR value indicates that the participant had a more difficult time differentiating durations as short or long.

A two-way repeated measures ANOVA with walking speed (3 levels; Exp 1: 40, 50, 63 fps; Exp 2: 25, 50, 100 fps) and walking direction (2 levels; forward & backward) as within subject factors, and PSE values as the dependent variable was conducted, separately for the two experiments. Our analysis of data from *Experiment 1* showed a main effect of walking speed (*F*(2, 62) = 47.04, *p* < .001, $\eta_p^2$ = .60), and no main effect of walking direction (*F*(1, 31) = 0.34, *p* = .55), or an interaction between the two variables (*F*(1.57, 48.52) = 2.34, *p* = .11, Greenhouse-Geisser Corrected). Post-hoc analyses showed that the difference between all walking speeds reached significance (all *p*s < .01). Data from *Experiment 2* showed the identical pattern of results, with a larger size of the significant main effect compared to *Experiment 1*; namely a main effect of walking speed (*F*(1.34, 41.64) = 105.44, *p* < .001, $\eta_p^2$ = .77), and no main effect of walking direction (*F*(1, 31) = 2.32, *p* = .14), or an interaction between walking speed and walking direction (*F*(2, 62) = 0.60, *p* = .55). Again, identical with Experiment 1, post-hoc analyses in Experiment 2 showed that the difference between all walking speeds reached significance (all *p*s < .001).

Identical repeated measures ANOVAs with WR as the dependent variable and walking speed and walking direction as the independent variables were conducted. The main effects reached significance for the WR in Experiment 1. On the other hand, in Experiment 2, there was a significant main effect of walking speed on WR (*F*(2, 62) = 7.48, *p* = .001). Post-hoc analyses showed that WR values in the slow walking condition (*M* = 0.151) were significantly lower compared to the normal (*M* = 0.176) and fast (*M* = 0.188) walking conditions (both *p*s < .05), while the latter two conditions did not differ significantly from each other (*p* > .05).

Finally, we aimed to see if the degree of the effects were more prominent with larger differences in walking speed as manifested by the experimental paradigm (i.e., as in Experiment 2 compared to Experiment 1). Thus, the data gathered in both experiments were subjected to a mixed ANOVA with walking speed and walking direction as two within-subjects factors, paradigm type as the between subjects factor (2 grouping levels; Experiment 1 & Experiment 2), and PSE as the dependent variable. Results showed a main effect of walking speed (*F*(1.61, 99.94) = 150.93, *p* < .001, $\eta_p^2$ = .71), in addition to an interaction between walking speed and the grouping factor (*F*(2, 124) = 30.23, *p* < .001, $\eta_p^2$ = .33), while no other main or interaction effects reached significance (all *p*s > .05). Post-hoc independent samples t-tests showed that, in both the forward and backward walking conditions, the PSE values in the slow and fast walking speed conditions in Experiment 2 were significantly lower and higher than those in Experiment 1, respectively (all *p*s < .05, Holm-Bonferroni corrected, see Figure 2.3), whereas there were no differences among the normal walking speed conditions in either direction (both *p*s > .05).

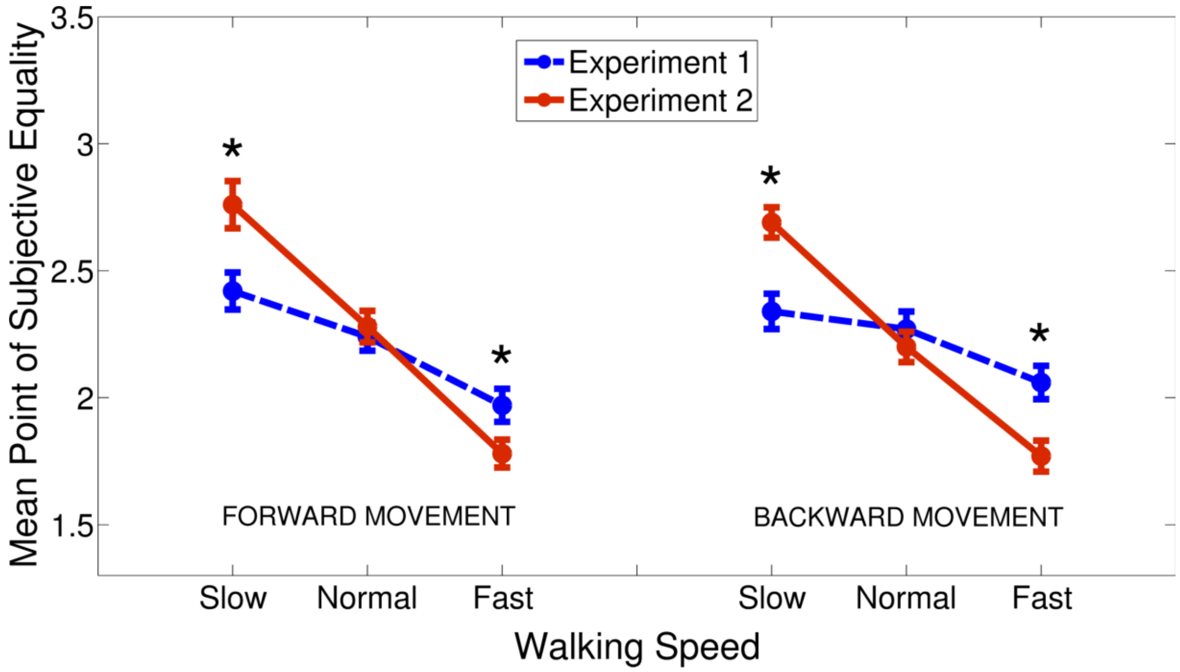

Figure 2.3 Results of independent samples t-tests comparing PSE values in the slow, normal and fast walking speed conditions in Experiment 1 (dashed blue lines) vs. Experiment 2 (solid red lines), separately for the forward (left panel) and backward (right panel) walking directions. Asterisks denote significant difference at the .05 level. Error bars show standard error of the mean.

