Number-Time Interaction: Search for a Generalized Magnitude System

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in
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CERTIFICATE

It is certified that the work contained in this thesis, titled **“Number-Time Interaction: Search for a Generalized Magnitude System”** by Anuj Kumar Shukla, has been carried out under my supervision and is not submitted elsewhere for a degree.

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Date

Prof. Bapi Raju Surampudi
(Advisor)

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Abstract

Space, time, and number are fundamental to human cognition. The mental representations on these entities are crucial for planning and decision-making. In our everyday lives, we are always thinking in terms of quantities — how long would we take to reach the workplace, what would be a shorter route to get to a specific store from where we are, how many cupcakes should we prepare for the people we have invited, how do we throw a stone that will dislodge a shuttlecock stuck in the tree, and so on. Even for simple tasks like grasping, reaching, or catching a ball, subtle calculations involving distance, speed, and time are essential. To successfully execute our actions, we need to synchronize these entities efficiently. For example, to grab an object kept on the table, one needs to integrate information from time, space, and number dimensions to evaluate the obstacles present in that environment and the distance between the object and our body. Further, spatiotemporal integration of information is needed for successful reaching and grasping. Over the last two decades, numerous studies have advanced our knowledge of how humans utilize perceptual information to estimate magnitudes such as space, time, and number. One of the most popular theories of magnitude processing, *A Theory of Magnitude* (ATOM), suggests that a generalized magnitude system in the brain processes information related to space, time, and numbers. Since these magnitudes are processed by a common magnitude system, they interact with one another. Earlier studies investigating the number-time interaction have provided support to ATOM's predictions. On the contrary, more recent studies have argued against ATOM and suggested that the cross-dimensional magnitude interactions may emerge from cognitive factors like attention and memory. Such contradicting findings raise a fundamental question as to whether a common magnitude system indeed exists, or such cross-dimensional magnitude interactions result from cognitive factors. This is still an unsettled question. In the present thesis, we examine the influence of numerical magnitude on temporal processing in a different experimental setup. More specifically, we investigated whether numerical magnitude affects our temporal experience or simply biases judgment of time. Further, we examined whether large numerical magnitude is always perceived to be longer in time (as predicted by ATOM) or attentional modulation can cause such cross-dimensional magnitude interactions. We also tested the generality of the ATOM framework in a cross-modal setting wherein numerical magnitude and temporal information were presented in two different modalities and evaluated ATOM's prediction in a cross-domain setting. The overall results from the five empirical investigations suggest that the processing of numbers and time may not require to invoke a common magnitude processing system. The cross-dimensional magnitude interactions (in this case, number and time) may emerge from the modulation of attentional mechanisms.

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Introduction and Overview of the Thesis

Being human, we are required to process information all the time. Specific sensory modalities are available to process different kinds of sensory input. For example, Eyes are designed to process visual information, and the ears to process auditory information. The visual and auditory information is explicit, and therefore it is easier for us to engage ourselves with explicit information. However, in the process of seeing the world coherently, significant amount of sensory information is processed implicitly. For example, to differentiate the order of the events, we need not only visual or auditory information but also temporal (in some cases, spatial) information to see the dynamically changing world in a coherent manner. The sense of time is crucial and fundamentally linked to our day-to-day activities. All our actions, and for that matter, life, are coded into time. Time wraps up our experiences and helps us store them in memory for long-term use. Although we have a sense of time like vision and audition, there are no dedicated sensory modalities to process the temporal information. One of the ideas is that our brain keeps track of such implicit information regularly. That is why we can recall how long a particular event lasts. For example, if I ask you how much time has elapsed since you started reading this report. While reading the report, you are not paying attention to time, but the moment I asked this question, your brain has diverted your attention to time. As humans, we are good at estimating time. However, have you ever asked how one keeps track of time without having a dedicated sensory modality that can process temporal information? Does subjective time resemble objective time?

1.0. TIME PERCEPTION

Time has been a fascinating concept for cognitive scientists for several decades. Psychologists primarily studied human behavior and mental processes (e.g., attention, perception, memory, etc.). Although these processes operate independently, time plays a crucial role in all the mental processes. Cognitive psychologists also study temporal phenomena in terms of the passage of time and call it *time perception*. The estimation of perceived time seems to differ from the clock time. Mach (1865) was the first person who suggested that clock time and perceived time are not the same (Debru, 2006).

In time perception research, the primary focus is on psychological time or perceived time and how it differs from physical time (actual clock time). Researchers have shown that human beings can estimate the passage of time internally across cultures, which suggests that the capacity to estimate time seems universal (Edlund, 1987; Eisler, 1993). In psychology, subjective time is defined in terms of how time is felt or how much time has been experienced to pass by. Therefore, the experience of the passage of time is not consistent across people. It can vary from individual to individual in different situations (Campbell & Bryant, 2007; Stetson et al., 2007). Although the clock time seems more objective, subjective time is more likely to be malleable and less accurate. The malleability of subjective time is highly influenced by mood, emotion, or situation (Angrilli et al., 1997; Droit-Volet & Meck, 2007). The malleability of time can be experienced in different kinds of temporal illusions, for example, when we look at a clock, the first tick of the second hand always feels to be longer than the subsequent ticks. This is because when a saccade is made to the second hand, for a very brief amount of time (milliseconds), the brain does not receive any sensory information. The blank duration is then overridden by the duration of the second hand's first tick, making it feel longer than the rest. This is referred to as 'chronostasis' or 'Stopped clock illusion' (Yarrow et al., 2001).

Experimental findings have suggested the overestimation of time for emotional stimuli compared to non-emotional or neutral stimuli (Meck, 1983; Stetson et al., 2007; Droit-Volet et al., 2004; Gil et al., 2007; Tipples, 2008). There has been extensive investigation to understand how different emotions (happy, sad, anger, etc.) affect our perception of time differently.

In some of the interesting experiments by Droit-Volet et al. (2004), Droit-Volet and Meck (2007), and Tipples (2008), researchers exploited the duration bisection task to understand the role of emotion in time judgment. In a temporal bisection task, initially, participants are familiarized with short and long anchor durations in a practice phase. Then in the test condition, participants are presented with the stimulus of intermediate durations. They are asked to judge whether that duration, short or long, is based on the learned anchor duration. These experiments suggest that participants overestimate the duration for emotionally charged faces (happy, sad, angry, and fearful) compared to neutral faces.

Similarly, Agnrilli et al. (1997) used the International Affective Picture System (IAPS) stimuli to investigate the role of valence and arousal on time perception. The results revealed no effect of arousal or valence, but a significant interaction was found between the two dimensions. In the high arousal condition, participants overestimated the duration of the negative pictures, whereas positive pictures were underestimated. However, in the low arousal condition, the opposite patterns were observed. Agnrille et al. (1997) suggested two possible mechanisms to explain their finding that are triggered by the arousal levels -- a controlled attention mechanism for low arousal and an automatic mechanism for high arousal.

Further, Gil and Droit-Volet (2011) reported consistent findings for emotionally charged stimuli across different paradigms such as bisection tasks, verbal estimation, and duration production tasks. Furthermore, the effect of emotion on time does not seem to be a modality-specific phenomenon. Researchers have shown the same effect in the auditory modality (Angrilli et al., 1997; Noulhiane et al., 2007; Mella et al., 2011).

Apart from the influence of the dominant modalities (visual and auditory), more recent studies have examined the influence on olfactory information on temporal processing. Studies by Gros et al. (2015), Millot et al. (2016), and Yue et al. (2016) utilize different odor’s to manipulate olfactory information and studied the impact on temporal processing. Gros et al. (2015) found that olfactory priming, regardless of the odor's valence, resulted in participants overestimating short sound durations in comparison to prior estimations without odor, indicating that odors have an arousing effect on the internal clock. Conversely, Schreuder et al. (2014) demonstrated that the rosemary odor led to overestimation of time while peppermint had no effect. However, the authors did not attribute this effect to arousal-based mechanisms, as physiological arousal measures remained unchanged. It has been suggested that these contradictory findings may be due to differences in the range of durations used, as prior studies have shown distinct mechanisms for short and long durations. Millot et al. (2016) found that an unpleasant odor led to participants underestimating short durations and overestimating long durations, while Yue et al. (2016) reported that exposure to the lavender odor led to longer time intervals in a time reproduction task, but only for short-time sound durations. In conclusion, the effects of odors on time perception are still relatively understudied and have produced mixed results in the few studies that have been conducted. While some studies have suggested that odors have an arousing effect on the internal clock, leading to overestimation of time durations, others have found distinct effects of different odors on time perception, with some resulting in underestimation and others in overestimation. The range of durations used in studies may play a role in these discrepancies, with short and long durations possibly being influenced by different mechanisms. Further research is needed to better understand the effects of odors on time perception and to investigate the potential underlying mechanisms. Previous studies investigating the influence of body temperature on temporal perception have indicated that when body temperature increases, individuals tend to perceive time as longer than it actually is, leading to overestimation of time duration. Conversely, decreasing body temperature tends to cause a compressed perception of time, leading to underestimation of time duration. However, the latter effect is less frequently observed. Research has shown that body temperature has a parametric effect on time perception, with higher temperatures generally leading to a faster subjective experience of time and lower temperatures resulting in a slower perception of time. This effect is particularly noticeable under conditions of increased arousal or during stressful events (Wearden & Penton-Voak, 1995).

The role of attention has been a fundamental issue in timing research. Studies investigating the relationship between attention and time perception show that paying more/ less attention to the stimulus duration may increase/ decrease the perceived duration, respectively (Tse et al., 2004). It has been argued that the accuracy of temporal perception relies on the ability to attend and process temporal information. Further, Stelmach, Herdman, & McNeil (1994) findings reveal that the attended stimuli are perceived to be shorter than that of the unattended ones, presenting the opposite results to attenuation theory. In a similar study done by Mattes & Ulrich (1998), a stimulus was presented on either left or right side on display. One of the locations was cued to manipulate attention. In contrast to the results of Stelmach, Herdman & McNeil (1994), their finding suggested that attended stimuli were perceived longer as compared with unattended stimuli.

Further, comparable results were observed when a similar task was performed in the auditory modality. The overall finding supports the attenuation hypothesis. Since the limited attentional resources are allocated to processing the stimulus present in the environment, the findings of these studies suggest that the temporal judgment performance would depend on the stimulus location. If stimuli are already cued to a location, one would perceive time to be shorter than that with a non-cued location.

Differences in subjective and objective times also depend on age, personality, and other cognitive activity (Grondin, 2010). Researchers have shown that time seems to pass slowly during childhood and whereas, during aging, time seems to fly (Wittmann & Lehnhoff, 2005). However, subjective time appears to be more than just a perception. It is an integral part of our self-awareness and helps us perform different cognitive processes, such as decision-making.

1.1. THEORETICAL MODELS OF TIME

There are various mental models of time perception, of which two important ones are discussed below. i) Internal clock model of time perception and ii) Scalar expectancy model (SET) of time perception.

It is known that subjective time is contingent upon cognitive and physiological processes, which are, in turn, well-adjusted to the passage of time. Fancois (1927) and Hoagland (1933) suggested a relation between subjective time and physiological variables such as body temperature. Based on this finding, researchers posit the presence of an internal mechanism like an internal clock to control temporal processing.

Based on the idea of the internal clock, Triesman (1963) proposed a cognitive model for time perception. According to Triesman, the internal clock acts like a “pacemaker”. It sends pulses to an “accumulator,” which collects these pulses. Apart from the pacemaker and the accumulator, there is a reference memory and a comparator. Reference memory stores the experience (target) time as a reference, and the comparator compares the reference time with the accumulated pulses.

Gibbon et al. (1984) extended Tresman's idea of the internal clock and presented experimental findings to support the theoretical idea. Gibbon called the new model scalar expectancy theory (SET). This theory was proposed in the framework of an information-processing model.

According to SET theory, perception of time follows Weber's law like other perceptual dimensions such as brightness, loudness, etc. This suggests that the ability to discriminate between two stimuli is directly proportional to the intensity of the stimulus. The SET model, proposed by Gibbon and colleagues, comprises an internal clock that contains a pacemaker-accumulator. The pacemaker generates ticks (similar to pulses) controlled by a switch attached to the accumulator that collects those ticks. The time duration of two stimuli, S1 and S2, can be compared for equality in length based on the number of accumulated ticks.

The onset of S1 causes the switch to allow the pulses to flow. The offset of the stimulus causes the switch to cut the connection. Once the accumulation of pulses by the accumulator stops, the duration is retained by memory in either the short-term memory store or the long-term memory store. Due to this phenomenon, the duration of the first stimulus can be stored even after the second one has been presented. Thus, S1 and S2 can be efficiently compared by us. Once a decision is made, an appropriate behavioral response is generated.

The aforementioned theories have provided insight into how we perceive temporal information even without a specific sensory modality to process time. These theories have laid the groundwork for further investigations and have demonstrated that various internal factors such as mood, emotion, attention, and body temperature, as well as external factors such as color, brightness, and motion, can impact our ability to process time. It has been suggested that these factors can affect time perception by two mechanisms a) by affecting the clock speed (internal-clock model) and b) by affecting the latency of the gate (attentional gate model).

In the context of the internal-clock model, the basic idea is that if the internal clock runs faster, then an individual would perceive time passing more quickly, while a slower internal clock would result in the perception of time passing more slowly. This is because the brain would process more or fewer pulses within a given time period, which would affect the subjective experience of the passage of time.

In the context of the attention gate model, the latency of the gate refers to the time delay between the onset of a stimulus and the opening of the attention gate. The latency of the gate can affect time perception in several ways. If the latency of the gate is short, then the attentional gate opens quickly, allowing sensory information to pass through more quickly and resulting in the perception of time passing more quickly. On the other hand, if the latency of the gate is long, then the attentional gate opens more slowly, which can make time appear to pass more slowly.

1.2. CONTRIBUTION AND THE OVERVIEW OF THE THESIS

Apart from the aforementioned stimulus features, researchers have reported that the temporal processing of stimuli is also affected by non-temporal stimulus properties such as stimulus magnitude (number and size). For example, the duration of a visual stimulus that is more bright, more numerous, or larger in size is perceived to last longer when participants were asked to select the stimulus that lasted longer in time. These influences of non-temporal magnitude information on temporal processing have been explained by "*A Theory of Magnitude*" (Walsh, 2003). According to the theoretical framework, A Theory of Magnitude (ATOM), the information related to space, time, and number is processed through a common metric system. Therefore, our judgment of one magnitude dimension may be biased by the presence of the other magnitude dimension. At first ATOM-like framework looked plausible and gained support from many studies. However, more recent studies have failed to support the common magnitude system and argued that such magnitude interactions might emerge from cognitive factors like attention and memory. Therefore, an open question is whether the interactive influence of space, time, and number, one upon the other, emerges from them being processed through a common magnitude system or the interactive influence emerges from cognitive factors.

In the present thesis, we have tested the ATOM predictions in different experimental conditions and studied the influence of numbers on temporal processing. Our behavioral investigations suggest that a generalized magnitude system may not be needed, and the ATOM-like effect can be explained via attentional mechanisms.

The thesis has been organized as follows. In Chapter-2, we present an overview of the theory of magnitude and a review of the literature related to number and time. In Chapter-3, we present an empirical investigation wherein we studied the influence of task-irrelevant numerical magnitude on temporal processing. We showed that numerical magnitude biases the temporal judgment but does not change the temporal experience *per se*. In Chapter-4, we examine whether the influence of numerical magnitude on temporal processing emerges from the “number magnitude” or results from the attentional mechanism induced by the number.

In Chapter-5, we studied the number-time interaction in a cross-modal setup. We presented the numerical magnitude information in the visual domain and the temporal information in the auditory either simultaneously with duration judgment task (Experiment-1), before duration judgment task (Experiment-2), and before duration judgment task but with numerical magnitude also being task-relevant (Experiment-3). This chapter specifically tested whether the common magnitude system has a central representation or is limited to only a unimodal system. In Chapter-6, we have further tested the influence of numerical context on temporal judgments and have shown that numerical magnitude affects temporal judgements only when they are present in the same (intermixed) block but not when presented separately (blocked). In Chapter-7, we have shown the relative influence of two task-irrelevant magnitudes (Size and Number) on temporal processing and provide further support to the results obtained in Chapter-5. Results especially provide possible hint towards active processing of task-irrelevant magnitude dimension in cross-dimensional magnitude interactions. Finally, Chapter-8 gives an overall summary, limitations and future directions.

Chapter-2

BACKGROUND AND RELATED WORK

2.0. INTRODUCTION

Space, time and number are fundamental to human cognition. The mental representations of these entities are crucial in planning and decision-making. In our everyday lives we are always thinking in terms of quantities — how much longer would we take to reach the workplace, what would be a shorter route to get to a specific store from where we are, how many cupcakes should we prepare for the people we have invited, how do we throw a stone that will dislodge a shuttlecock stuck in the tree, and so on. Even for simple tasks like grasping, reaching, or catching a ball, subtle calculations involving distance, speed, and time are essential. In order to successfully execute our actions, we need to have an efficient synchronization of these entities. For example, to grab an object kept on the table, one needs to integrate information from time, space, and number dimensions to evaluate the obstacles present in that environment, and also the distance between the object and our body. Further, for successful reaching and grasping, spatiotemporal integration of information is needed. Very few research studies have been undertaken in this domain to understand if there exists any shared magnitude system. Previous research focused mainly on whether there is neurocognitive magnitude overlap for time, space, and number dimensions or if each dimension is processed by a separate mechanism that involves dimension-specific processes (Fabbri et al., 2012; Hayashi et al., 2013; Vicario et al., 2013). Gallistel (2011) calls these dimensions "mental magnitudes". According to Gallistel, the mental magnitude can be both continuous and discrete quantity experienced by an animal and represented in the mind/brain. For example, the representation of space takes place when an animal constructs a mental representation of the different locations and objects encountered in its environment in order to find its way back. Interestingly, it has been established that the animal not only forms a mental map but can easily estimate the number and also remember how long it has been since they had food by representing temporal information. Like other animals, humans also estimate the magnitude of various dimensions, such as the number of people in a crowded street, the height of a building, the duration of an event and so on. Humans have shown extraordinary capabilities regarding the processing of these mental magnitudes. When it comes to the processing of these mental magnitudes, Gallistel (2011) suggested that these magnitude dimensions are linked with arithmetic processing. Therefore, the discriminability threshold of two magnitudes called the *just-noticeable difference* (JND) follows a mathematical relationship that corresponds to *Weber's law.* According to Weber's law, the minimum amount required to notice a change in stimulus level is proportional to the change in the original stimulus level. For example, it is easy to discriminate between masses of 1 kg and 2 kg. On the other hand, it is really hard to subjectively experience the difference between 100 kg and 102 kg. One of the possible reasons for the latter case is that the magnitudes are represented along a logarithmic scale. Consequently, the sensitivity to notice a difference between two subsequent magnitudes is higher when the distance between the two magnitudes is small whereas smaller sensitivity is required when the distance between the two magnitudes is larger (Cantlon et al., 2009). Alternatively, it could be the case that the noise in the magnitude representation increases due to inherent scalar variability of magnitudes that may result in errors of judgment. The higher the magnitude, the more likely an error (Petzschner, Glasauer, & Stephan, 2015).

2.1. THEORETICAL MODELS OF TIME AND NUMBER

In this section, two models are discussed -- the accumulator model for temporal discrimination and a theory of magnitude (ATOM) that posits a common magnitude for space, time and number magnitudes.

2.1.1 THE ACCUMULATOR MODEL

The accumulator model was the first proposal that points to a possible overlap of functional mechanisms for the representation of temporal and numerical information (Meck and Church, 1983). In a series of experiments, rats were trained to discriminate the number and duration of sounds. Rats were introduced to two different sets of stimuli that differed in terms of duration and number of sounds. The first set of stimuli had 2 sounds that lasted for 2 seconds, whereas the second set had 8 sounds that lasted for 8 seconds. During the learning phase, rats learned to respond to the sets by pressing a left, or a right lever respectively and reward was given for correct trials. Subsequently, in addition to the trained sound, a set of new sounds (different from training) were introduced during the experimental phase, while the reward criterion remained the same. Unlike the trained sounds where both the dimensions (number and time) were changing, in the new sound, one of the dimensions was constant and the other was varied. For example, in the *duration-discrimination trial*, the duration of the sound varied from 2-8 seconds while the number of the sounds was always 4. Similarly, in the *number-discrimination trial*, the number of sounds was varied from 2 to 8 while the duration was kept at 4 seconds. Interestingly, rats generalized the learned association and performed the discrimination based either on the total duration or on the number of sounds.

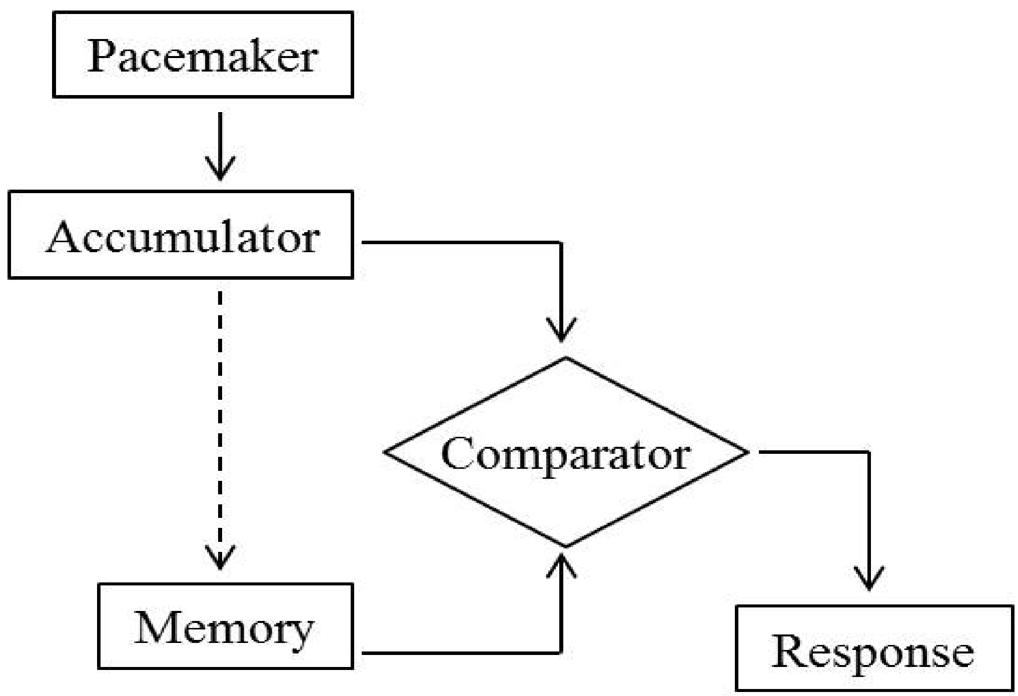

Figure-2.1: Schematic representation of accumulator model (adopted from Meck & Church, 1983): The accumulator model suggests three distinct stages: accumulation, maintenance in working memory, and decision making. The processing of number and time in an animal may rely on the different stages mentioned in the accumulator model and give rise to a common mechanism that provides the basis for common magnitude processing.

2.1.2 A THEORY OF MAGNITUDE (ATOM)

In 2003, a British psychologist proposed a theoretical framework that accounts for all sorts of magnitude processing experiments (independent of their domain) through a common magnitude system in the brain. This proposal is called “A Theory of Magnitude” (ATOM). According to ATOM theory, a generalized magnitude system processes stimuli related to space, time, and quantities and converts them to a common magnitude. Since a generalized magnitude system processes magnitudes of various kinds, it is assumed to share common processing resources, potentially leading to cross-domain magnitude interaction. Thus, magnitude from one domain could bias the processing of the magnitude in another domain. Growing pieces of evidence from neuroimaging literature point out that the intraparietal sulcus (IPS) in the brain might be the substrate for a shared representation of space, time, and number as proposed in the ATOM theory (Hayashi et al., 2013a). ATOM argues that this shared neural substrate confers benefits because it supports the coordination of magnitudes that are relevant for action. For example, when human and non-human animals want to grasp an object kept on a table, magnitude is crucial to perceive the size of the object, the distance of the object from the organism and time required to reach the object so that the palm could be placed appropriately to grasp the object. The grasping task can follow two schemas (see figure 2.2) to process space, time, and number-related information. In the first one, Space, time and number magnitude information can be independently analyzed, processed, and compared, according to their respective metrics (Figure 2.2 a) to generate a motor output. On the other hand, the second possibility considers a common metric system where various kinds of magnitudes are processed similarly and then generates an output (Figure-2.2 b).

The ATOM predicts that estimation of one magnitude dimension would be affected by the mere presence of the task-irrelevant magnitude from another dimension. It is proposed that there may be a monotonic relationship between task-irrelevant and task-relevant magnitude processing such that the larger the task-irrelevant magnitude, the larger one should perceive task-relevant magnitude dimensions. In other words, ATOM theory suggests that increasing (decreasing) the magnitude of one dimension (task-irrelevant) should increase (decrease) the perceived magnitude of another dimension (task-relevant).

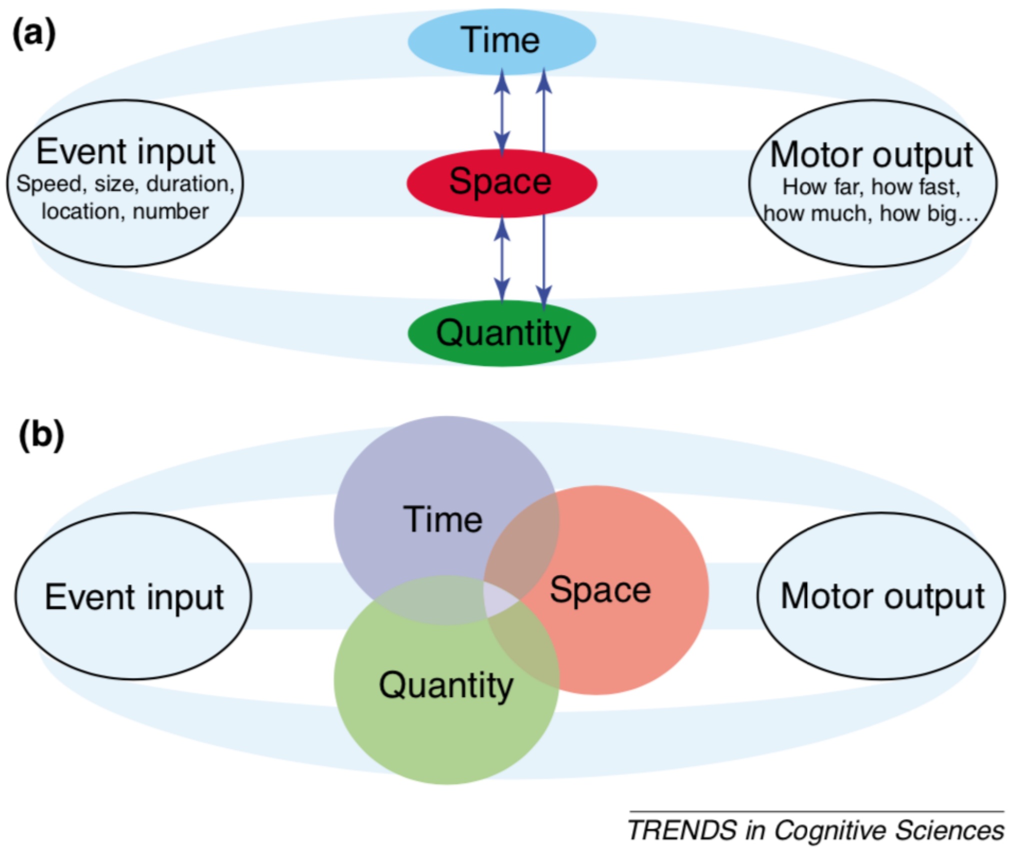

Figure-2.2: A Theory of Magnitude: (a) The processing of temporal, spatial and numerical information is independent. (b) A generalized magnitude system in which space, time and quantities are processed through a generalized magnitude system which translates various kinds of magnitude into a common currency and therefore generates behavioural output accordingly. (Figure reproduced from Walsh, 2003)

2.2. GENERALIZED MAGNITUDE SYSTEM

Since the theoretical model of ATOM is of importance for understanding number-time (and space) interaction, empirical support for and against such a proposal of generalized magnitude system is presented in the next two sections.

2.2.1. EMPIRICAL EVIDENCE FOR A GENERALIZED MAGNITUDE SYSTEM

Studies from developmental psychology suggest that interaction across magnitude domains may exist at every developmental age, including the prelinguistic stage. For example, Stavy & Tirosh (2000) have shown that children's judgement of magnitude is affected by the magnitude of the irrelevant dimension. In this study, children were shown two trains running on a parallel track. They were provided with essential information about the trains running at the same speed. However, it was noticed that the size of the train influenced participants' judgement about the speed of the train. Children reported the longer train to be faster compared to the shorter train. This suggests that the judgement of one magnitude domain (speed) can be affected by the presence of information in the other magnitude domain (size). Similar results were observed when children were asked to judge the duration of luminous flashes of varying intensity. Children reported that brighter flashes lasted longer (Levin, 1982, 1979). In a more recent study by Lourenco and Longo (2010), the authors suggested similar cross-talk across magnitude dimensions among 9-month old infants and interpreted their findings based on a generalized magnitude system. This finding points to the existence of a generalized magnitude system even at a prelinguistic stage.

In order to verify ATOM's prediction (i.e., space, time and numbers are processed through a common metric system) in adults, researchers have used various approaches to study the interaction among these magnitudes. The logic behind why such interaction is plausible is that if space, time and number are processed by a common neural code then domain-specific magnitude processing outcomes should interfere with one another, and we should be able to observe a bi-directional interaction across different magnitude dimensions. In the past, researchers had extensively studied the interaction effect for different cognitive processes. One of the most popular ones is Stroop-effect, where participants were presented colour words painted either with a congruent or incongruent colour. Participants are asked whether the presented combination was correct or incorrect. Participants indicated their response by pressing an appropriate key on the keyboard. Interestingly, low latency was observed when the colour and the written word were arranged congruently compared to the incongruent presentation. The Stroop phenomenon demonstrates that it is difficult to name the ink colour of a colour word if there is a mismatch between ink colour and the word. For example, the word GREEN printed in red ink would present incongruence making it difficult to name the ink colour (See Fig-2.3).

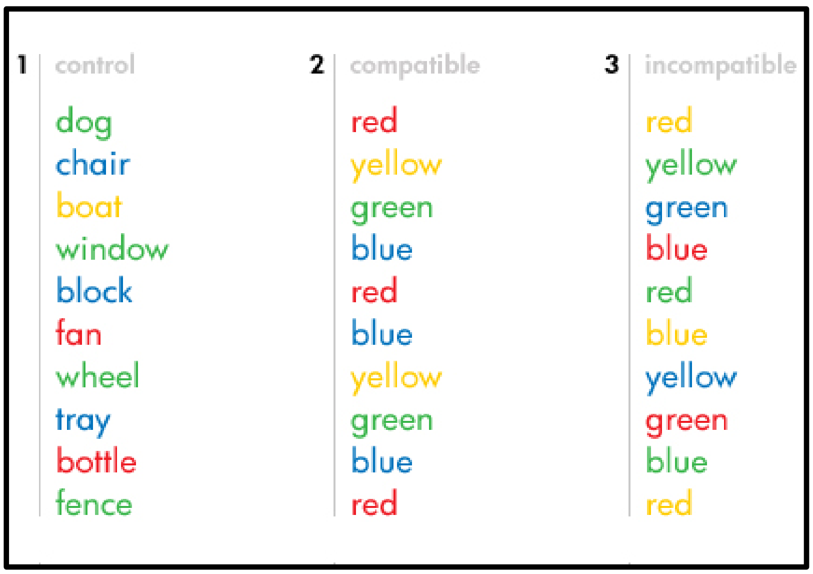

Figure-2.3: Sample of Control, Congruent and Incongruent stimuli in Stroop Task [Taken from: http://www.whatispsychology.biz/wp-content/uploads/2012/02/stroop-effect.jpg]

Similarly, one known effect in the literature is the size-congruency effect. In which participants' response latency was affected when judging magnitude of numbers when the physical size of the digit stimulus was varied. For example, task performance (speed and accuracy) was observed to be better when the size of the digit was congruent with its magnitude value (e.g. small "1" or LARGE "9"). In contrast, if the size of the digit stimulus was incongruent with its magnitude value (e.g. LARGE "1" or small "9"). To understand the interface between space, time and number, Xuan et al. (2007) also used a congruent versus incongruent paradigm. All the participants were presented with various non-temporal magnitudes (numerosity, size, brightness, and number) along with temporal information and asked to judge the duration of the non-temporal magnitudes.

Results showed that temporal judgments were influenced by the manipulation of the physical size of the non-temporal stimuli.

Further, Oliveri et al. (2008) have observed similar results with *number and time*. Participants were presented with a target number (“1”, “5” and “9”) with varied durations against a fixed reference number (“5”) associated with a fixed reference duration. They were required to make a forced judgement as to whether the target number lasted longer or shorter compared to the reference. Participants overestimated the duration of a large number and underestimated the duration of a small number. The findings reiterate the idea of cross-domain monotonic mapping. Furthermore, to investigate whether number influences duration judgement at the perceptual level, Chang et al. (2011) used a temporal reproduction task to reduce the involvement of categorical decisions. The findings suggest that participants estimated large magnitudes to last longer, resulting in production of longer durations. The authors interpreted the modulation in the perceived duration to be due to the influence of a common numerical magnitude representation, in line with ATOM. They further posited a common neural mechanism for space, time, and number in the brain. Apart from the behavioural studies, many neuroimaging studies have also substantiated predictions of the ATOM and proposed that the intraparietal sulcus (IPS) might be the substrate for common representation of space, time, number and quantities (Kaufmann et al., 2008; Bueti & Walsh, 2009; Hayashi et al., 2013a; Skagerlund et al., 2016).

There have been many studies that reported how number biases temporal processing in line with the ATOM hypothesis (Cantlon et al., 2009; Cappelletti et al., 2009; 2011; Dehaene & Brannon, 2010; Walsh, 2003). However, it is important to note that the ATOM hypothesis was verified primarily based on the *sub-second timescale* where the processing may rely on sensory-motor mechanisms unlike the *supra-second timescale* that might involve high level perceptual and neural mechanisms (Allman et al., 2014; Gilaie-Dotan et al., 2011; Lewis & Miall, 2003; Mauk & Buonomano, 2004). Yet, there are a handful of studies that investigated the influence of task-irrelevant magnitude on temporal processing in the supra-second timescale as well.