## Conclusion

We conducted two experiments in which participants' task was to categorize six durations of animations depicting a stick-figure, walking forwards or backwards, at three different of walking speeds. The two experiments differed only in the degree of difference between the faster and the slower walking speed. When data from both experiments were examined separately, as well as in conjunction, our results suggested that subjective time dilates with faster observed walking speed and it constricts with slower observed walking speed. On the other hand, the direction in which the stick-figure walked (forward or backward) did not have a main effect or an interaction effect in any of the experiments.

There are two primary mechanisms through which subjective time can be modulated within the "pacemaker-accumulator" theoretic framework; these are 1) changes in the pacemaker rate and 2) changes in the probability by which pacemaker signals are integrated in the memory. In relation to our experimental manipulation, higher walking speed can be assumed to either increase the pacemaker rate (e.g., due to arousal) or a decrease in attention to time (e.g., due to divided attention) and vice versa for slower walking speeds. Under the first possibility (i.e., change in pacemaker rate), subjective time would be expected to dilate with faster walking speed, while the opposite predictions would be made if the effects were on attention to time. To this end, our results directly support the effect of observed walking speed on pacemaker rate. Importantly, walking speed had a parametric effect on clock speed; compare the effect sizes in two experiments with differential degrees of deviation between walking speed (Figure 2.3).

Although WRs were relatively constant across conditions in Experiment 1, they differed in Experiment 2 (higher WRs with faster walking speed). It is possible that an additive noise component contributed by observing a faster biological motion was not captured in Experiment 1 but in Experiment 2 due to differences in the size of the experimental manipulation.

In both of our experiments, we modulated fps values in order to increase/decrease the speed at which the stick-figure seemed to move. Importantly, a higher fps stimulus (our fast walking condition) by definition employs more frames that are presented to the participant per unit time. In relation to theories of timing that emphasize “perceived change per unit time” as the fundamental index of perceived duration (Poynter, 1989), it can be argued that it wasn’t the high speed of movement per se that constricted perceived durations in our paradigm, but rather the number of frames perceived by the participant per unit time. However, given that all of the frame rates used in our study were above the 24 level (e.g. Condon & Ogston, 1966; Haggard & Isaacs, 1966) beyond which most subjects perceive continuous motion, such an argument seems implausible. Nonetheless, this possibility could be tested for by keeping the frame rate constant (e.g. 50 fps) among speed conditions in a future study. Finally, both of our experiments employed stimuli depicting a simple walking motion performed by an obviously human-like agent. As mentioned above, biological plausibility is possibly linked to the mechanism by which an object is timed. Therefore a future study that tests how self-governing, non-biological motion stimuli are timed in contrast to stimuli depicting biological motion could further elucidate the mechanism by which this modulation of time perception was achieved in the current study.

# CHAPTER III

## Magnitude but not Font Size of Arabic Numerals Modulate Perceived Time

## Abstract

Physical quantities have been previously argued to rely on similar magnitude-based representational systems with shared metric properties. In support of this theoretical assertion, different quantifiable dimensions that characterize timing stimuli (e.g., size, speed, loudness, brightness, numerosity) have been shown to modulate perceived duration, which have been attributed to the cross-modal interaction among different magnitude-based representations. However, these studies have typically tested the isolated effects of a single stimulus dimension on perceived duration, leaving their potential interactive effects unaddressed. Current study aimed to investigate the effect of value and physical (font) size of Arabic numerals and their interaction on perceived time in a perceptual timing task (i.e., temporal bisection). Six durations were presented with different combinations of three numerals and font sizes and participants were asked to categorize them as short or long. Our results showed the psychometric function for “3” was located to the right of those gathered with stimuli “6” and “9”, suggesting lower rate of temporal integration for the smallest numeral in the set with no effects of font size or the interaction effect of these two factors. These results suggest higher efficacy of the value of Arabic numerals over their physical size in terms of its influence on temporal choice behavior.

Keywords: Numerals, Size, Magnitude, Temporal Bisection, Time Perception

## Introduction

Accurate mental representation of magnitudes of space, time and numerosity is critical for organizing and integrating information (Allan 1979; Buhusi & Meck, 2005; Meck, Penney & Pouthas, 2008), which is fundamental for adaptive behaviors (see Gallistel, 1990; Buhusi & Meck, 2005). Despite their separate physical counterparts, representations of different quantities such as distances, time, and numerosity have been argued to be closely intertwined and to be underlain by overlapping neural systems (Bueti & Walsh, 2009; Conson, Cinque, Barbarulo, & Trojano, 2008; Hubbard, Piazza, Pinel & Dehaene, 2005; Walsh, 2003; Pinel, Piazza, Le Bihan & Dehaene, 2004). This assumption of common metric for different dimensions suggest that quantity judgments in one domain can affect the quantity judgments regarding other domains. In support of this prediction, larger, brighter, higher-frequency, louder static stimuli, or dynamic stimuli with faster motion, are perceived to have lasted longer compared to stimuli with opposing features, suggesting a functional overlap particularly between the perception of physical and temporal magnitudes (e.g., Allan, 1984; Beckmann & Young, 2009; Brigner, 1986; Brown, 1995; Kaneko & Murakami, 2009; Matthews, Stewart & Wearden, 2011; Ono & Kawahara, 2007). A study by Oliveri et al. (2008) showed that these effects can also generalize to symbols with well-learned semantic references based on the finding that Arabic numerals can also affect temporal estimations (see also Dormal, Seron & Pesenti, 2006; Xuan, Zhang, He, & Chen, 2007; Oliveri, Koch & Caltagirone, 2009). Specifically, these researchers found that larger numbers (e.g., “9”) are perceived to have lasted longer compared to small ones (e.g., “5”). This overlap is further supported by the fact that participants are more accurate at classifying presented durations as “short” or “long” if the value of the numerals were congruent with the classified duration (a small number presented for a short duration) as opposed to the when they were incongruent (a small number presented for a long duration; Xuan, Chen, He, & Zhang, 2009). Participants also make faster decisions regarding the magnitude of given numeral when the symbolic representation of a number matches its physical size (a small “3” or a large “7”; Henik & Tzelgov, 1982; Kallai & Tzelgov, 2012).