Lu, Hodges, Zhang, and Zhang (2009) studied the influence of number magnitude on duration reproduction tasks. In this study, the participants were given numbers (1-9) in the supra-second durations. The findings suggest that the large number is overestimated compared to a small number. Also, the digit effects were enhanced by adding the suffix “kilograms” and reduced by adding “grams”. The results point towards a pronounced contextual-dependency for the influence of numeric magnitude. Further, Vicario (2011) presented small and large numbers in a separate as well as in a mixed block design. Both the blocks were presented for the sub- and supra-second durations. Participants were asked to reproduce the durations from sub- and supra-second scales presented along with numbers of different magnitude. The results suggest that the magnitude of the number biases temporal performance in supra-second only when small and large numbers were presented together in one block (intermixed block) but not when they were presented in a separate block. In this study, they fail to replicate the classic number-time interaction in the sub-second time scale. Similarly, Hayashi et al. (2013b) used a temporal reproduction task with a supra-second time range. Participants have presented numerosity (small and large) along with supra-second durations and they were asked to reproduce the standard durations. The finding suggests that numerical information influences time estimation in supra-second time range only in females, but not in the male. In addition, Gilaie-Dotan et al., (2014) studied number-time interaction in Dyscalculics and control population. They were given a supra-second temporal estimation task along with a non-temporal control task and the performance was correlated with the mathematical abilities of the participants. The results suggest an impairment in the supra-second temporal task for dyscalculic participants. However, temporal processing ability was positively correlated with mathematical proficiency. Therefore, the impairment in the temporal task was attributed due to the problem in the estimation of number rather than a problem in a general magnitude mechanism. In a more recent study, Yamamoto et al. (2016) presented single- and double-digit numerals in different experimental blocks. Participants were asked to reproduce the stimulus duration of 600 or 1200 ms while small and large numbers are presented on the screen. The findings of the study suggest the effect observed in 600ms for both single- and double-digit numerals was high compared to 1200ms. In 1200 ms, the effect was more pronounced for the double-digit numerals compared with single-digit. The finding suggests that the relative magnitude is a crucial factor in time-number interaction in the supra-second timescale. On the other hand, Rammsayer & Verner (2016) investigated the combined effect of stimulus size and numerical magnitude on temporal estimation. In this study the reproduction durations of 800, 1000 and 1200 ms were used, and participants were asked to pay attention to the magnitude explicitly. Therefore, they used an attentional account to explain their results. Similarly, Rammsayer & Verner (2014) also used a dual-task paradigm to investigate the effect of magnitude processing on temporal estimation and observed overestimation for large size and underestimation for small size magnitude.

To summarize, the relationship between space, time, and number, particularly focusing on how numerical magnitude influences time perception is explained by A Theory of Magnitude (ATOM). According to the ATOM, there is a common neural mechanism for processing space, time, and number in the brain, and several studies have found evidence supporting this idea, particularly in the sub-second timescale. However, the influence of task-irrelevant numerical magnitude on temporal processing in the supra-second timescale is less well understood. Studies have found that large numbers are overestimated compared to small numbers in supra-second duration reproduction tasks, and that this effect is context-dependent. The relative magnitude of the numbers presented also plays a crucial role in time-number interaction in the supra-second timescale. Dyscalculic individuals perform worse in supra-second temporal estimation tasks, but their performance is correlated with mathematical proficiency, suggesting that the impairment in temporal task is due to problems in the estimation of number rather than a problem in a general magnitude mechanism.

2.2.2. EMPIRICAL EVIDENCE AGAINST A GENERALIZED MAGNITUDE SYSTEM

ATOM suggests that space, time, and number are processed through a common magnitude system. Therefore, it is conceivable that the processing of information of one magnitude would be influenced by the presence of information in another magnitude dimension. Thus, if ATOM's hypothesis is correct then there should be a symmetric influence of the magnitude processing on each other. In other words, if space, time and numbers are processed through a common code then they should influence each other symmetrically. For example, the way numbers affect the processing of time (Large

Number = Long Duration), time (temporal durations) should also affect number processing (Long Duration = Large Number). Researchers have tested ATOM's prediction both ways and the results are still inconclusive. Most of the findings suggest, in fact, an *asymmetric interaction* across magnitude dimensions.

Dormal & Pesenti (2007), using a Stroop task, studied the nature of interaction across length (size) and numerosity. Participants were given a judgement task. They were required to compare the length or the numerosity of the dot arrays. Their findings suggest for the numerosity judgements, the response time was observed faster when the length and numerosity were presented in a congruent manner than that of incongruent one. On the other hand, the numerosity did not affect the performance on the length (spatial) task. In order to test the bidirectionality of interactions across dimensions, Casasanto and Boroditsky (2008) conducted a series of experiments wherein participants had to perform spatial and temporal reproduction tasks. The authors claimed that the reproduction task would allow them to quantify the size of the interaction (e.g., when reproduced duration is compared to the objective duration) and would help them to test the asymmetry in a robust manner. Participants were presented with either lines or dots on the computer screen and were required to reproduce the duration or spatial displacement. They observed overestimation of the duration when the line was long and underestimation for the short line presented on the computer screen. However, no effect of duration was observed on the spatial reproduction task. Further, Bottini & Casasanto (2010) observed that duration judgements were influenced by the presentation of varied word length. Specifically, they found that the estimation of the duration increases as a function of the spatial length of the word. For example, the word "train" was perceived to last longer on the screen compared to the word "pen". However, spatial judgement was not affected by the duration (how long the word was presented). This indicates a lack of bi-directionality in magnitude interactions. Similar asymmetries have also been observed for time and number interaction. In an investigation of time and number, Dormal, Seron & Pesenti (2006) observed that number magnitude information affected temporal processing but not the other way around. In this study, a Stroop task paradigm was used to present congruent and incongruent conditions incorporating numerical and duration information. In the duration judgement task, participants were faster when the number and duration information was presented in a congruent order compared to incongruent condition. Similar to previous studies, no effect of duration was observed for the numerosity judgement task. Droit-Volet et al. (2003) also studied the number and time magnitude interaction by using a temporal bisection task across three different age groups (5-years, 8-years and adults). In the temporal bisection task, participants are given training on two anchor durations: a small and long durations. Once the participants learned the anchor durations, they were presented with intermediate durations along with the anchor duration with number magnitude information and participants were required to judge whether the presented duration was closer to short or long anchor durations. Similar to other studies, their findings also suggest that increase in numerical information increases the “long” responses in the duration task. However, they did not observe interference of duration information on the processing of number in a numerical bisection task. Interestingly, the interference effect of number on time was found stronger in 5-year-old children compared to 8-year-old children and adults. This points out that interaction asymmetries appear early in development. This may be because at an early age, children are still developing their cognitive abilities, including their ability to process different types of information simultaneously. As a result, they may be more susceptible to interference between magnitudes, such as numbers and time, when they are presented together. Additionally, the fact that the effect is stronger in younger children may also indicate that there is a developmental trajectory for the emergence and refinement of these interactions during development. Further, this finding can be linked to the development of cognitive factors such as executive function and attentional control. It is known that children’s executive functions, such as inhibitory control and working memory, continue to develop throughout childhood. Inhibitory control is particularly relevant to the interference task, as it requires an ability to inhibit automatic responses and focus on relevant information in this case, time. Younger children may have weaker inhibitory control, making it more difficult for them to ignore the irrelevant magnitude dimension (number, size) and focus on the relevant magnitude dimension (time) in the task. As children develop better inhibitory control and attentional control during developmental period, they may become better able to suppress the interference from the magnitude dimension, resulting in weaker interference effects in such task.

In summary, although there is a symmetric interaction among the magnitudes from various domains, the extant literature suggests an asymmetry, with the temporal information (duration) being the most affected dimension. In order to explain such asymmetries, it has been argued that magnitude information of the non-temporal stimuli is processed automatically and therefore interferes with the less automatic temporal magnitude processing. In a recent study by Bonn & Cantlon (2012) proposed that "asymmetries in interference would arise from different amounts of weight given to each dimension in estimating a particular stimulus' value".

There could be two possibilities when one magnitude dimension is processed more automatically over another. (a) The task difficulty across the stimulus domains may not be balanced. For example, if the number-task is too easy/evident than the duration task, then most likely, the number of information would bias duration judgements. Such task difficulty asymmetries might lead to an asymmetric interference effect across magnitude dimensions, by weighing one kind of magnitude information more than the other. (b) The second possibility is that these asymmetries arise due to an unequal allocation of computational resources while processing the two different kinds of magnitude information, e.g., number and time. However, this is still an open question for an investigation of how the resource allocation takes place when two different kinds of magnitude dimensions are presented together.

2.3. RESEARCH GAPS

From the literature review, it is quite evident that interaction between number and time has been studied extensively with various experimental paradigms to test ATOM's predictions. However, the evidence in support of ATOM theory is mixed (equivocal). When we look at *Number-Time Interaction* versus *Time-Number Interaction*, both yield different results. This suggests that ATOM's predictions seem to operate only in a specific direction and cannot be generalized for bi-directional magnitude interaction. Apart from these, there are many questions that need to be answered before accepting ATOM as a generalized magnitude processing module in the brain. The following gaps are identified for future investigation.

1) It has been established that the mere presence of numerical information interferes with temporal processing. However, it is still an open question whether such interactions are the result of simple bias (large = longer) or in fact that numerical magnitude changes our *subjective temporal experience* itself.

2) A large body of literature has shown that numerical magnitude affects temporal processing. This suggests that the task-irrelevant magnitude dimension is important to bias the temporal processing. Many other studies argued that such bias can come from cognitive factors like attention. Therefore, an important question emerges here as to what is crucial in number-time interaction: a "magnitude" or cognitive factors.

3) Previous studies have verified magnitude interaction while presenting numerical and temporal information in one modality. However, further investigation needs to be done in a *cross-modal setting* where numerical information needs to be presented in one modality and the temporal information in another modality. Such an investigation would allow us to shed some light on whether magnitude interactions generalize across multiple modalities.

4) The ATOM's hypothesis suggests that magnitude information from all the domains is converted into a common currency and therefore one expects to see the influence of information from one domain on the other. The fundamental assumption of such a common magnitude processing system is that the task-irrelevant dimensions sneak in while processing the task-relevant magnitude dimension. Such implicit influence on one magnitude on the processing of another magnitude has given strength to ATOM-like framework. However, such assumptions raised a fundamental question as to whether in fact, task-irrelevant magnitude dimensions are processed or not. If the task-irrelevant magnitude dimensions are processed and that affects the processing of the task-relevant magnitude dimension, then it may reflect the issues related to attentional resource mechanism. But if the task-irrelevant magnitude dimensions are not processed at all and yet influence the processing of the task-relevant magnitude dimension, it indicates the existence of a common magnitude processing system. So far, studies investigating cross-dimensional magnitude interactions have used only one task-irrelevant magnitude dimension and one task-relevant magnitude. Thus, it is difficult to ascertain whether the task-irrelevant magnitude dimension was processed or not. Therefore, this needs to be tested whether the task-irrelevant numerical magnitudes are processed at all.

5) If there is a common magnitude system which processes different kinds of magnitude, independent of their physical dimension, then one should test this while presenting different magnitudes (small and large) in separate blocks and in an intermixed manner to tease out the monotonic property proposed by ATOM, i.e., “Large = Longer” independent of the presentation of the numerical magnitudes.

Chapter-3

Does Numerical Magnitude Change the Temporal Experience?[1]

3.0 INTRODUCTION

In earlier studies, time, space, number, and other magnitude-related processes in the mind/brain have been studied extensively and independently. Based on the findings from the studies in these magnitude domains, a popular theoretical framework was proposed by Walsh (2003). This framework is called “A Theory of Magnitude (ATOM)”. ATOM proposes a generalized magnitude system for all kinds of magnitude-related processing in the brain. Specifically, ATOM states that a shared common mechanism supports time, space, and number processing. One of ATOM’s predictions is that of a monotonic mapping across different magnitude systems, i.e., the lesser magnitude in one domain (say, smaller duration) will be associated with the lesser magnitude in another domain (say, a smaller number, for example), and the same goes for larger magnitudes as well. ATOM theory extrapolates from these correlated monotonic mappings that different magnitude dimensions influence one another during the processing stage. In the past two decades, many behavioural studies have gathered evidence in favour of a generalized magnitude system and argued for the presence of a common magnitude system (Xuan et al., 2007; Srinivasan & Carey, 2010; Cai, & Connell, 2015; Schwiedrzik, Bernstein, & Melloni, 2016; Yamamoto, Sasaki, & Watanabe, 2016). On the contrary, more recent studies have provided evidence for independent processing of these magnitude domains and argued against a generalized magnitude system (Dormal, Seron, & Pesenti, 2006; Dormal, Andres, & Pesenti, 2008; Agrillo, Ranpura, & Butterworth, 2010; Young, Laura, & Cordes, 2013; Hamamouche et al., 2018). Apart from the behavioral studies, a handful

[1] The contents of this chapter have been published previously in a peer-reviewed journal and have been reproduced here with minor modifications.
Reference: Shukla, A., & Bapi, R. S. (2020). Numerical magnitude affects accuracy but not precision of temporal judgments. *Frontiers in Human Neuroscience*, 14, 623.

of neuroimaging studies have also supported the idea of common magnitude processing and reported that cross-domain magnitude interaction takes place in prefrontal and parietal cortices in the brain (Hubbard et al., 2005; Bueti and Walsh, 2009; Hayashi et al., (20013a); Skagerlund, Karlsson & Träff, 20016). It has been argued that such cross-domain magnitude interaction may also result from automatic analogical processing when magnitudes from different dimensions are processed together. Such analogical processing is also represented in frontal and parietal brain regions (for interesting discussion see, Bunge et al., 2005, Speed, 2010, Vicario & Martino, 2010).

It is important to note that studies arguing in favor of the common magnitude system have shown overestimation of duration for a large magnitude and underestimation of duration for a small magnitude with respect to each other. For example, the relative overestimation of time for the large magnitude has always been typically reported in the context of a small numerical magnitude. However, it may be possible that such relative temporal processing differences can be observed due to differential cognitive demands involved in the processing of small and large numerical magnitudes and may not necessarily be modulated by a common magnitude system. Thus, the fundamental question that needs to be asked is whether numerical magnitudes affect duration genuinely. Suppose a common magnitude system processes time and number dimensions. In that case, the small numerical magnitude should elicit more “short” responses, and the large numerical magnitude should generate more “long” responses, which ultimately leads to underestimation and overestimation of duration, respectively. It would be particularly interesting if large numerical magnitude elicits more “long” responses for the given objective duration than that of small numerical magnitude. This would suggest that numerical magnitude not only biases our temporal judgments but also affects the overall experiences of duration itself. Consequently, it makes sense how the duration associated with a large numerical magnitude is perceived to be longer than that associated with a small numerical magnitude. So far it is not clear whether numerical magnitudes change our temporal experience or simply bias our duration judgments. Therefore, in the present paper, we investigate whether the task-irrelevant numerical magnitude interacts with temporal processing by influencing temporal accuracy or temporal precision, or both.

To examine the above objective, we conducted an experiment using a temporal discrimination task wherein a task-irrelevant numerical magnitude was presented for a varied duration. Participants were asked to judge the duration of the numerical magnitude. We hypothesize that if numerical and temporal information are processed through a common magnitude system, the large numerical magnitude would elicit more “long” responses than the small numerical magnitude for a given duration, thus resulting in the overestimation of duration for large numerical magnitude. Similarly, the small numerical magnitude would elicit more “short” responses than that of large numerical magnitude for a particular duration and in turn, lead to the underestimation of duration for small numerical magnitudes.

3.1. METHODOLOGY

3.1.1. APPARATUS

The stimuli were presented and controlled using E-Prime Standard-2.0 (Schneider et al., 2002) on a 17’’ CRT monitor (1024 × 768 resolution) running at a frame rate of 100 Hz.

3.1.2. PARTICIPANTS

Twenty-seven participants (15:12 M:F; age range 20-27 years) were recruited from the International Institute of Information Technology, Hyderabad, India. All the participants had normal or corrected-to-normal vision. The study was approved by the Institute Review Board (IRB), International Institute of Information Technology, Hyderabad, India. Participants gave written informed consent prior to the experiment. They received remuneration against their participation.

3.1.3. STIMULUS

The experiment began with a fixation cross presented at the center of the monitor. Participants were asked to press the spacebar to start a new trial. Black stimuli (numerals) were presented on a white background. The trial starts with a fixation cross followed by a standard stimulus with fixed duration followed by a comparison stimulus presented with varying durations. An Inter-Stimulus Interval (ISI) of 700ms was used to separate the standard and the comparison stimuli. Participants were informed that they would be shown a standard duration with number “5” followed by comparison durations with numbers “1”, “5” or “9”. They were required to judge whether the comparison stimuli lasted longer or shorter than the standard stimulus in every trial. They were asked to make their duration judgments independent of the presented magnitudes. Participants executed their response by pressing a dedicated key (“L” for long and “S” for short) on the keyboard for “long” and “short” responses. The response keys were counterbalanced across participants.

3.1.4. DESIGN AND PROCEDURE

In the current study, we used three numerals: “5” being the reference magnitude, “1” being small, and “9” being large comparison magnitudes. In “identical” trials, the reference and comparison were of the same magnitude. These numbers were displayed with a 2◦ visual angle. We took seven objective durations from 250 ms to 850ms with steps of 100ms and a fixed standard duration of 550ms. Participants were taken to a dimly-lit experimental room. They were asked to sit comfortably. The distance between the participant and the computer monitor was 57 cm. Instructions were given in both verbal and written format. All participants received 10 practice trials before starting the main experiment. The durations used in the practice trials were different from the durations used in the main experiment. Each duration was repeated 7 times for each numerical magnitude constituting a total of 147 trials per participant.

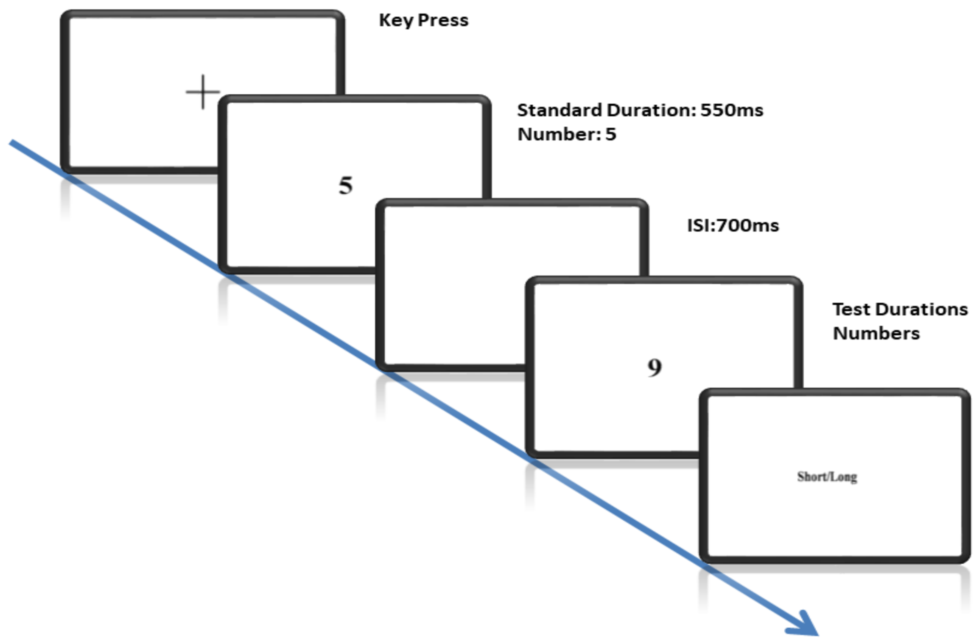

Figure-3.1. Illustration of the Task: Each trial starts with the fixation cross followed by a standard stimulus with a fixed duration and subsequently a comparison stimulus with variable durations and numbers. The standard and the comparison stimuli were separated by an interstimulus interval of 700ms. Participants were required to compare whether comparison stimulus lasted longer as compared to the standard stimulus.

3.2 RESULTS

Out of 27 participants, data from 3 participants had to be removed from the final analysis as their data could not be fit to the psychometric function.

Previous studies using temporal reproduction tasks have shown that participants reproduced longer durations in the presence of large magnitude and shorter duration for small magnitude. Such results have allowed researchers to believe in a cross-domain monotonic relation between the number and duration dimension. To test the cross-domain monotonic relation between numerical magnitude and durations, we pooled the durations into Short Duration, Same Duration, and Long Duration. The durations below the standard (550ms) were binned as “short duration” and those above the standard (550ms) were binned as “long duration”. When the standard (550ms) duration was used as standard as well as comparison duration we call it as the “same duration”. The average proportion of long responses [hereafter denoted as p(long)] were computed for each numerical magnitude across the three durations and were analyzed using a robust analysis, the rank-based ANOVA-type statistic (Noguchi et al., 2012). To evaluate whether large numerical magnitude generated more long responses and small numerical magnitude more short responses, a 3 (Magnitude: Small, Identical and Large) x 3 (Duration: Short, Same and Long) within-subject repeated measures ANOVA-type analysis was used. Given the previous findings in similar settings, one can expect that if the number and time have a monotonic relation, combining short duration with a small number would elicit more "short" responses for the given duration. Similarly, combining long durations with a large number would elicit more "long" responses.

The 3x3 repeated measure ANOVA-type statistic revealed a main effect of duration on the proportion of long responses [$F(1.88, \infty) = 320.57$, $p < .05$]. This suggests that the p(long) responses were systematically increased with increased duration. The post hoc analysis suggested that Short (0.118 ± 0.10; mean ± SD), Same (0.516 ± 0.25), and Long (0.851 ± 0.12) durations were statistically different from one another ($p < .05$), indicating that short durations were judged shorter and long durations were judged longer. Further, the results also suggested a main effect of magnitude [$F(1.99, \infty) = 12.94$, $p < .05$]. The post hoc analysis indicated that the mean p(long) responses for small magnitude (0.479 ± 0.34) and large magnitude (0.547 ± 0.34) were found to be significant ($p < .005$). Similarly, the p(long) responses for identical magnitude (0.459 ± 0.35) and large magnitude (0.547 ± 0.34) were also significant ($p < .05$). However, the p(long) responses for the small (0.479 ± 0.34) and identical magnitude (0.459 ± 0.35) were not found to be statistically significant ($p > .05$). This indicates that large numerical magnitude elicited more long responses compared to identical and small numerical magnitudes. However, we did not observe Magnitude × Duration interactions [$F(2.38, \infty) = 0.071$, $p > .05$]. This insignificant interaction suggests that the p(long) responses for the magnitude were not different across durations. In other words, large numerical magnitude did not elicit more "long" responses than that of small or identical magnitudes on the given durations.

Further, we plotted the average proportion of long responses, p(long) across probe durations (250-850ms) for each numerical magnitude and fitted a logistic function using psignifit-4, a MATLAB-based toolbox to estimate the point of subjective equality (PSE). The PSE is the point on the psychometric fit where the frequency of long and short responses are found to be the same (i.e., 50%). PSE is also considered as the accuracy of temporal judgments. A leftward shift of the psychometric curve indicates overestimation of duration and a rightward shift of the curve an underestimation of duration. We estimated the PSE values for each numerical magnitude across the participants. The goodness-of-fit (R^2) was calculated for each numerical magnitude [R^2(small) = .92 ± .07; R^2(identical) = .93 ± .08; R^2(large) = .93 ± .05]. These values indicate that the model fits the empirical data well in all the conditions.

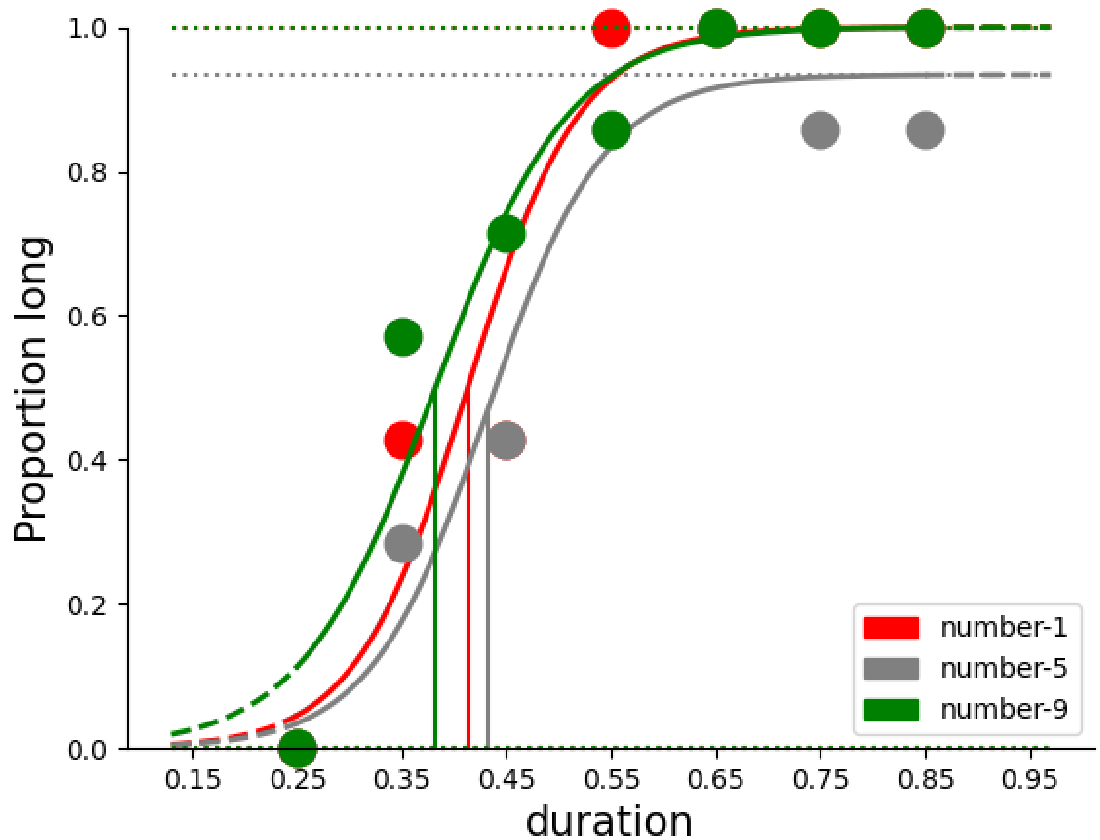

Figure-3.2: The red line represents the fit for Small numerical magnitude (“1”), while the green line represents the fit for Large numerical magnitude (“9”). In addition, a gray line shows the fit for the numerical magnitude “5”. The leftward shift of the psychometric curve indicates temporal overestimation of duration, while the rightward shift suggests underestimation of duration.

To test whether the numerical magnitudes affected temporal perception, we submitted the estimated PSE values for each magnitude to a one-way repeated measures ANOVA. The analysis yielded a significant main effect, thereby indicating that the PSE values differed significantly across the numerical magnitudes [F (2, 46) = 10.23, $p < .001$, eta-squared = 0.30]. Further, the *post hoc* test (*holm's*) suggested that duration judgments associated with large numerical magnitude (523.54 ± 65.8ms) were significantly overestimated than those with small (554.88 ± 79.8ms) and identical (582.66 ± 84.8ms) magnitudes ($p < .05$). This suggests that temporal perception may be affected by the numerical magnitude that was presented conjointly.

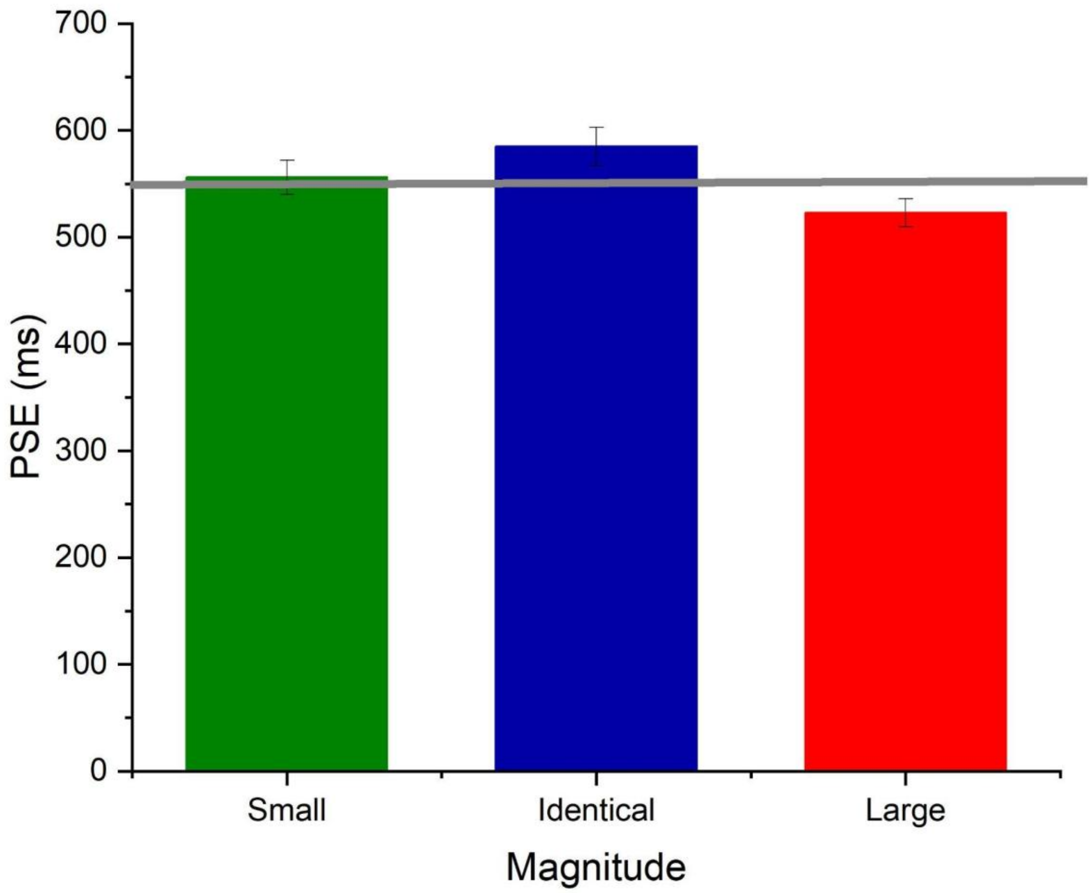

Figure-3.3: This graph displays the average PSE (Point of Subjective Equality) across different magnitude conditions. The green bar represents the average PSE for the Small (Number-1) condition, while the red bar indicates the average PSE for the Large (Number-9) condition. The blue bar shows the average PSE for the Identical (Number-5) condition. The error bar illustrates the standard error of the mean. The gray horizontal line indicates the standard duration of 550ms, and it shows how the PSEs from different conditions differ from the standard duration.

In the time perception literature, temporal overestimation is indicated when the estimated PSE is smaller than the standard duration. Similarly, temporal underestimation is indicated when the PSE is larger compared to the standard duration. In this experiment, we used 550ms as the standard duration. Therefore, we felt that it would be interesting to test whether the numerical magnitude genuinely affected temporal perception. In other words, we set out to test whether the estimated PSE for each numerical magnitude was significantly different from the standard duration. One can assume that if the numerical magnitude directly interacts with temporal processing, the numerical magnitude would cause significant deviation in duration perception from the standard duration itself. To test this, we did a one-sample t-test and compared the estimated PSE for each magnitude against the standard duration, i.e., 550ms, taken as the target value. The results of the one-sample t-test suggested that the PSE for Small (554.88 ± 79.8ms), Identical (582.66 ± 84.8ms), and large (523.54 ± 65.8ms) magnitudes did not differ significantly from the standard duration, i.e., 550ms ($p > .05$) suggesting that the numerical magnitude affected temporal perception in relative terms but may not have altered temporal processing itself with respect to the objective duration.

To test whether numerical magnitude affected temporal sensitivity, we calculated the Weber ratio for each numerical magnitude. The Weber ratio is an index of temporal sensitivity, i.e. the Difference Limen (D(p(long)) = .75 D(p(long)) - .25 D(p(long))/2) divided by standard duration. The lower the weber ratio, the steeper the curve, and the higher the temporal sensitivity. The calculated weber ratio was analysed using Friedman ANOVA. The results indicate that the temporal sensitivity did not differ across the three numerical magnitudes [$\chi2(2) = 2.33$, $p > .05$], indicating that the numerical magnitudes did not help in discriminating the duration to be longer or shorter instead they might have biased the temporal perception. Further, to examine the null result on temporal precision we used Bayesian RM ANOVA using JASP 0.12.2 to test whether the Weber ratio across three numerical magnitudes significantly differed from one other. The Bayes factor analysis yields a value of B10 = 0.146, considering that it is below 1, we can conclude that there is favorable evidence for rejecting the alternative hypothesis (in other words, the results are 6.85 times more likely to have occurred under the null model).

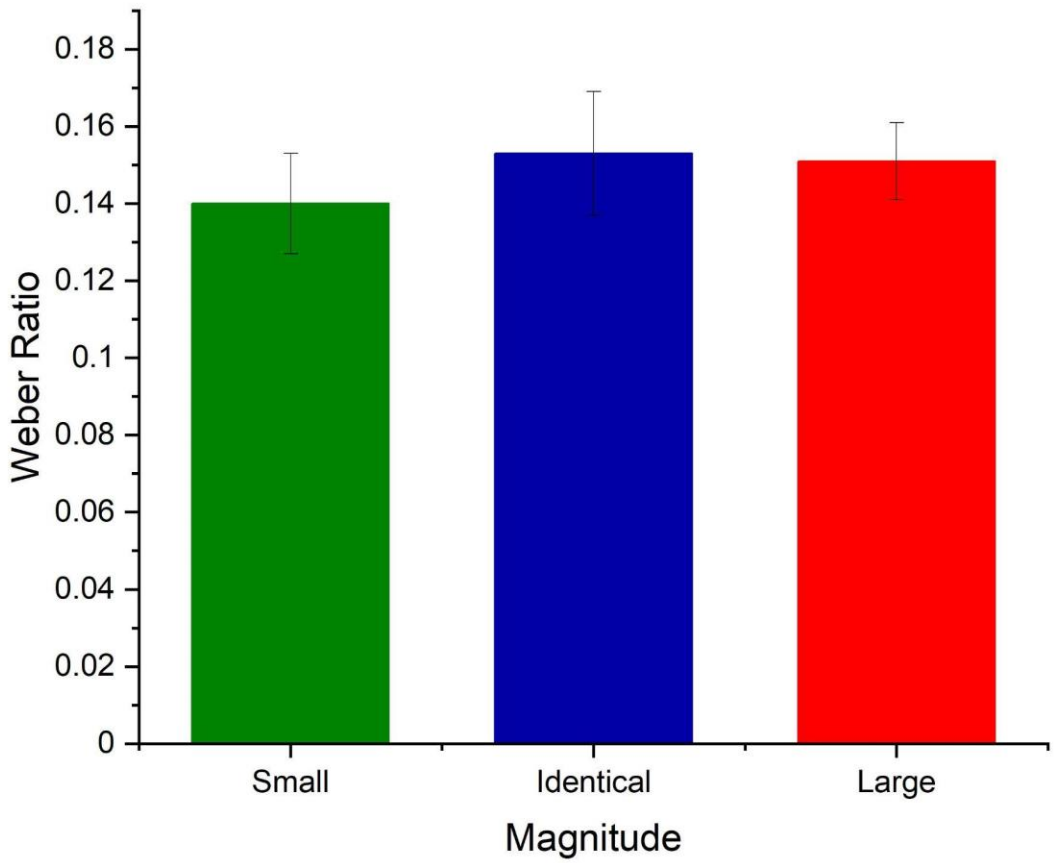

Figure-3.4: Average Weber ratio values of small (1) Identical (5) and large (9) numerical magnitude trials. The error bar represents the standard error of the mean.