In turn, processing of temporal magnitudes have been found to interfere with that of numerosity (e.g. Brown, 1997), and categorizations based on numerosity (i.e. “less/more”) were found to spontaneously transfer to durations despite the differential arguments regarding the nature of the transfer function. For instance, Meck & Church (1983) argued that such spontaneous transfers are based on mappings at the level of mental magnitudes (representational raw material) whereas Balcı & Gallistel (2006) demonstrated that the transfer can rather rely on a unitless metric such as proportions. While such results linking perception and representation of space, time, and numerals are abundant in the literature, no study so far has attempted to investigate the interaction effect of these dimensions. In this study, we have attempted to elucidate the interaction between various font sizes and values of Arabic numerals in terms of their presumed directional effect on temporal judgments.

Although there is converging evidence demonstrating cross-modal interaction and transfer of information between different quantitative dimensions (see Alards-Tomalin, Leboe-McGowan, Shaw & Leboe-McGowan, 2014), information-processing models aimed at explaining them fall short of formally accounting for such representational correspondences. The most prominent of such models employs a pacemaker-accumulator theoretic framework, such that; 1) a pacemaker-accumulator component that generates and temporarily stores mental magnitudes in the form of pulses or neural oscillations, 2) a memory component where the total number of pulses from the previous component are stored , and 3) a decision stage (i.e., comparator) where a random sample from the memory store is compared to the value currently stored in the accumulator (e.g. “shorter/longer response”; Gibbon, Church, & Meck, 1984; see Allman, Teki, Griffiths & Meck, 2014 for a review). While the basic schematics of this theoretical approach have been applied to other domains as well (e.g., non-verbal counting; see Meck & Church, 1983), the pacemaker-accumulator family of models has garnered the largest amount of interest with regard to interval timing (see Grondin, 2010 for a review). An internal clock model (Treisman, 1963) utilizing such a multi-staged information-processing delineation provides the analytical flexibility and tractability to account for distortions of time perception due to stimulus features (Coull, Vidal, Nazarian, & Macar, 2004; Wearden, 1999; Zakay & Block, 1997; Penney, 2003; Zakay, & Block, 1995), for instance in reference to physiological arousal (pacemaker), attention (switch as a temporal gating mechanism), information maintenance efficacy (accumulator), and/or decision biases (comparator) while successfully accounting for well-established psychophysical properties (Balcı & Simen, 2016; Simen, Rivest, Ludvig, Balcı & Killeen, 2013; Wearden & Lejeune, 2008). Yet, the theoretical underpinnings of such centralized internal clock models generally do not explain why magnitude information gathered on one domain (e.g. duration or size) may influence magnitude judgments regarding another domain (e.g. numerosity or brightness). As such, existing pacemaker-accumulator models do not provide the necessary mechanistic grounds for formulating clear directional hypotheses regarding the interaction between numerical magnitude and font size on perceived duration.

Due to the metric properties of space, time, and numerosity (e.g., Montemayor & Balcı, 2007), some researchers have attempted to reconcile these entities' attestable interaction by adhering to the notion of a "common magnitude representation metric" (*A Theory of Magnitude*; Walsh, 2003), allowing for translation of magnitude codes among various quantitative dimensions. According to this approach, upon translation into the common magnitude code, any perceived magnitude becomes an approximate representation or a unitless quantity (see also Balcı & Gallistel, 2006). Such an analog representation therefore becomes amenable to cross-modal comparison/transfer, and cross-modal interaction due to the common neural metric employed and the neural noise inherent in the system, respectively (Gallistel & Gelman, 2000). Arguments for such a common magnitude system have also received considerable support from brain-imaging research which points to the Parietal Cortex --specifically the Intraparietal Sulcus (Dormal & Pesenti, 2012)-- as the common neurostructural basis for the processing of symbolic and non-symbolic magnitudes (Bueti & Walsh, 2009; Hayashi et al., 2013), in addition to subserving the perception of time. Although, its assumptions better accommodate the cross-modal interactions, similar to the internal clock model, the common magnitude metric framework does not make directional predictions as to how magnitudes represented by numerals would interact to distort perceived duration.

While magnitude-based variables have been shown to comprise a directional relationship with perceived duration (larger size → longer duration; larger number → longer duration; Rammsayer & Verner, 2014; Ono & Kawahara, 2007; Xuan et al., 2007), and have been shown to be processed faster and more accurately when both representations are congruent (“a large 9” vs “a large 2”; Xuan et al., 2009), no study so far has tested to see if the combined effect of varying levels of size and numerical magnitude on perceived duration. The current study aimed to fill this gap in the literature. Overall, our results showed that while perceived durations lengthened with increasing values of numerals, these symbols’ font sizes had no effect on the perceived durations, either by themselves or in conjunction with the numerical values. These results suggest that a more readily and automatically processed --and thus more salient-- source of magnitude information (i.e., numerical magnitude) overshadows the information gained through a less reliable source (i.e. number font) in terms of modulating perceived duration.

## Methods

### *Participants*

34 participants (13 male, $M_{age} = 20.1$, $Range_{age} = 18 - 29$) took part in the experiment. 10 participants received 1 course credit, and 24 participants received 12 liras (approx. 4 dollars) for their participation. All participants had normal or corrected-to-normal vision. The study was approved by the Institutional Review Panel for Human Subjects of Koç University. All participants provided written consent for their participation.

### *Stimuli and Apparatus*

Stimuli used consisted of three different font sizes (small, medium and large; 50, 100 and 200 pts, respectively) of Arabic numerals “3”, “6” and “9”. The actual small, medium and large font sizes projected on the screen were approximately 2, 4 and 6 cm in height, and 1, 2 and 3 cm wide, respectively. All stimuli and instructions were presented on a 21” screen (60 Hz refresh-rate) on an Apple iMac G4 computer, generated in Matlab using the PsychToolbox extension (Brainard, 1997; Pelli, 1997). Varying sizes of the numbers 3, 6 and 9 were presented individually and centrally in white color with no outline. All stimuli and instructions were presented on a gray background (see Figure 3.1 for a graphic depiction). Participants sat at a distance of approximately 60 cm from the screen, and provided their responses using a mechanical keyboard.