3.3. DISCUSSION

In the present study, we investigated the influence of task-irrelevant numerical magnitudes on the temporal perception using a *temporal discrimination task*. We proposed that if number and time are processed through a common magnitude system, we would observe differences both in temporal accuracy and temporal precision. Our experimental data indicate that while the numerical magnitude might bias our temporal judgments, it did not change the precision itself. The additional analysis supports that numerical magnitude may not directly affect temporal processing but could influence via attentional mechanisms.

3.3.1. DOES TIME AND NUMBER REQUIRE A COMMON MAGNITUDE PROCESSING?

Several studies support the notion of the common magnitude system and extend the idea across various magnitude dimensions (Xuan et al., 2007; Srinivasan & Carey, 2010; Cai, & Connell, 2015; Schwiedrzik, Bernstein, & Melloni, 2016; Yamamoto, Sasaki, & Watanabe, 2016). On the contrary, many studies found substantial evidence against the existence of and need for a generalized magnitude system (Agrillo, Ranpura, & Butterworth, 2010; Young, Laura, & Cordes, 2013; Hamamouche et al., 2018). Our experimental data replicated the classical number effect on temporal processing, suggesting that duration is overestimated for the trials containing a large numerical magnitude than those containing small and identical numerical magnitudes. At the first glance these results seem to support ATOM's main predictions. However, when we analysed our data beyond the relative magnitude effect, the PSE for each magnitude did not differ significantly from the standard duration (see Figure-4.3). This raises an interesting question as to whether indeed the numerical magnitude affects temporal processing genuinely, or the observed difference across different numerical magnitudes might always be in relative terms and may have occurred from the differential engagement of the cognitive processes required in processing the task-irrelevant magnitudes. Our experimental data indicate that influence of numerical magnitude on temporal processing is purely relative in nature and may not require positing a generalised magnitude system. If the common magnitude system processes numerical magnitude and time, then we should have observed the differences in PSE values not just in the relative sense but also when compared against the standard duration. This indicates that numerical magnitude may not change the temporal experience but perhaps biases temporal judgments in the presence of relative magnitudes.

3.3.2. CAN THE INFLUENCE OF NUMERICAL MAGNITUDE ON TIME BE EXPLAINED BY A CLOCK MECHANISM?

Previous studies using the temporal reproduction paradigm have suggested that participants reproduced longer duration for large numerical magnitudes and shorter duration for the small numerical magnitudes. It has also been argued that numerical magnitude may affect the speed of the internal clock. Thus, large numerical magnitude causes speeding-up of the internal clock, and small numerical magnitude may slow down the speed of the internal clock. Consequently, the speeding-up or slowing-down of the internal clock might have affected the reproduction duration significantly. In contrast, our proportion of long response [p(long)] results do not support the idea of the acceleration of clock speed but suggest that numerical magnitude did not modulate temporal experience (partially supported by the analysis of PSE values as well) across durations.

Further, the Weber ratio analysis also provides indirect evidence against the common magnitude system. It has been argued that space, time and number have a cross-domain monotonic relation and therefore these magnitude dimensions can be mapped on to each other. If this is the case, then such cross-domain monotonic relation should affect the temporal discriminability resulting in differential temporal sensitivity across the three numerical magnitudes. However, our results suggest no temporal sensitivity differences across small, identical and large numerical magnitudes (see Figure-3.4). This again suggests that number-time magnitude interaction may not arise from a change in temporal precision but could be the result of the change in temporal accuracy.

3.3.3. IF NOT, THEN WHY DOES NUMERICAL MAGNITUDE CHANGE TEMPORAL PERCEPTION?

The results of the present study indicate that numerical magnitude and time may not need a common magnitude processing system. Partly, we have replicated the effect in a broader perspective, and when looked at other measures of temporal processing, numerical magnitude did not seem to influence the temporal experience. On the contrary, numerical magnitudes could bias temporal perception while making temporal judgments in more relative terms. Such relative temporal perception may be attributed to the automatic processing of numbers requiring differential attentional mechanisms that get engaged with differing numerical magnitudes. There seems to be some evidence to this from the results of previous research studies where small and large numerical magnitudes were either presented in a blocked or intermixed condition (Vicario, 2011). It has been observed that numerical magnitude affected temporal processing only when the numbers were presented in an intermixed order but not when presented in a separate block. Such effects have been attributed to the differential attentional requirements for the processing of the relative numerical magnitude. Thus, we suggest that the differential temporal perception observed in our experiments could also be due to the modulation of general attentional mechanisms involved in automatic processing of numerical magnitude dimensions (or numbers).

Apart from the behavioral studies, a handful of neuroimaging studies have also supported the idea of common magnitude processing and reported that cross-domain magnitude interaction takes place in prefrontal and parietal cortices in the brain (Hubbard et al., 2005; Bueti & Walsh, 2009; Hayashi et al., (20013a); Skagerlund, Karlsson & Träff, 2016). It has been argued that such cross-domain magnitude interaction may also result from automatic analogical processing when magnitudes from different dimensions are processed together. Such analogical processing is also represented in frontal and parietal brain regions (for interesting discussion see, Bunge et al., 2005, Speed, 2010, Vicario & Martino, 2010). These results suggest the role of spatial attention in processing of numerical and temporal information.

3.4 SUMMARY

The study reported in this chapter investigated whether number-time interaction arises from the change in temporal accuracy or temporal precision or both. Our data suggest that the temporal accuracy (judgments) is biased by the presence of numerical magnitude but did not modulate temporal precision (discrimination) itself. We suggest that such biases can occur from the attentional mechanism and may not be contingent on the existence of a common magnitude processing system proposed under the ATOM framework. the

In the next chapter, we shall investigate whether the large numerical magnitude always yields an overestimation of time. More specifically, we shall examine the influence of positive and negative numerical magnitudes on temporal processing and evaluate the influence of large magnitude from both positive and negative number domains on temporal processing.

Chapter-4

Does Large Numerical Magnitude Always Lead to Overestimation of Time?[2]

4.0 INTRODUCTION

Over the last two decades, numerous studies have advanced our knowledge of how humans utilize perceptual information to estimate magnitudes such as space, time, and number. One of the most popular theories of magnitude processing, a theory of magnitude (ATOM), suggests that a generalized magnitude system processes information related to space, time, and numbers and converts these into a common currency (Walsh, 2003). Growing evidence from neuroimaging studies has supported the idea of common magnitude processing and reported that cross-domain magnitude interaction occurs in the prefrontal and parietal cortices in the brain. On a behavioral level, many studies have found support in favor of a shared magnitude system and argued that cross-domain magnitude interactions arise because magnitudes dimensions are processed through a generalized system. On the contrary, many researchers have provided evidence against the existence of such a generalized magnitude system. Such mixed evidence has raised a question on the nature of the cross-domain magnitude interaction and its neuro-cognitive mechanisms. Suppose we assume that the common metric system does not process space, time, and numbers. In that case, we need to provide an alternative explanation for the results from the existing literature that found evidence for ATOM. In the present chapter, we investigated whether the influence of one magnitude on the processing of the other magnitude results from a common processing mechanism or is mediated by cognitive factors. Specifically, here we examine how task-irrelevant numerical magnitude from different domains affects temporal perception.

[2] The contents of this chapter have been published previously in a peer-reviewed journal and have been reproduced here with minor modifications.
Reference: Shukla, A., & Bapi, R. S. (2021). Attention mediates the influence of numerical magnitude on temporal processing. *Scientific reports*, 11(1), 1-10.

To examine the above question, we used positive and negative numbers as task-irrelevant magnitude dimensions and studied its influence on temporal processing. The negative number is an interesting case. Unlike a positive number, the relation between the numerical magnitude to the absolute value of a number is the opposite in the case of a negative number. For example, -1 is bigger than -9 when considering the absolute values, but 1 is smaller than 9. Thus, from a magnitude perspective, -1 is larger than -9, whereas, in the case of positive numbers, this relation is reversed; one (1) is smaller in number and magnitude as compared to nine (9).

It has been shown that merely perceiving positive numbers can cause an automatic shift of attention in the mental space (such as on a mental number line) without making an eye-movement (Fischer et al., 2003). However, negative numbers may not be effective in inducing such shifts of spatial attention (Fischer & Rottmann, 2005). Given the differences in the processing or the cognitive representation of negative numbers, it would be interesting to understand how negative numerical magnitudes interact with duration judgments. Such a study would also be particularly interesting to understand whether numerical magnitude affects/interferes with temporal judgments directly or is mediated by a shift of attention evoked due to the numbers.

4.1. EXPERIMENT-1: POSITIVE AND NEGATIVE NUMBER MAGNITUDE (BLOCKED)

To examine the influence of numerical magnitude on temporal processing, we conducted two experiments using a temporal comparison task. We presented positive and negative numerical magnitudes in a blocked design. We hypothesized that if a generalized magnitude system processes the magnitudes of both time and number, we would expect numerical magnitude to influence duration judgments independent of the number format (positive and/or negative) in both the blocks.

4.1.0. METHODOLOGY

4.1.1. APPARATUS

The stimuli were presented and controlled using E-Prime Standard-2.0 on a 17-inch Samsung CRT monitor (1024 × 768 resolution) running at a frame rate of 100 Hz.

4.1.2. PARTICIPANTS

A total of 35 right-handed naïve participants (19:16 M:F) were recruited from the International Institute of Information Technology, Hyderabad, India. The age range of the participants was 20-28 years. They had normal or corrected-to-normal vision. All the experimental procedures and methods were performed in accordance with the relevant guidelines and regulations and the study was approved by the Institute Review Board (IRB), International Institute of Information Technology, Hyderabad, India. Informed consent forms were obtained from all the participants, and remuneration was paid for their participation.

4.1.3 STIMULUS AND PROCEDURE

Participants were taken to a dimly lit experimental room. They were asked to sit comfortably. The distance between the participant and the monitor was 57 cm. A temporal comparison task was used, and the participants were asked to discriminate whether the comparison stimulus lasted for a longer duration compared to the standard stimulus. Each participant performed two number blocks: Positive and Negative blocks. In the positive number blocks, the numerals “1” and “9” were used as comparison stimuli and the numeral “5” as a standard stimulus.

Similarly, for the negative number blocks, the numbers “-1” and “-9” were used as comparison stimuli and the number “-5” as the standard stimulus. The motivation behind using two different (positive and negative) sets of numbers is to have control over the absolute number at the same time negative sign makes the magnitude different for the same absolute number. For example, in the positive set, the number “1” represented a small numerical magnitude, whereas “9” represented a large numerical magnitude. On the contrary, the negative number “-1” was used to represent a large numerical magnitude, and “-9” represented a small numerical magnitude. The polarity of the number (positive and negative) was blocked, and the order of the presentation was counterbalanced across the participants.

All the stimuli were presented at the center of the screen and were of a 2º visual angle. Each trial started with a self-paced fixation cross, followed by the standard stimulus (“5” in positive and “-5” in the negative block) for a fixed duration of 500ms. The second number (comparison stimulus) was presented for nine varied durations from 100ms to

900ms in steps of 100ms. The comparison and the standard stimuli were separated by an inter-stimulus-interval (ISI) of 1000ms. At the end of the trial, a white blank screen was presented until a response was received. Participants were instructed to judge whether the second stimulus lasted longer or shorter compared to the standard stimulus. They were also asked to make their judgments independent of the presented numbers. Participants executed their responses by pressing a dedicated key on the keyboard for the long and the short responses. The long and short response key-mapping was counterbalanced across the subjects. Each participant performed 144 trials of each of the positive and negative blocks. Each block contained 2 (Magnitude: Small and Large) × 9 (Durations: 100-900ms in steps of 100ms), and each duration was repeated 8 times. The stimulus presentation and the block order were randomized across the subjects. After the experiment, participants were given a magnitude judgment task to make sure that they knew which magnitude was larger and smaller, especially for the negative numbers. All the participants correctly judged the large magnitude value in negative as well as positive numbers.

4.1.4. RESULTS

All the subjects performed a Positive and Negative number block. On each trial, subjects performed a duration discrimination task for the two sequentially presented number magnitudes. In the positive number block, the first magnitude (standard) was “5” and had a fixed duration of 500ms. The second magnitude (comparison) was either “1” or “9” presented with varying durations from 100 to 900ms in steps of 100ms. Similarly, in the negative number block, everything was presented like in the positive block, but the number was presented with a – (negative) sign. The standard- and comparison-stimuli were separated by an inter-stimulus-interval (ISI). Subjects were instructed to judge whether the duration that the comparison stimulus lasted was longer or shorter compared to that of the standard stimulus.

The responses were recorded in terms of “long” and “short” keypresses on the keyboard. 35 participants took part in the experiments. However, two participants could not complete one of the experimental blocks, and another two participants’ data failed to fit the psychometric function in one of the magnitude conditions. Therefore, their data were excluded from the final analysis. Hence, the statistical analysis reported here includes data from 31 participants. We calculated the point of subjective equality (PSE) – the duration at which 50% of the time comparison stimulus duration was judged longer compared to the standard stimulus duration. Lower the PSE value higher the overestimation of time, and vice-versa. The PSE was estimated using Psignifit4 (a MATLAB-based toolbox) by fitting a Logistic Function to each numerical magnitude (small, large) data across positive and negative blocks (see Fig. 4.1). Thus, a total of four PSEs were estimated for each participant.

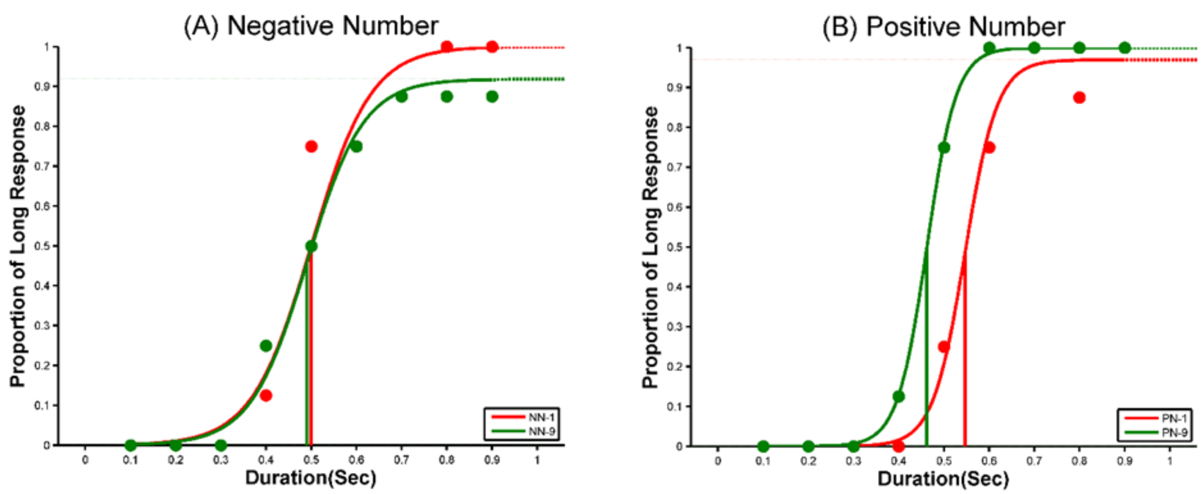

Figure-4.1: Psychometric fit for the results of a representative participant (Experiment-1). The left panel shows a psychometric plot of small and large numerical magnitudes for negative number (NN) blocks, and the right panel shows the same for the positive number (PN) blocks.

In the positive number block, the PSE for large magnitude, i.e., for “9,” was 469.80 ± 68.35ms (mean ± SD), whereas the PSE for the small magnitude, i.e., for “1” was 506.21 ± 57.04ms. Similarly, in the negative number blocks, the PSE for large magnitude, i.e., for “-1” was 491.14 ± 66.63ms, whereas the PSE for small magnitude “-9” was 472.53 ± 78.14ms.

To test whether numerical magnitudes interfere with temporal processing, we used 2 (Block: Positive vs Negative) × 2 (Magnitude: Small vs Large) repeated measures ANOVA. The results suggest that the main effect of blocks was not significant, $F(1, 30) = 0.635$, $p = 0.432$, partial $\eta^2 = 0.021$. Similarly, the main effect of numerical magnitudes was also non-significant, $F(1, 30) = 0.877$, $p = 0.356$, partial $\eta^2 = 0.028$. However, the Block × Magnitude interaction was found to be significant, $F(1, 30) = 18.780$, $p = 0.001$, partial $\eta^2 = 0.385$. Further, the simple main effects analysis (see Fig. 4.2) indicates that the numerical magnitude affects temporal processing in positive number blocks, $F(1, 30) = 15.128$, $p = 0.001$, partial $\eta^2 = 0.335$ but not in the negative number blocks: $F(1, 30) = 1.995$, $p = 0.168$, partial $\eta^2 = 0.062$.