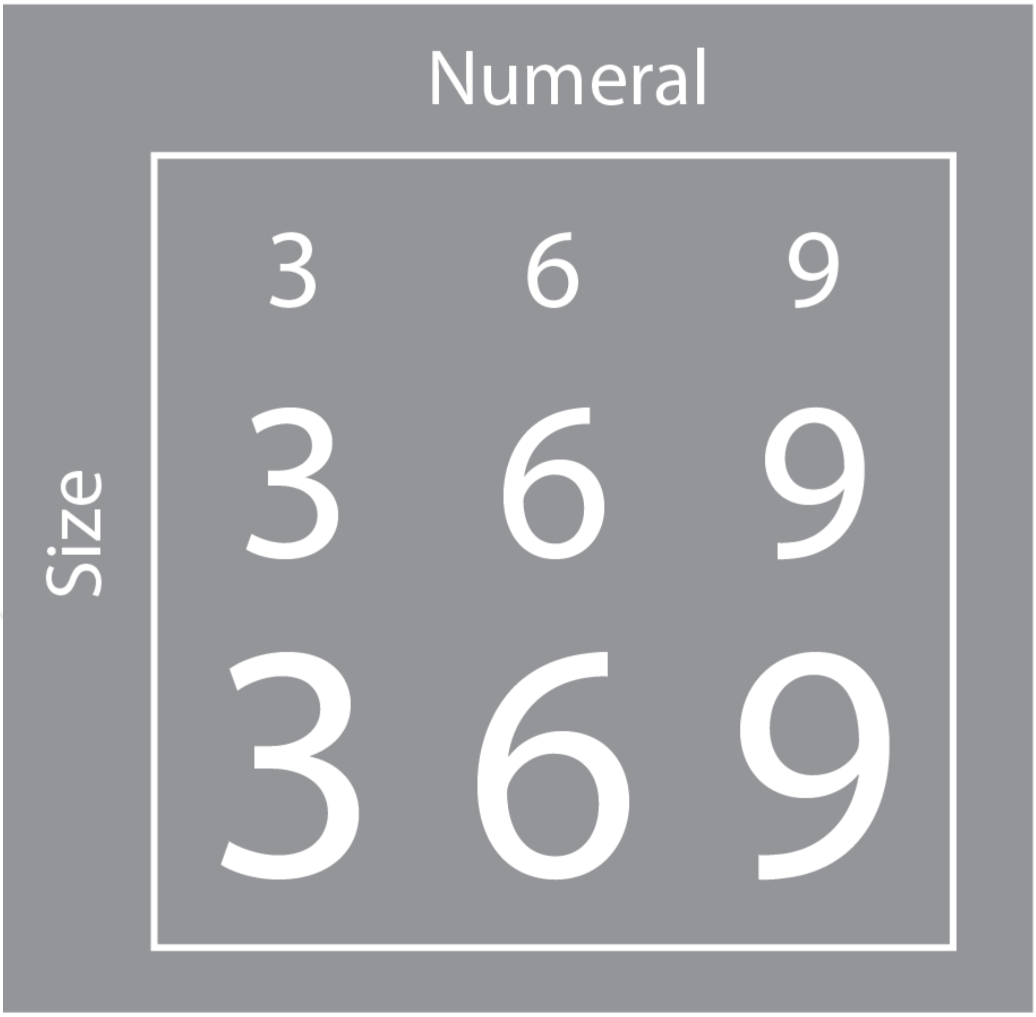

Figure 3.1 Depiction of the relative sizes (small, medium & large) of all numerals (3, 6 & 9) used in the experiment. Each of these numerals and size pair served a timing stimulus signaling the duration to be judged.

### *Bisection Procedure*

***Training.*** Each experimental session started with a training block, where participants were first presented the two reference durations (short and long; 1s & 3.5 s, respectively), represented by the presentation duration of circular black-white-gray mottled texture with a diameter of approximately 8 cm. Participants were then presented with these two reference durations 5 times in random order, and reported the perceived duration of the stimuli using one of two buttons on the keyboard (“F” or “K”) which denoted a “short” or a “long” response (key mappings were counterbalanced across participants). Training instructions explicitly stated that only the two previously experienced durations, and no intermittent ones, were being presented at this stage of the experiment. An incorrect response was followed by a correction trial with identical parameters. Upon 10 correct responses the training block was terminated. Participants were instructed not to count or use any chronometric heuristics or methods (such as keeping a rhythm). Each participant took part in a single 50-60 minute session. Participants were instructed to take a break any time they felt tired or failed to maintain their attention on the task.

***Test.*** For the remainder of the session, participants' task was to categorize (as "short" or "long") six probe durations (1.0, 1.5, 2.0, 2.5, 3.0 & 3.5 seconds) represented by the presentation duration of one of the three numerals (3, 6 or 9) with one of three font sizes (small, medium or large). Key mapping for the responses were identical to that in the training session. All possible combinations of the two variables (3 X 3) randomly appeared 10 times for all probe durations, leading to a total of 540 trials per participant. Each stimulus was presented upon a key press ("Space" button for all participants), followed by a fixed stimulus-to-response prompt interval of 0.5 seconds, after which participants were allowed to respond. No feedback was given after responding either for reference or intermediate durations.

## Results

For each combination of the three levels of the independent variables (numeral & font size), a total of nine sigmoidal psychometric functions were formed for each participant by plotting the mean percentage of "long" responses as a function of the six probe durations (see Figure 3.2 for psychometric functions fit to average data). Points of subjective equality (PSE) were calculated by fitting a cumulative Weibull distribution function to these data and calculating the median of the best fit Weibull distribution (i.e., the duration at which the probability of a long response was %50). We were primarily interested in the modulation of the PSE values as a function of numerical value, font size, or a combination of these two variables. Shape and scale parameters of Weibull fits with adjusted-R-squared values less than 0.7 were replaced by a random value drawn from the sample distribution so that it did not alter the mean or the standard deviation of the sample. Two participants with more than two "bad" Weibull fits were excluded from further analyses. Finally, as a measure of the steepness of the Weibull function, Weber Ratios (WR) were calculated by dividing the difference limen (DL; [($p$(long) = 0.75 – $p$(long) = 0.25)) / 2]) by the PSE. The WR value indicates the discriminability of the durations.