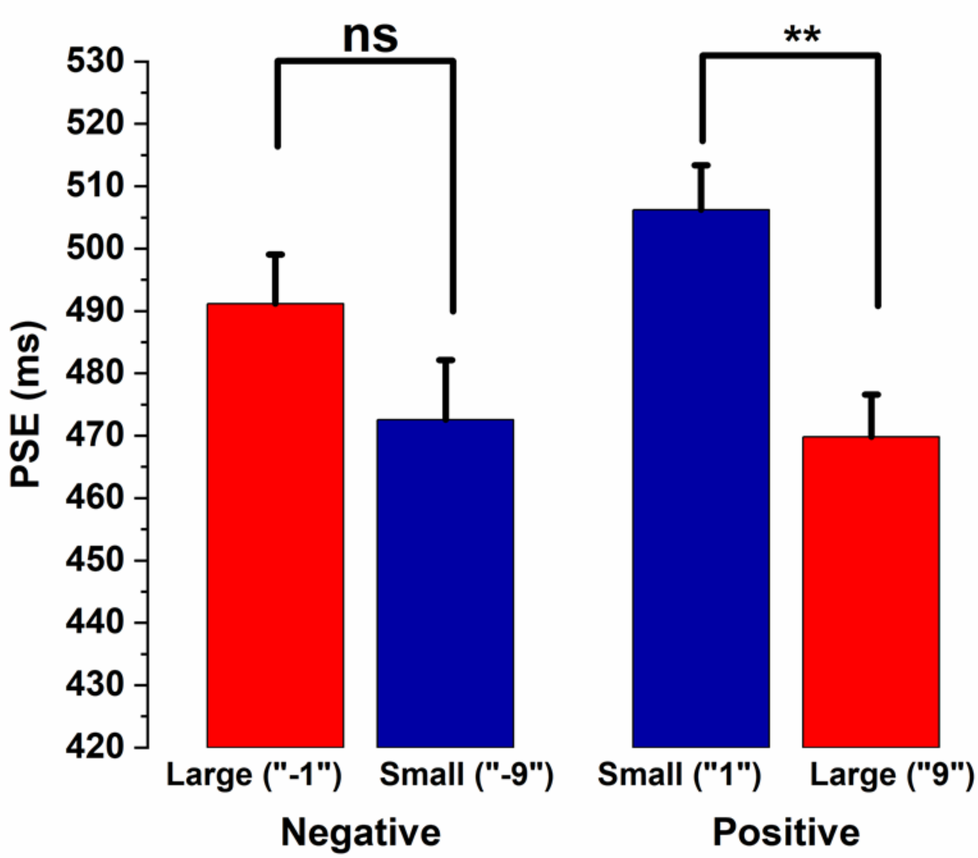

Figure-4.2: Comparison of PSE values across positive and negative number blocks (Experiment-1). Average PSE values of small and large numerical magnitude trials for positive and negative number blocks. The error bar indicates standard error of the mean. **Indicates statistically significant differences ($p < 0.01$).

At the end of the experiment, participants were given a debrief task wherein the numbers (positive or negative) were presented side by side. The order of the presentation of numbers was counterbalanced across participants. Participants were asked to indicate which of the numbers was larger in magnitude. All the participants indicated the large magnitude number in both positive and negative number comparisons with 100% accuracy. This indicates that the sense of numerical magnitude (large and small) remained intact in both positive and negative number comparisons.

4.2.0 EXPERIMENT-2: POSITIVE AND NEGATIVE NUMBER MAGNITUDES (INTERMIXED DESIGN)

In this experiment, we presented the positive and negative numbers within a single block in an intermixed order. The idea here is to test whether large numerical magnitudes yield a longer temporal perception within the number domain (positive and negative).

4.2.1. METHODOLOGY

4.2.1.1. APPARATUS

The stimuli were presented and controlled using E-Prime Standard-2.0 on a 17-inch Samsung CRT monitor (1024 × 768 resolution) running at a frame rate of 100 Hz.

4.2.1.2. PARTICIPANTS

A total of 31 participants (21:10 M:F) were recruited from the International Institute of Information Technology, Hyderabad, India. The age range of the participants was 23-28 years. All the participants reported normal vision. Informed consent forms were obtained from all the participants and remuneration was paid for their participation.

4.2.1.3. STIMULUS AND PROCEDURE

All the stimulus and procedure were identical to experiment-1 except that the positive and negative numerical magnitudes were presented in an intermixed order. Unlike in experiment-1, here, we presented “0” as the standard stimulus. Apart from these two changes, the protocol of experiment-2 was identical to that of experiment-1. Similar to experiment-1, each participant performed a total of 288 trials. The trials comprised 4 (Numbers: -9, -1, 1, 9) × 9 (Durations: 100-900ms in steps of 100ms), and each duration was repeated 8 times. Like in experiment-1, participants were given a magnitude judgment task after the experiment to make sure that they knew which magnitude was larger and smaller, especially for the negative numbers. All the participants correctly judged the large magnitude value in negative as well as positive numbers.

4.2.1.4. RESULTS

Data was collected from 31 participants. However, one participant could not complete the task, and another participant's data did not fit the psychometric function in one of the magnitude conditions. Therefore, their data were excluded from the final analysis. Hence, the statistical analysis reported here includes 29 participants' data. Like in experiment-1, PSE was estimated using Psignifit4 (MATLAB-based toolbox) by fitting a Logistic Function to each numerical magnitude (small, large) data for both positive and negative numbers (see Fig. 4.3). Thus, a total of four PSEs were estimated for each participant in experiment-2 as well.

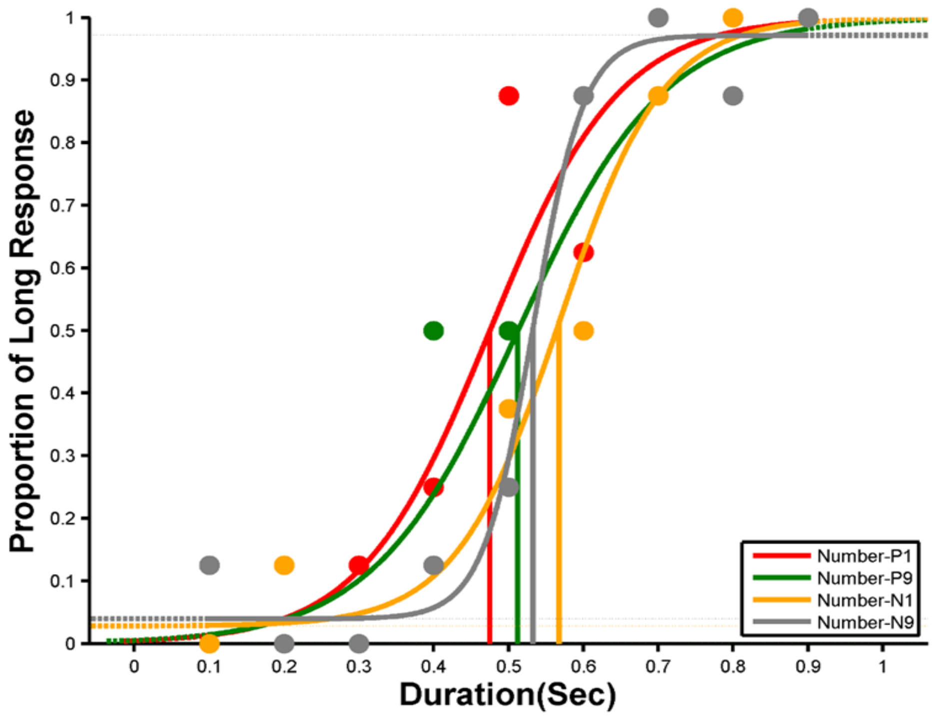

Figure-4.3: Example psychometric fit for a representative participant (Experiment-2). In the positive number domain, the small magnitude "1" (Number-P1) is shown in red color, and the large numerical magnitude "9" (Number-P9) is presented in green color. In the negative number domain, the small numerical magnitude "-9" (Number-N9) is indicated in gray color, and the large numerical magnitude "-1" (Number-N1) in yellow color.

A one-way repeated measures ANOVA was used to compare whether the temporal processing for the numerical magnitude (small and large) differs across positive and negative numbers. Post hoc analysis (using the Holm correction to adjust p) was performed to probe the temporal processing differences across different numbers.

The ANOVA results (see Fig. 4.4) revealed that the PSEs were significantly different from one another $F(3, 84) = 6.592$, $p = 0.001$, partial $\eta^2 = 0.191$. The post hoc analysis (using the Holm correction to adjust p) suggests that the duration for "1" was significantly overestimated compared to "-1" ($p = 0.004$). Similarly, the duration for "9" was also significantly overestimated compared to "-9" ($p = 0.029$). Further, the duration of large positive numerical magnitude ("9") was significantly overestimated than that of the large negative magnitude ("-1") ($p = 0.012$). Similarly, overestimation of duration was also observed for the small positive numerical magnitude ("1") compared to the small negative magnitude ("-9") ($p = 0.012$). However, we observed no significant differences in the PSEs when compared within the positive and negative numerical magnitudes (1 versus 9 and -1 versus -9).

In addition to the above ANOVA, we analyzed whether the temporal perception is different for the positive and negative numbers in general. To test this, we computed the average PSEs for positive (1 and 9) and negative (-1 and -9) numbers and submitted them to a paired samples t-test. The results suggest that the duration for the positive numbers was significantly overestimated (490.57 ± 67.39) compared to that of the negative numbers (530.91 ± 67.69), $t(28) = 3.795$, $p = 0.001$, Cohen's $d = 0.70$.

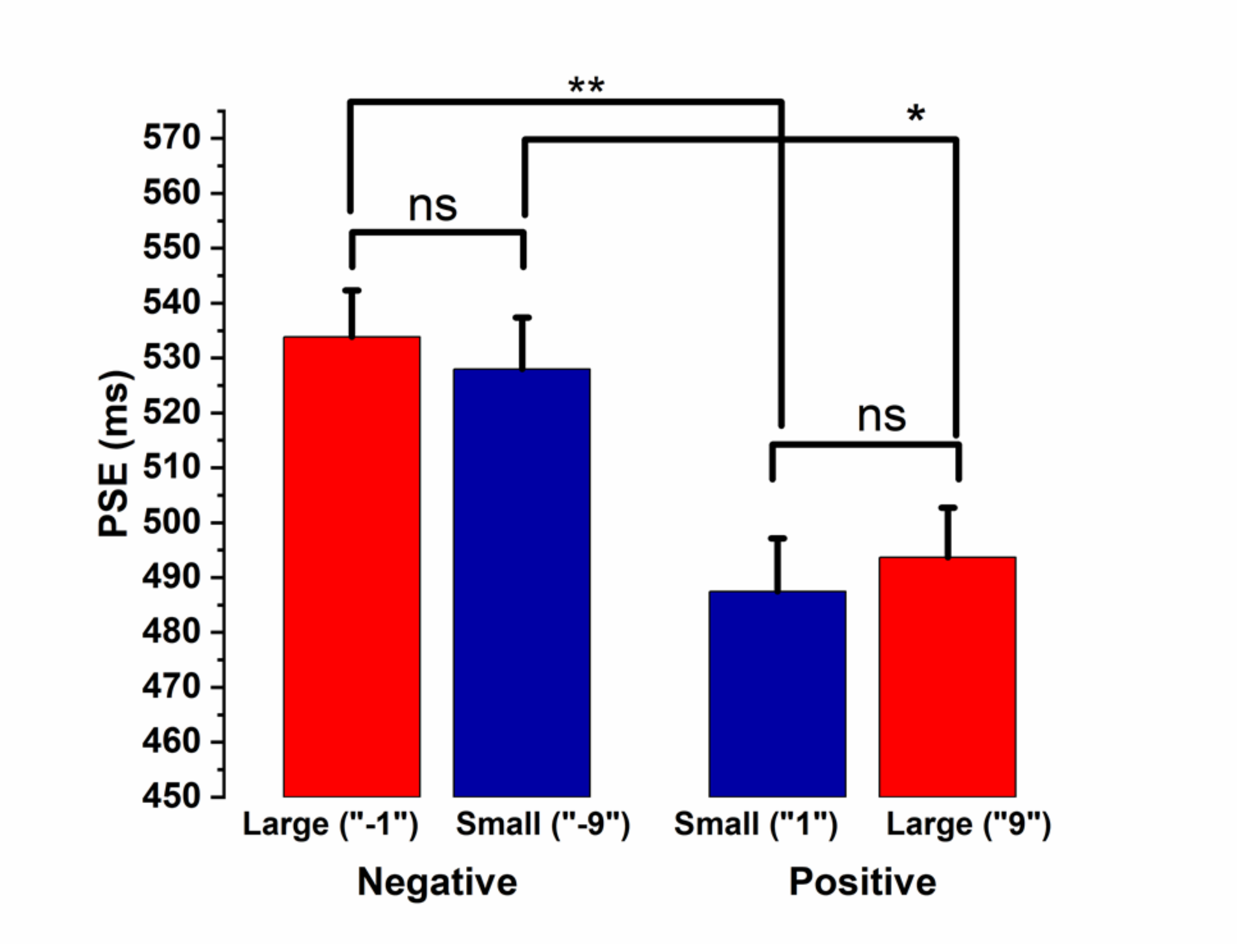

Figure-4.4: Comparison of PSE values across different numbers (Experiment-2). Average PSE values of small and large numerical magnitudes are shown for positive and negative numbers. The error bar indicates standard error of the mean. *Indicates statistically significant differences ($p < 0.05$) and ** represents ($p < 0.01$).

Like in experiment-1, participants' knowledge about the magnitude (large and small) was tested by presenting the two numbers side by side and asking them to indicate which number was larger in terms of magnitude. All the participants indicated the large magnitudes with 100% accuracy for both positive and negative number domains. This suggests that the participants were aware of large and small numerical magnitudes in positive and negative number cases.

4.3. DISCUSSION

We investigated the influence of positive and negative numerical magnitudes on duration judgments. We proposed that larger numerical magnitude would be perceived to last longer in time than smaller numerical magnitude irrespective of the number format in line with ATOM and previous studies. We used a temporal-discrimination task to present positive and negative numbers. We estimated the temporal accuracy in terms of point of subjective equality (PSE) - the point at which participants judged the comparison duration to be longer or shorter with 50% accuracy for each numerical magnitude (small and large) and number domain (positive and negative).

Previous studies have shown that task-irrelevant numerical magnitude can interfere with temporal processing (Xuan et al., 2007; Oliveri, et al, 2008; Chang et al., 2009). For example, durations tend to be overestimated in the presence of large numerical magnitudes and underestimated with small numerical magnitudes. Such interference has been attributed to common magnitude processing proposed by ATOM(Walsh, 2003). Our results indicate that numerical magnitude affects temporal processing only in the case of positive numbers but not in the case of negative numbers (Experiment-1). When “-1” and “-9” were presented in the same block (negative number block) along with the standard duration presented in conjunction with “-5”, the results indicated that numerical magnitude did not interfere with temporal processing. However, in the positive number block, we observed an overestimation of time for the large numerical magnitude (“9”) compared to the small numerical magnitude (“1”). Thus, our results from experiment-1 suggest that magnitude affects temporal processing only when presented in a positive number format but not in a negative format. This result is particularly interesting considering that the participants had a clear sense of the relative magnitudes both in the positive and negative number domains as assessed during the debrief session. We suggest that the positive and negative blocks may be different due to the more frequent use of positive numbers in real life. Thus, the sense of magnitude in positive numbers seems intuitive as compared to negative numbers. Consequently, intuitive cross-domain magnitude mapping was feasible in positive number blocks but not in negative number blocks. It is also important to note that in the present study, participants were asked to make temporal judgments independent of the presented numerical magnitudes. Despite this, automatic processing of positive numbers seems to have affected duration judgment.

In experiment-2, four numbers (1, 9, -1, and -9) were presented against a common reference, “0”. In line with ATOM’s prediction, we expected two kinds of results. Firstly, differential temporal processing across positive and negative numbers, and secondly, within each specific number domain (positive, negative), participants would overestimate the durations in the presence of larger numerical magnitudes as compared to trials with smaller numerical magnitude. In particular, the second result related to the specific number domains is important to establish the generality of ATOM-like phenomenon. While assessing the temporal processing for positive and negative numbers, we observed overestimation of duration for positive numbers (“1” or “9”) compared to negative numbers (“-1” or “-9”). Results also indicate that large positive numerical magnitude (“9”) was perceived to last longer compared to large numerical magnitude (“-1”) in the negative domain. Similarly, overestimation of duration was observed for small positive numerical magnitude (“1”) compared to that of the small numerical magnitude of the negative number domain (“-9”). Interestingly, the temporal perception for the pairs of numbers that are equal in magnitude in the absolute sense (“1” vs “-1” and “9” vs “-9”, note here that |1| = |-1| and similarly |9| = |-9|) was also found to be different. Once again, duration overestimation takes place for positive numbers, but underestimation occurred for negative numbers. Therefore, our present results suggest that the duration of positive numbers would always be overestimated than that of negative numbers. Given the fact that positive numbers are large in magnitude compared to negative numbers, at first, this result seems consistent with the previous findings advocating ATOM’s proposal, i.e., overestimation in the presence of large numerical magnitudes and underestimation in the presence of small numerical magnitudes. On the contrary, ATOM’s prediction did not hold true when we looked at how large and small numerical magnitudes affected temporal processing within each number domain separately. Surprisingly, no temporal processing differences were observed when small and large numerical magnitudes were compared within the positive (“1” vs “9”) and negative (“-9” vs “-1”) number domains individually. Therefore, the present results are inconsistent with ATOM’s proposal and seem to indicate that temporal processing is not always affected by the presence of (task-irrelevant) numerical magnitudes.

The overall results from experiment-2 raise a fundamental question as to what kind of information is crucial in cross-domain magnitude processing/interaction. What would lead to overestimation/underestimation of duration? Is it the numerical magnitude (large or small) or the number format (positive or negative polarity) that result in these effects?

Findings from experiment-2 (see Fig. 4.4) indicate that positive numerical magnitudes ("1" or "9") are perceived longer compared to negative numerical magnitudes ("-1" or "-9"). One way to analyze these results is in terms of magnitude. Since positive numbers are large in magnitude compared to negative numbers, one can argue that the results observed in the present study may be driven by the interference from a common magnitude processing system as posited by ATOM. However, when we examine the magnitude effects within each number domain (positive and negative, separately), the effects vanished, i.e., 1 and 9 as well as -1 and -9 are not perceived differently from the perspective of duration judgment. Such inconsistent results may indicate that the differential temporal processing of positive and negative numbers is modulated by number's polarity (positive and negative) but not by magnitudes per se. Further, suppose the numerical magnitude and durations were processed through a common magnitude system. In that case, we should have observed the influence of numerical magnitudes on temporal processing for positive and negative numbers. Yet, temporal perception of large and small numerical magnitudes within positive and negative number domains did not differ, providing further evidence in favor of processing of the polarity of the number. Hence, the results of experiment-2 should be attributed to the automatic processing of the sign (positive and negative) rather than magnitudes.

Taken together, the results of experiments 1 and 2 suggest that automaticity plays a crucial role in both the experiments. In experiment-1, positive numbers (1 and 9) have shown differential temporal processing but not negative numbers (-1 and -9). It could be that the relation between the numerical magnitude to the absolute value of a number becomes critical. The number-to-magnitude relation is different for positive and negative numbers. For example, -1 is bigger than -9. However, when considering the absolute values, 1 is smaller than 9. Thus, from a magnitude viewpoint, -1 is larger than -9, whereas, in positive numbers, this relation is reversed; one (1) is smaller in number and magnitude than nine (9). Therefore, we propose that such conceptual mapping (absolute number-to-magnitude) may evoke a sense of automaticity that leads to differential processing for positive and negative number blocks in experiment-1. Similarly, in experiment-2, the sense of automaticity is elicited by the numbers' polarity, leading to differential temporal processing for positive and negative numbers when presented in the same block against a common reference.

Alternatively, it has been argued that number and time are strongly associated with space and can be represented in the form of a mental number/timeline. Large magnitudes (number and time) are associated with the right side of space, and small magnitudes (number and time) are linked to the left side of space. Evidence from the number processing studies shows that the mere presence of numbers (small or large) induces shifts of attention (leftward or rightward, respectively) in the mental space (Fischer et al., 2003). Thus, it may be the case that automatic processing of a positive number influences temporal processing while causing a shift of attention in the mental space. Therefore, we suggest that the influence of positive numbers on temporal processing may be mediated by the spatial attention evoked due to automatic magnitude processing of positive numerical magnitudes. The shift of spatial attention is more feasible when the magnitudes are presented in the positive number format as numerical magnitudes are the same as absolute values of the numbers (for example, $|1| = 1$). However, this is not true for the negative number case. For the negative number, a large numerical magnitude (-1) is a small number in an absolute number sense (for example, $|-1| < |-9|$, although -1 is to the right of -9 on the real number line). Therefore, it may be possible that the shift of attention evoked by numerical magnitude may not be so automatic in the case of negative numbers. Hence, it may be the reason why we did not observe the influence of numerical magnitude on temporal processing in the negative number case when presented in a separate block (Experiment-1). Further, we speculate that a similar mechanism might be operating for positive and negative numbers when presented together in an intermixed order (Experiment-2). The polarity of numbers may cause an automatic shift in spatial attention and may lead to differential temporal processing for positive and negative numbers. The arguments invoking the influence of numbers on shifts of spatial attention need to be made with caution considering the recent failure of replication in a multilab study (Colling et al., 2020), but also see (Fischer et al., 2020).

Further, a closer look at the data reveals an interesting pattern that the positive numbers behaved differently across the two experiments. A large positive numerical magnitude is perceived longer than that of a small numerical magnitude when presented in a separate block (experiment-1, Fig. 4.2). However, the influence of positive numerical magnitude on temporal processing disappears when positive numbers were presented with negative numbers in an intermixed order as in experiment-2 (see Fig. 4.4). One can ask why positive numbers behave differently across the different experimental conditions. We speculate that the anchor (reference) magnitude plays a key role in setting up the context. For example, in experiment-1, the positive numbers “1” and “9” were presented with a reference number “5”. Whereas in experiment-2, the positive (as well as negative) numbers were presented against a common reference “0”. Although the numerical distance (between 1 and 9) is sufficiently large to provide a sense of relative numerical magnitude (small and large) in both the experiments, we did not observe any difference in temporal processing for 1 and 9 in experiment-2, indicating a possible context effect. This suggests that the polarity context drives differential temporal processing for the same absolute numbers. On the other hand, negative numbers seem to behave similarly across the two experiments in that the relative magnitude does not seem to influence temporal processing in both experiments.

4.4. SUMMARY

To conclude, the present study investigated the influence of task-irrelevant numerical magnitudes on duration judgments using positive and negative numbers in two different settings (experiments). The findings suggest that positive numbers (1 versus 9) affect duration judgments. On the other hand, the negative numbers did not interfere with duration judgments when presented in a separate block. Further, the magnitude effect seen for positive numbers (1 versus 9) seems to disappear when positive and negative numbers were presented in an intermixed order. The findings also provide evidence that the processing of the polarity of numbers affects duration judgments but not the number magnitude. Our results also indicate that the number-time interaction may be mediated by the spatial relations of the two magnitudes. This is particularly evident when the two magnitudes were presented in such a way that we could represent them in a spatial format (for example, 1 versus 9 in the context of 5 in experiment-1, -1 versus 1 in the context of 0 in experiment-2, etc.), then number interacted with temporal processing. However, when the two magnitudes were presented in such a way that no spatial representation was possible or can be formed (for example, -1 versus -9 in the context of -5 in experiment-1, 1 versus 9 in the context of 0 in experiment-2, etc.), we did not observe the numerical influence on temporal processing. Thus, we suggest that the number-time interaction arises from the modulation of attentional mechanisms and may not be processed by the generalized magnitude system proposed by Walsh (2003). In the future, we should conduct experiments where the numbers are presented in the left and right of space instead of presenting them in the center to validate the alternative explanation proposed here.

So far, we have examined the influence of numerical magnitude on temporal processing in a unimodal setting and our knowledge about the common magnitude system (for number and time) is limited to experiments in unimodal setting only. In the next chapter, we shall investigate the generality of the ATOM-like framework by studying the influence of numerical magnitude on temporal processing in a cross-modal setting.

Chapter-5

Does Visual Number Modulate Temporal Processing of Tone?[3]

5.0 INTRODUCTION

Previous studies have shown that temporal judgments are biased in the presence of non-temporal magnitudes (Xuan et al., 2007; Srinivasan & Carey, 2010; Cai & Connell, 2015; Schwiedrzik, Bernstein, & Melloni, 2016; Yamamoto, Sasaki, & Watanabe, 2016). More specifically, large numerical magnitudes are judged to last longer compared to small magnitudes. Such cross-domain magnitude interaction has motivated A Theory of Magnitude (ATOM). According to ATOM, magnitudes such as space, time, and quantities are processed through a common metric system in the brain (Walsh, 2003). Due to a common metric system, one magnitude dimension interferes with the processing of the other magnitude even though one magnitude dimension is task-irrelevant. For example, participants overestimated the duration when paired with a large numerical magnitude and underestimated when presented with a small numerical magnitude, although the numerical magnitudes were task-irrelevant (Oliveri et al., 2008; Chang et al. 2011; Cai & Wang, 2014; Hayashi et al., 2013b; Rammsayer & Verner, 2014; 2016). Growing evidence from neuroimaging studies has suggested that such cross-dimension magnitude interactions occur in the frontal and parietal regions of the brain (Hubbard et al., 2005; Bueti & Walsh, 2009; Hayashi et al., 20013a; Skagerlund, Karlsson & Träff, 2016). Based on this evidence, it has been argued that a common magnitude system processes all kinds of magnitude. On the contrary, a handful of studies have found evidence against the generalized magnitude system and suggested that the magnitudes are processed by domain-specific processing mechanisms (Dormal, Seron, & Pesenti,

[3] The contents of this chapter have been published previously in a peer-reviewed journal and have been reproduced here with minor modifications.
Reference: Shukla A and Bapi RS (2022) Number-time interaction: Search for a common magnitude system in a cross-modal setting. *Front. Behav. Neurosci. 16:891311. doi: 10.3389/fnbeh.2022.891311*

2006; Dormal, Andres, & Pesenti, 2008; Agrillo, Ranpura, & Butterworth, 2010; Young, Laura, & Cordes, 2013; Hamamouche et al., 2018). Further, it has also been argued that cross-domain magnitude interaction can also result from visuospatial attention (Vicario et al., 2008, Vicario, 2011, Di Bono et al., 2020; Shukla & Bapi, 2021) or the memory mechanism (Cai & Wang, 2014; Cai et al., 2018). The previous findings compel us to ask a fundamental question as to whether cross-dimension magnitude interactions result from a generalized magnitude system or arise due to differential cognitive processing mechanisms, for example, due to processes such as attention and memory. In the present study, we would go beyond the basic questions and investigate whether ATOM-framework accounts for multimodal cross-domain magnitude interaction, specifically for the magnitudes of number and duration of time.

Previous studies have demonstrated the influence of numerical magnitude on temporal processing and noted that a large numerical magnitude would cause overestimation of time compared to a small numerical magnitude. However, it is essential to note that the number-time interaction has been studied extensively while simultaneously presenting numerical and temporal information, predominantly in the visual domain. Therefore, our current understanding of the generalized magnitude system for processing number and time magnitudes is limited to a particular modality. It is largely unknown how a generalized magnitude system integrates the information presented in a cross-modal manner. The idea here is to test whether or how task-irrelevant/relevant magnitude information presented in one modality affects the processing of task-irelevant magnitude of another modality. The central question is whether ATOM-framework accounts for cross-modal information integration for number and time.

To investigate this objective, we conducted three experiments using a temporal bisection task. We presented numerical magnitude information in the visual domain and temporal information in the auditory either simultaneously with duration judgment task (experiment-1), prior to duration judgment task (experiment-2), and prior to duration but with the numerical magnitude being task-relevant in a dual-task paradigm (experiment-3). We hypothesized that if, according to ATOM, a central representation exists and integrates magnitude-related information across different modalities, then the presentation of the task-irrelevant magnitude information in one modality would affect the processing of magnitude in another modality in all the three experiments. Also, as posited by ATOM, if a common magnitude system processes time and number, the priming of task-irrelevant magnitude in one modality would influence magnitude processing in the other modality. Essentially, the idea is that if magnitudes are processed by a generalized system, priming with large/small task-irrelevant magnitude in one modality should activate the representation via a generalized magnitude system and therefore affect the processing of task-relevant magnitude processing in the other modality.

5.1.0 METHODOLOGY

5.1.1. APPARATUS

The stimuli were presented and controlled using OpenSesame stimulus presentation software (Mathôt, Schreij, & Theeuwes, 2012) on a 17” CRT monitor (1024 x 768 resolutions) running at 100 Hz frame rate.

5.1.2. PARTICIPANTS

Seventy-two participants from International Institute of Information Technology, Hyderabad, India (33 females; age range: 22-27 years) participated in the study. The number of participants (i.e., 66) was estimated using G∗POWER 3 (Faul et al., 2007). As per the study design, we used the parameters: alpha level = 0.05, Power = 0.95, and effect size = 0.25. We recruited 72, instead of 66 participants, to avoid any possible drop out due to outliers. Participants were divided into three experimental groups. Out of the 72 participants, 25 participants took part in experiment-1 and another 25 participants in experiment-2. The remaining 22 participants were assigned to experiment-3.

5.1.3. STIMULUS AND PROCEDURE

We used two kinds of stimuli to study the cross-modal influence—a visual and an auditory stimulus. The numerical information was always presented in the visual domain as numerals, i.e., “1” and “9” displayed on the monitor. The temporal information in the auditory domain was presented as a sound tone. The numerals were presented in black color against a white background. The tone used was based on a sine wave and was 1000ms in duration with a frequency of 440 Hz. The sound tone was presented binaurally through JBL headphones from 100ms to 900ms in steps of 100ms. The volume of the sound was adjusted for each participant as per their comfort.

Experiment-1: Simultaneous

Participants were tested in a quiet room. They were asked to sit comfortably. The distance between the participant and the computer monitor was 57 cm. The instruction was given in both verbal and written format. The study took part in 3 phases—training, feedback, and testing phases. In the training phase, the sound tone was presented for 100ms and 900ms as a short and a long anchor duration, respectively. To get a sense of the long and short durations, participants received 10 trials of short and 10 trials of long anchor durations aurally (in the form of tone) along with the numeral “5” on the computer screen. After the training phase, participants were given a feedback phase wherein the sound tone was randomly presented either for 100ms or 900ms duration with the numeral “5” displayed on the screen. They were asked to identify whether the tone presented corresponded to the long anchor or to the short anchor duration. Participants were required to respond by pressing the dedicated key for the long/short on the keyboard. Once the response was made, the feedback as correct or incorrect was presented on the computer screen. In this phase, we ensured that participants performed the duration judgment task with 90% accuracy. Once the participants reached this performance threshold, they were taken to the next phase, i.e., the testing phase. In the testing phase, participants were presented a small numerical magnitude or a large numerical magnitude, i.e., “1” or “9” on the visual display and a sound tone was presented in the auditory domain with varying probe durations from 100ms to 900ms durations in steps of 100ms. Participants were asked to judge whether the presented sound tone was closer to the small anchor or to the long anchor duration they memorized earlier in the training phase. They were asked to press the button “L” on the keypad if they felt the tone duration was closer to the long anchor duration and the button “S” if it was closer to the short anchor duration. Participants were instructed to judge the tone durations without being influenced by the numerical magnitude presented in the visual domain. Each participant performed a total of 126 trials [2 (Number: 1 and 9) x 9 (Durations: 100ms to 900ms) x 7 (Repetitions)].

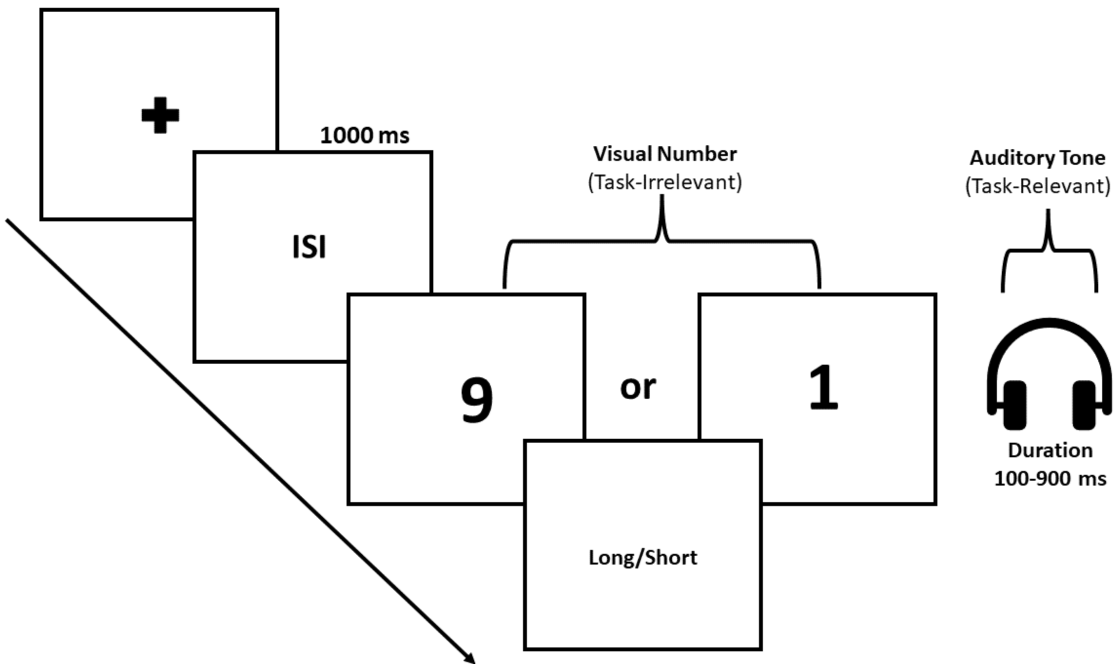

Figure-5.1: Task-Illustration. The trial begins with the fixation cross, followed by the inter stimulus interval (ISI). After the ISI, the numerical information was presented in the visual domain and temporal information in the auditory domain in the form of tone for varied durations. Thus, the numerical and temporal information were presented simultaneously in two different modalities. Participants were required to judge whether the duration of the auditory tone was closer to long or closer to short anchor duration.

Experiment-2: Number-Time Priming

The stimuli and procedures used in this experiment were like in the Experiment-1 except for the testing phase. Unlike in experiment-1, we used a priming paradigm to prime the participants with small and large numerical magnitudes in the visual domain and subsequently presented the sound tone in the auditory domain. Specifically, we presented the numerical magnitudes on the screen for 300ms followed by the tone for probe durations varying from 100ms to 900ms in steps of 100ms. Participants were asked to judge whether the presented tone duration was closer to the short anchor or to the long anchor duration memorized during the training phase. In this experiment, we tried to separate the numerical information from that of the temporal. The idea behind such separation is to test whether the numerical and temporal information are processed by a common magnitude system. The assumption behind using the priming paradigm is to activate the common magnitude system while presenting a small and a large numerical magnitude in one modality and study its impact on the temporal processing of the tone in the auditory modality.