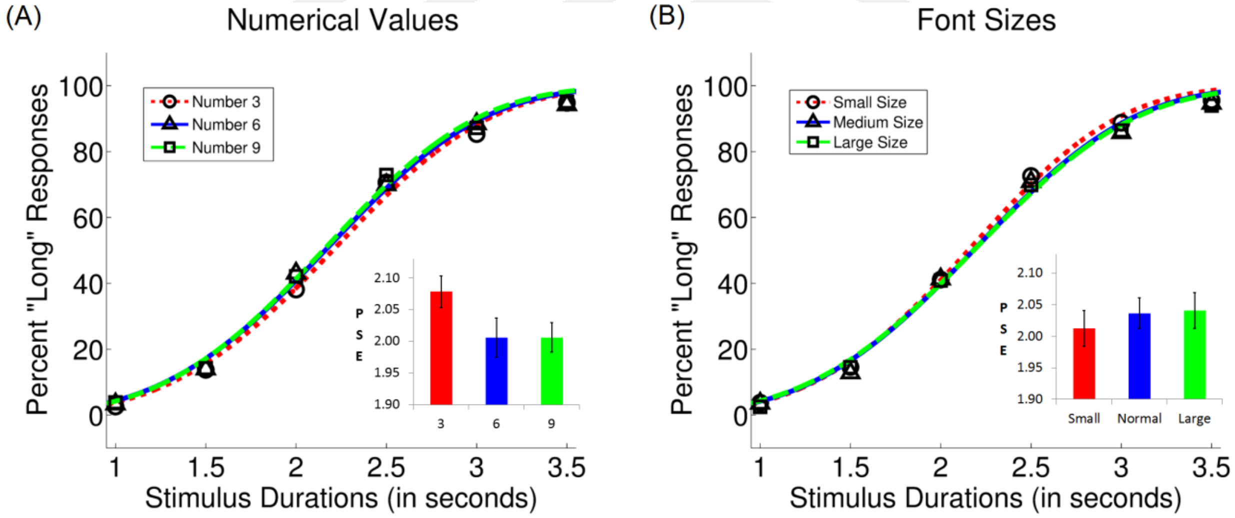

Figure 3.2 Weibull distribution functions fit to the mean percentage of "long" responses as a function of probe durations. PSE values calculated for the three levels of the (A) numerical value, and (B) font size variables are plotted as insets. Inset error bars denote within-subjects error (%95 CI; Cousineau, 2005).

A two-way repeated measures ANOVA with PSE as the dependent variable, and numerical value (3 levels) and font size (3 levels) as within subject factors was conducted. Results showed a main effect of numerical value ($F(2, 62) = 6.41$, $p < .01$, $\eta_p^2 = .17$), and no main effect of font size (*F*(2, 62) = 0.42, *p* = .4), or an interaction between the two variables (*F*(2.98, 92.48) = 1.11, *p* = .4, Greenhouse-Geisser corrected). Post-hoc analyses showed that presentation of the number 3 led to the highest PSE (*M* = 2.08) compared to PSE for number 6 and 9 (both *Means* = 2.01; both *p*s < .05, Holm-Bonferroni corrected), whereas the difference between the latter two numerals did not reach significance (*p* > .05). Identical repeated-measures ANOVAs with WR, DL and response time (RT; the duration from the end of the 0.5 s stimulus-to-response interval to the response; see *Methods* section) as the dependent variables were conducted. None of the main or interaction effects on any of these dependent variables reached significance (all *p*s > .05).

## Discussion

Physical magnitudes in different domains tend to be correlated; a larger rock rolls down a cliff faster, for a longer time with more noise. Similarly, an object that is hotter also shines brighter, and if left simply to the devices of entropy, the warmer it was to begin with, the longer it takes to cool down and get dimmer. Such relations might also be inherently present in the representational assumptions as a result of learning or due to the evolved architecture of the perceptual system. In light of convergent behavioral evidence demonstrating such an interaction among the perception of these abstract domains (see Eagleman, 2008 for a review), a theoretical framework for a translational system for analog representations has been postulated (Walsh, 2003). Within this framework, representations of space, time, and number are neurally coded as ratios ("a little" or "a lot") instead of their absolute magnitudes (see also Balcı & Gallistel, 2006), thereby allowing for interactions within this noisy (see Meck & Church 1983; Feigenson, Libertus, & Halberda, 2013), all-purpose magnitude transactional system (Bueti & Walsh, 2009). However, empirical studies on the interaction among magnitude representations have tended to pick only two domains within which the effect of experimental manipulation on one domain (e.g. presenting a larger disk or a larger number) over the judgments of another are demonstrated (e.g. dilation of subjective time; Rammsayer & Verner, 2014; Xuan et al., 2007). While this represents a straightforward approach, it nonetheless fails to capture the integration of simultaneously extracted information from multiple domains.

We have extended this questioning to encompass the symbolic representation of magnitude information and their physical features by devising an experimental procedure in which numerical magnitude and physical size of the timing stimulus (i.e., Arabic numeral) were simultaneously modulated. In line with previous literature, our results suggest that presentation of larger numerical values lengthened perceived durations. However, in contradiction with the literature, presentation of physically smaller or larger numbers had no discernable effect on subjective time, and this otherwise effective predictor of temporal modulations (e.g. Rammsayer & Verner, 2014; Ono & Kawahara, 2007; Xuan et al., 2007) failed to interact with symbolic numerical representation.

Our results suggest that the magnitude information conveyed by their symbolic references is sufficient to induce clock speed-like effects whereas the physical size of these symbolic references do not lead to the rather well-established effects of the stimulus dimensions on time perception. We find this an interesting and important empirical observation as it adheres to the two postulates of symbolic representations; a) Symbols are linked to semantic content and activate it (Gelman & Gallistel, 1992), and b) Symbols are arbitrary with no inherent resemblance to their semantic content (e.g, “3” in Arabic numeral system and “11” in binary code refer to the same discrete quantity). Consequently, one would indeed expect to observe the typical interaction between two analog representations even when one of them is presented in its symbolic form (Piazza, Pinel, Le Bihan, & Dehaene, 2007). On the other hand, one would not expect the physical size of a symbol to tap into a similar representational interaction as it is irrelevant to the semantic referencing by symbols. In other words, the arbitrariness of symbol-semantics relation would be expected to block the induction of stimulus size-duration interaction in our specific experimental design.

It is however also possible that at least in special cases where the informational value and the ease and automaticity with which magnitude information is derived from one domain (i.e. numerical value) is significantly higher than another one (i.e. size), the common magnitude representational system may actively dampen the information flow from the latter, more unreliable source of information. This is similar to linguistic category information becoming a better predictor of color judgments when a more fine grained perceptual information suffers from relatively higher uncertainty (Cibelli, Xu, Austerweil, Griffiths & Regier, 2016). Thus, our empirical observations might not be peculiar to symbolic representations; well-learned and widely used symbols might rather just meet the requirements of high stimulus saliency. Finally, our differential findings might have more to do with innate-architectural rather than situational factors; the "cross-modal affinity" of magnitude-based representations might be different for different domains. For instance, compared to spatial manipulations, it might by default be easier to induce effects of numerosity-related manipulations on duration judgments due to the inherent properties of specific magnitude-based representations and/or higher degree of overlap between their corresponding neural substrates. This might result in the *a priori* prioritization of certain kinds of information over others particularly if the channels of cross-modal interaction/integration are constrained by the limits of cognitive resources such as attention. These possibilities constitute a fertile theoretical ground for future studies on interval timing in specific, and magnitude representations in general.

One drawback of our study is that numbers are automatically processed and are fairly absolute, while without any contextual background, size is relative and therefore carries too little information regarding environmental statistics. In order to overcome this shortcoming, future studies may employ non-numerical/artificial symbols to represent numerosity while maintaining the size manipulation. Additionally, a static frame around the presented stimuli would reduce the relativity of physical size and instead make it a better source of quantifiable information. Finally, the degree of shift in PSE was rather small in the current study (i.e., ~70 ms corresponding to 4% of the average PSE). Larger ratios between the used numerals (e.g., “11” vs. “99”) might be a potential way to achieve larger effects.

# GENERAL DISCUSSION

The chapters that formed this thesis focused on the modulation of time perception in response to changes in the properties of timed stimuli, using two commonly used timing tasks namely, “temporal reproduction” and “temporal bisection”. Overall, results of all three studies complemented our current understanding of how subjective time is modulated by non-temporal characteristics of experience.

The first set of studies (Chapter I) aimed to fill an important gap in the literature regarding the relationship between motion coherence (i.e. SNR) and time perception. Multiple target intervals and SNR levels were utilized in three separate experiments in order to better characterize the key quantitative features of the potential effects (i.e., multiplicative vs. additive), allowing for the interpretation of findings in terms of differential dynamics of the underlying processes. The results of the studies in Chapter I have consistently shown that increasing the SNR from the standard/training stimulus to the test/reproduction stimulus resulted in the underestimation of perceived durations. The magnitude of this bias increased as a function of the parametric difference in motion coherence. Importantly, this effect was not “mirrored” when there was a decrease in SNR in any of the experiments, revealing a clear and consistent asymmetry regarding the sensitivity of subjective time to changes in signal quality. Additionally, the third experiment in this chapter tested the relationship between these behavioral changes and the change in the number of eye movements from the training to the reproduction phases, revealing a predictive relationship when there is an increase in SNR. Overall, these findings in Chapter I point to an effect of varying SNR levels from training to reproduction on the operational characteristics of the temporal gating function within the pacemaker-accumulator theoretic framework, albeit solely in response to an increase SNR.

The second set of studies (Chapter II) extended the question relating motion perception to time perception by employing animations depicting a familiar biological motion (i.e. walking) as the to-be-timed stimuli. The effects of different quantitative (i.e., three different walking speeds) and qualitative (i.e., walking forward vs. backward) features of biological motion on time perception were investigated in two different experiments. We hypothesized subjective time to dilate with faster and constrict with slower walking speeds. Furthermore, we expected these effects to be more prominent in the forward compared to backward walking conditions due to higher biological plausibility of forward walking motion (Blake & Shiffrar, 2007; Shi, Weng, He, & Jiang, 2010). Our results showed that the speed of biological motion has a parametric effect on subjective time, irrespective of its qualitative features. This work partially replicated previous findings in the literature, while denoting limitations on how biological plausibility should be interpreted in relation to its effect on perceived time.

Finally, the third set of studies (Chapter III) aimed to investigate the potential interaction between symbolic and non-symbolic magnitude representations on the perception of time. Magnitudes of size (non-symbolic) and numerical value (symbolic) in and of themselves are known to have a directional relationship with perceived time. The study presented in Chapter III further explored this relationship by systematically manipulating numerical value and font size simultaneously and assessed the resultant changes in perceived time. Interestingly, while an effect of symbolic magnitude was observed, the expected effect of size (or an interaction between the two factors) was not present in our data. These results were discussed within the framework of a common magnitude representational system, whereby more reliable sources of magnitude information (in our case numerical value) may dampen the informational value of another source, if both dimensions belong to the same visual object (in or case Arabic numeral). We hypothesized that this passive dampening effect may result from the fact that numerals are well-learnt and highly salient stimuli that automatically convey accurate magnitude information to the observer, allowing for higher cross-modal interaction between symbolic and temporal representations.

Overall, the findings gathered as part of this thesis demonstrate that subjective time is amenable to a multitude of non-temporal factors providing behavioral benchmarks for further model development and neural characterization of interval timing.

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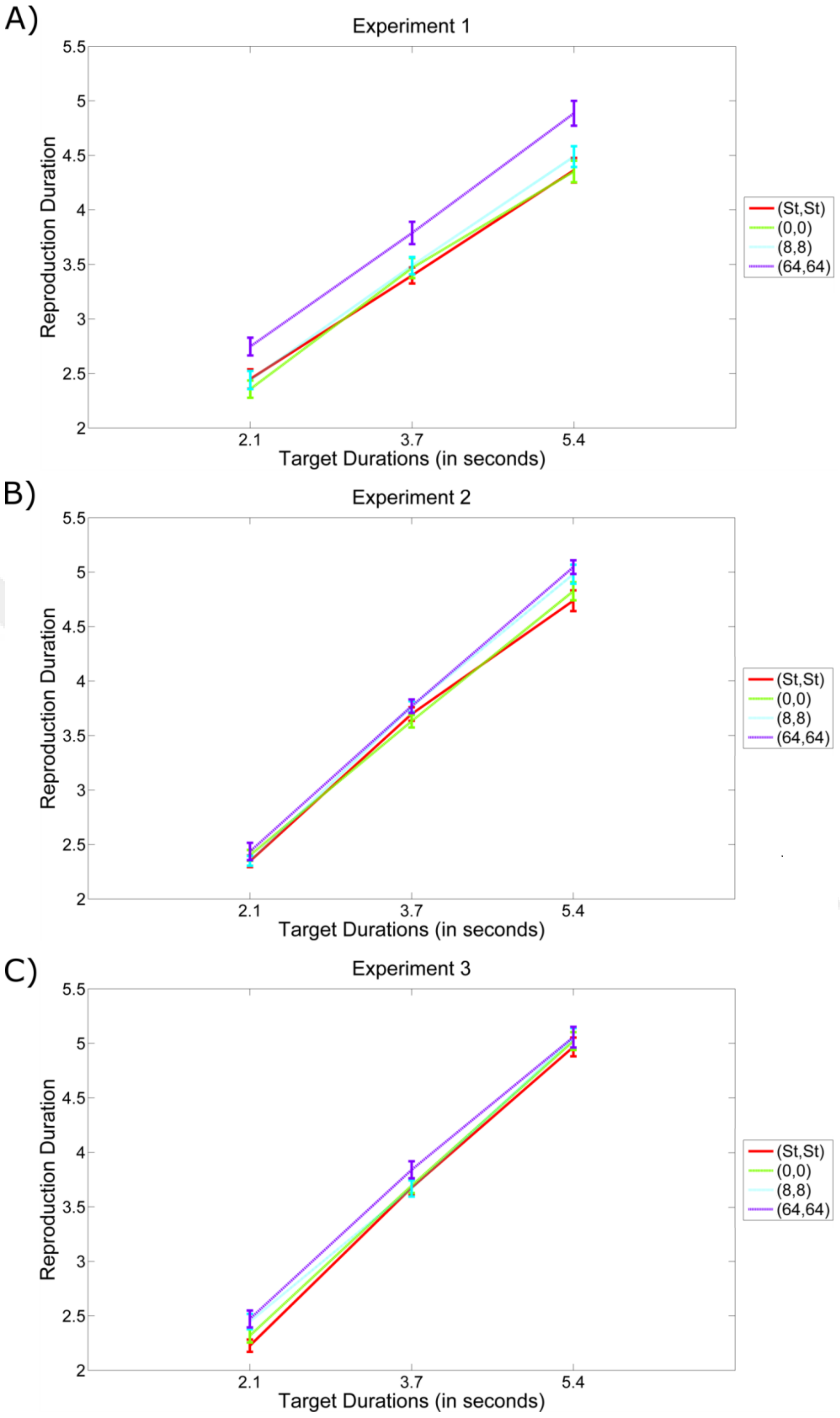
# SUPPLEMENTARY MATERIALS - Chapter I



Supplementary Figure 1. Reproduced duration as a function of same coherence pairs and target duration in (A) Experiment 1, and (B) Experiment 2, (C) Experiment 3. Error bars denote standard errors of the mean.[1]

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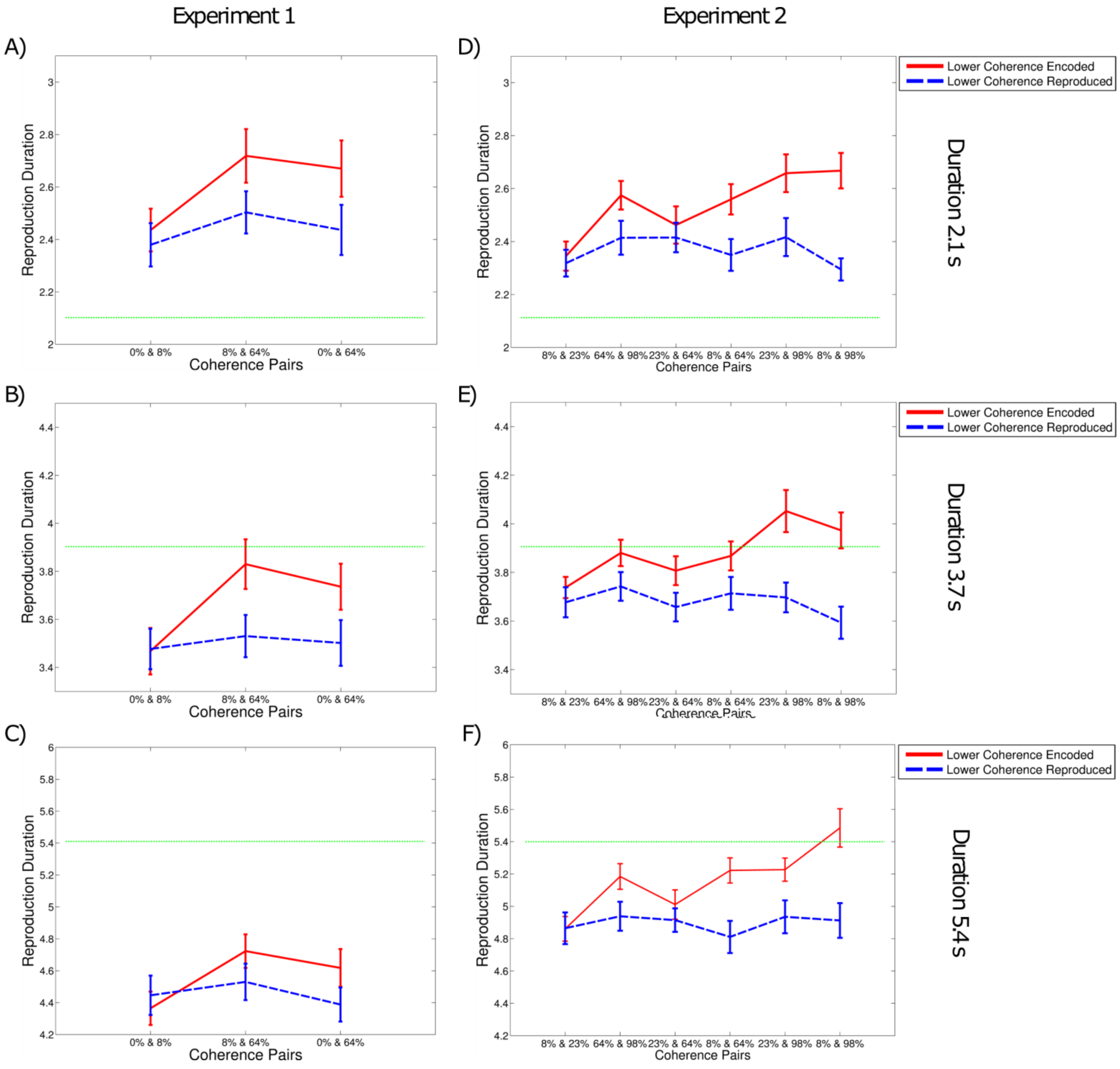
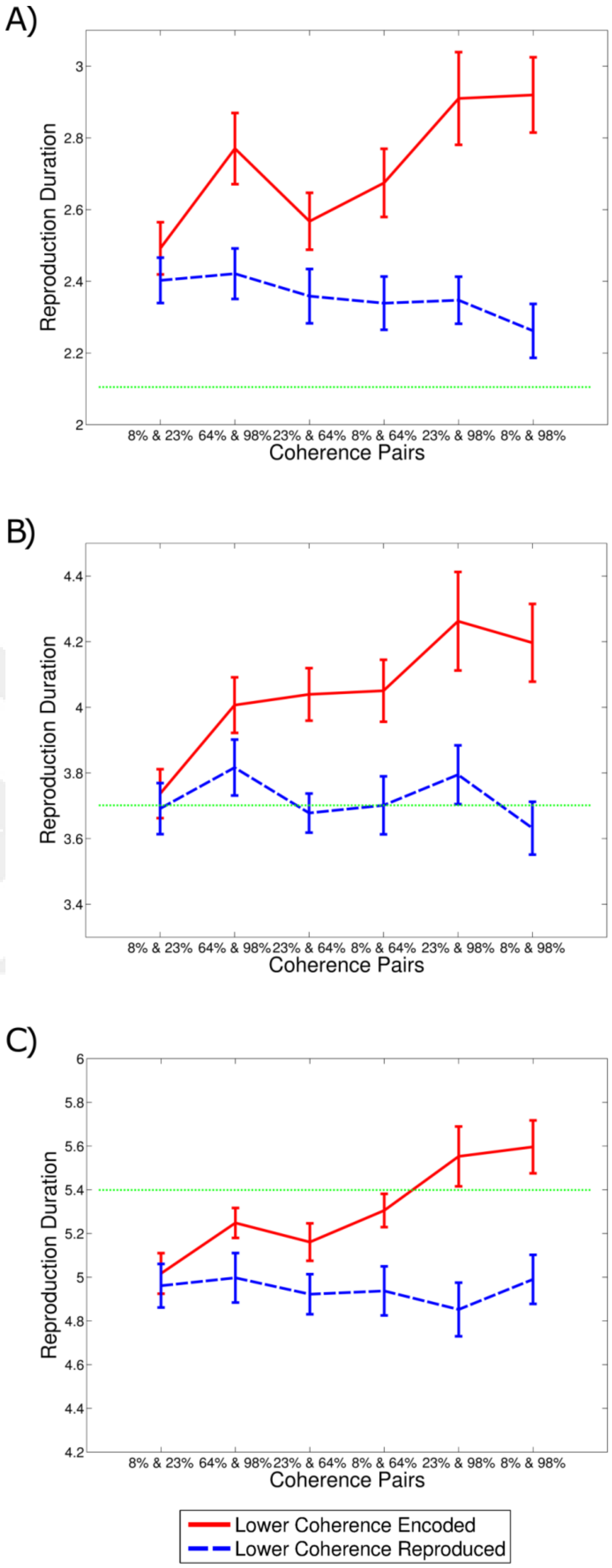
[1] Note: The parenthetical notation in the legends to refer to the coherence level of the encoded (i.e., first) and the reproduced (i.e., second) stimuli pairs within a trial.



Supplementary Figure 2. Reproduced durations as a function of coherence pair and the order of lower coherence in Experiment 1 (A-B-C) and Experiment 2 (D-E-F) in 2.1 second (A & D), 3.7 second (B & E), and 5.4 second (C & F) conditions. Coherence pairs are ordered in ascending order according to their difference. Dashed green horizontal line denotes hypothetical perfectly accurate performance. Error bars denote standard errors of the mean.



Supplementary Figure 3. Reproduced duration as a function of coherence pair and the order of lower coherence in Experiment 3. Coherence pairs are ordered in ascending order according to their difference. Dashed green horizontal line denotes hypothetical perfectly accurate performance. Error bars denote standard errors of the mean.