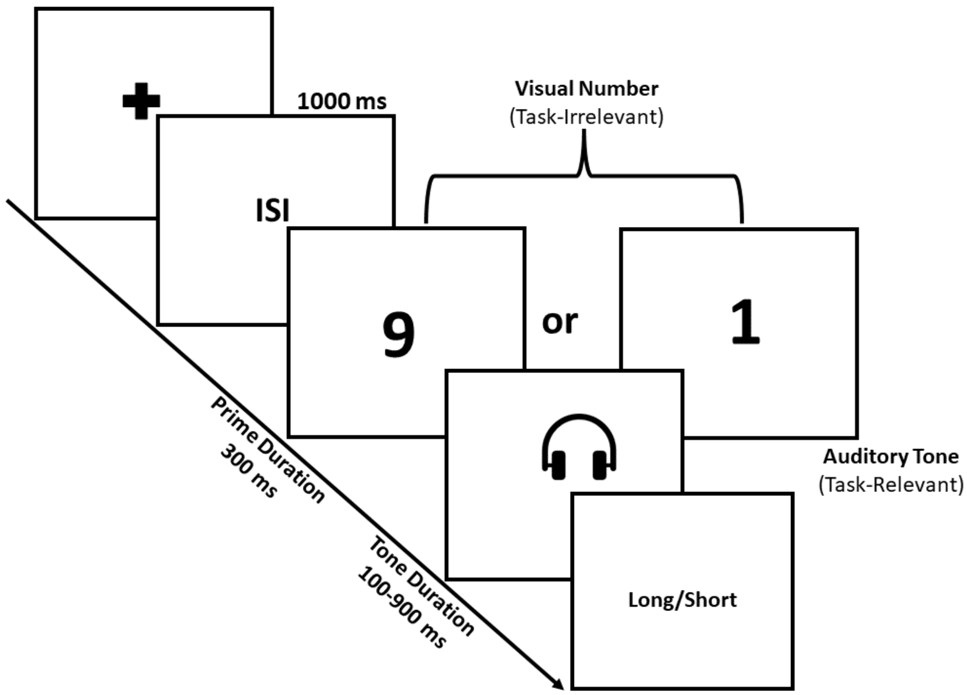

Figure-5.2: Task-Illustration. The trial begins with the fixation cross followed by the 1000ms of inter stimulus interval (ISI). After the ISI, the numerical information was presented in the visual domain for 300 ms, followed by the temporal information in the auditory tone. The duration of the auditory tone varied from 100 to 900 ms. Participants were required to judge whether the duration of the auditory tone was closer to long or closer to short anchor duration.

Experiment-3: Number-Time Dual-Task Priming

The experimental protocols were identical to those in experiment-2 except for a small difference introduced in the testing phase. Unlike in experiment-2, participants were asked to perform the duration judgement task, in a dual-task paradigm, the participants were required to hold the numerical information in the memory while performing the duration judgment task. After the duration judgment, they were required to speak the number presented at the beginning of the trial.

5.2. RESULTS

The data were recorded in terms of long and short responses. We used psignifit-4, a MATLAB-based toolbox, and estimated a Bisection Point (BP) for each numerical magnitude condition using a logistic function. The BP is the point at which 50% of the time participants would have perceived the presented duration to be closer to the short anchor and 50% of the time closer to the long anchor duration. The bisection point (BP) is also called as PSE and hereafter we use PSE instead of BP. A left shift of the psychometric curve results in smaller estimates of PSE, whereas a right shift results in larger estimates of PSE. Further, a larger PSE would be interpreted as underestimation of duration and a smaller PSE as overestimation of duration (see Figure-5.3).

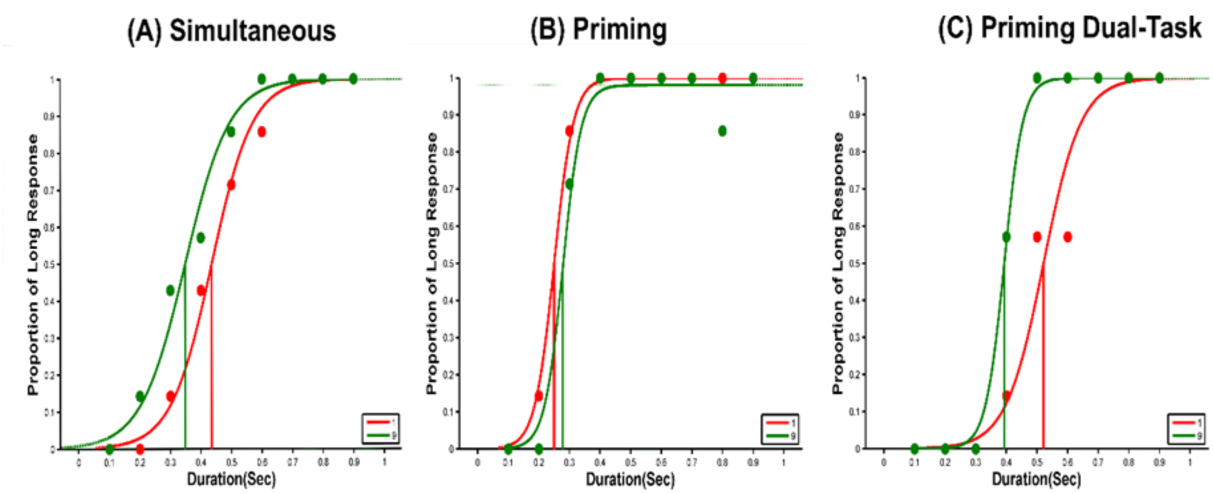

Figure-5.3: Example psychometric functions for one participant from each task condition. (A) shows the psychometric plot from the simultaneous condition wherein the numerical magnitudes were presented in the visual domain and duration in the auditory at the same time. (B) shows the psychometric plot from the priming condition wherein the visual numbers were presented for 300ms in the visual domain prior to the presentation of the duration information in the auditory domain. (C) shows a psychometric fit from the priming dual-task condition where numerical magnitude is used as visual prime and was presented 300ms prior to the duration task. Unlike the other two tasks, numerical magnitudes were task-relevant in this condition. The red line indicates the fit for the small visual number (“1”), and the green line indicates a fit for the large visual number (“9”).

To examine the cross-modal influence of numerical magnitude on temporal processing across different task conditions, we used a 2 (Magnitude: Small and Large) × 3 (Task: Simultaneous, Priming and Priming with Dual-Task) mixed repeated measures ANOVA, wherein Magnitude was a within-subject repeating factor, and task was a between-group factor. Further, the post hoc comparisons were made using the Bonferroni correction.

The results of the two-way mixed ANOVA revealed that there was a main effect of magnitude ($F(1,69) = 23.603$, $p < .001$, partial $\eta^2 = 0.255$), suggesting that the duration of the tone was overestimated when presented with the large numerical magnitude (360.52 ± 78.39) as compared to when presented with the small numerical magnitude (391.20 ± 82.22). In addition, there was also a significant main effect of task ($F(2, 69) = 8.223$, $p < .001$, partial $\eta^2 = 0.192$). The post-hoc test indicated that the temporal perception was significantly different for priming with dual-task (Experiment-3) (423.16 ± 74.19) compared to the priming task (Experiment-2) (344.25 ± 72.731) and the simultaneous task (Experiment-1) (365.84 ± 78.36) conditions. However, we did not observe a significant difference in the temporal perception for the priming task (344.25 ± 72.731) compared with simultaneous task (365.84 ± 78.36) conditions.

In addition to the main effect, we also observed a significant interaction between the magnitude and task ($F(2, 69) = 4.367$, $p < .05$, partial $\eta^2 = 0.112$) pointing out that the influence of numerical magnitude on temporal processing varied across the task conditions (see Figure-2). Further, the simple main effect analysis suggests that the duration of the tone was significantly overestimated for the large numerical magnitude (i.e., "9") than that for a small numerical magnitude (i.e., "1") in the priming dual-task condition [$F(1, 21) = 24.406$, $p < 0.01$] and in simultaneous condition [$F(1, 24) = 4.580$, $p < 0.05$]. On the contrary, the temporal perception across different magnitude did not differ in priming condition [$F(1,24) = 1.252$, $p = 0.247$] (see figure-5.2). Further, to examine the magnitude of the null result observed in priming experiment, we used Bayesian paired t-test using JASP 0.16.1 to test whether the PSE across the two numerical magnitudes significantly differed from one other. The Bayes factor analysis yields a value of B10 = 0.369, considering that it is below 1, we can conclude that there is favourable evidence for rejecting the alternative hypothesis (in other words, the results are 2.707 times more likely to have occurred under the null model).

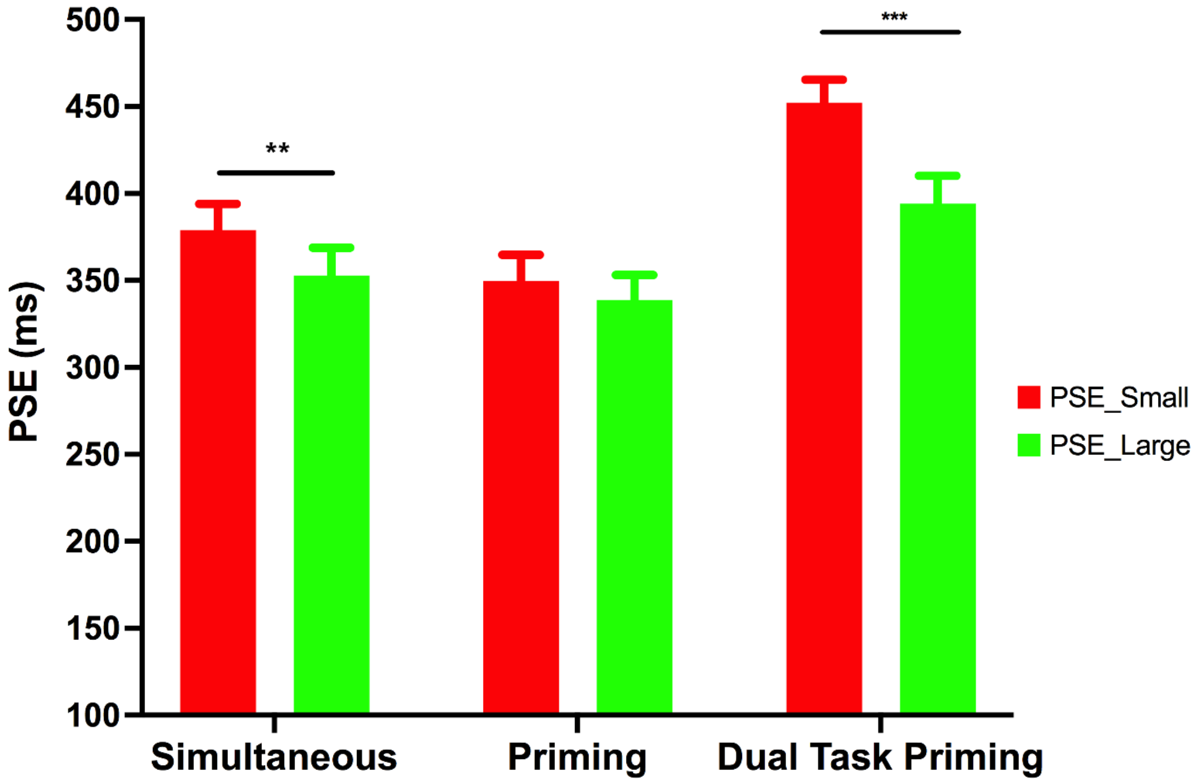

Figure-5.4: Mean PSE across the task conditions. The red bar shows the mean bisection point for the small numerical magnitude (“1”), and the green bar shows the mean bisection point for the large numerical magnitude (“9”). The error bar represents the standard error. *** indicates statistically significant differences ($p < .001$).

5.3. DISCUSSION

Previous studies have demonstrated that the processing of duration is affected by the presence of numerical magnitudes. Such cross-dimensional interaction has been explained by ATOM advocating for a generalized magnitude system (Xuan et al., 2007; Oliveri et al., 2008; Chang et al., 2011; Cai & Wang, 2014; Hayashi et al., 2013b; Yamamoto, Sasaki, & Watanabe, 2016). Our study tested the idea of number-time interaction in cross-modal settings and the results suggest that the visual numbers may affect duration judgments of tone only when the number was available while making temporal judgements. The tone duration was significantly overestimated with a large numerical magnitude compared with the small numerical magnitude presented in the visual domain. The results from experiment-1 & 3 suggest that the numerical magnitude affected the perceived duration of the tone. However, such an effect was not observed in experiment-2 (see Figure-5.4). Therefore, we suggest that the cross-modal magnitude interaction might occur via two possible mechanisms-- a) interaction via working memory: since the numerical and temporal information are presented in two different modalities, these pieces of magnitude information need to be available together for any interaction to take place. Such information integration might take place in the working memory. Therefore, we speculate that cross-modal number-time interaction may occur in the working memory, and attentional mechanism might act as a gatekeeper, preventing task-irrelevant numerical information from getting into the working memory where the temporal processing is already taking place. Thus, the influence of visual number on temporal processing of tone may not be contingent on a common magnitude processing system operating across sensory modalities. A more recent study has already shown that the cross-domain magnitude interaction (space-time) arises from memory interference (Cai et al., 2018). b) Alternatively, explicit processing of numbers may invoke visuospatial processing—it has been shown that the processing of numerical magnitude might elicit a shift of spatial attention which in turn might affect the temporal processing of visual events (Casarotti et al., 2007; Di Bono et al., 2020).

In fact, experiment-2 is designed in this spirit where we presented task-irrelevant numerical magnitude in one modality and temporal information in another, assuming that the central representation of a generalized magnitude system could operate based on visually presented numbers either along with duration or priming cues. We thought visually presented task-irrelevant numerical magnitude would activate the common magnitude processing system that would influence the subsequent temporal information. Surprisingly, the influence of numerical magnitude on temporal processing disappeared and we did not observe a significant difference in the processing of tone duration across different numerical magnitudes (see Figure-5.4). Results of experiment-2 indicate that task-irrelevant numerical information did not modulate the representation of duration information. It could be that the numerical information might have been filtered out by the attentional system and did not get into the working memory. Thus, visual task-irrelevant numbers did not affect the subsequent temporal processing of tone. Alternatively, it can also be possible that the priming of the numerical information did not activate the common magnitude system. Therefore, no temporal processing difference was observed when primed with small or large numerical magnitudes. The findings from experiment-2 seem to oppose the idea of a central representation of a generalized magnitude for processing time and number when presented cross-modally. Perhaps the generality of such a magnitude processing system is limited to a unimodal context.

At this juncture, the findings of experiment-3 prove to be interesting and seem to be complementary to the results of experiment-2. When we made the primed number task-relevant in experiment-3, numerical magnitude affected the temporal processing of the tone. This further suggests that the numerical magnitude might be processed and held in working memory along with the temporal information. Therefore, the influence of numerical magnitude on temporal processing of the tone was observed even when the numerical information was temporally separated from the duration judgment task (see Figure-5.4).

Taken together, results from the three experiments suggest that the processing of time and number may not require a common magnitude system. The cross-dimensional magnitude interaction may take place in the memory. Our results clearly suggest that cross-modal magnitude information modulates the processing of tone duration only when both numerical and temporal information are task-relevant (Experiment-3) and available at the time temporal judgements (experiment-1), and no magnitude interaction was observed when the two pieces of magnitude information are task-irrelevant and temporally separated from each other (experiment-2).

5.4 SUMMARY

In summary, our experimental findings suggest that cross-modal numerical and temporal information interact with each other, and attention and memory processes may mediate such cross-domain magnitude interactions. Both the numerical and temporal information should be available in the working memory for cross-modal number-time interaction to take place. In the next chapter, we shall investigate the role of numerical context of number-time interaction. In other words, we shall investigate whether the presence of numerical magnitude affects temporal processing when the two magnitudes (small and large) are presented in different blocks (blocked) and when presented in the same block (intermixed).

Chapter-6

Does Numerical Context Affect Temporal Processing?[4]

6.0. INTRODUCTION

Our daily life activities require us to process magnitudes from various domains. For example, a simple action like grabbing a pen from the desk requires subtle processing of information from space, time, and number domains. It has often been observed that the processing of one magnitude domain interferes with the processing of other magnitude dimensions. For example, when we want to grasp an object, for instance, magnitude is essential to perceive different dimensions of the object, such as distance, size, height, and so on. There are two distinct mechanisms for processing time, space, number, and other magnitude dimensions. In the first case, the various magnitudes can be analyzed, processed, and compared independently according to each individual metric. However, the second option is to consider a generalized magnitude system (ATOM), in which all magnitudes are processed similarly and according to a common metric system. According to ATOM, the later one is more efficient from the action selection point of view. Many behavioral and neuroimaging studies have substantiated ATOM's prediction advocating for a common magnitude system (Hubbard et al., 2005; Xuan et al., 2007; Bueti & Walsh, 2009; Srinivasan & Carey, 2010; Hayashi et al., 20013a; Cai & Connell, 2015; Schwiedrzik, Bernstein, & Melloni, 2016; Yamamoto, Sasaki, & Watanabe, 2016; Skagerlund, Karlsson & Träff, 2016). However, some studies did not support the idea of a common magnitude system and argued in favor of domain processing (Dormal, Seron, & Pesenti, 2006; Dormal, Andres, & Pesenti, 2008; Agrillo, Ranpura, & Butterworth, 2010; Young, Laura, & Cordes, 2013; Hamamouche et al., 2018). Further, more recent studies have provided evidence against the common magnitude system and argued that such

[4] The contents of this chapter have been published previously in a peer-reviewed journal and have been reproduced here with minor modifications.
Reference: Shukla, A., & Bapi, R. S. (2022). Relative Numerical Context Affects Temporal Processing. *In Proceedings of the Annual Meeting of the Cognitive Science Society (Vol. 44, 2954-2958).*

cross-dimensional magnitude interactions emerge from the cognitive factors like attention and memory (Vicario et al., 2008, Cai & Wang, 2014; Cai et al., 2018; Di Bono et al., 2020; Shukla & Bapi, 2020: Shukla & Bapi, 2021; Shukla & Bapi, 2022). Such inconsistent findings have raised a question on the existence of the common magnitude system. It is still an unsettled question and a matter of investigation. Therefore, the present paper examines whether there is a common magnitude system or the cross-dimension magnitude interactions are modulated by cognitive processes like attention and memory. More specifically, we investigate the influence of numerical magnitudes on the perceived duration.

Previous studies have shown that the task-irrelevant numerical magnitude modulates time processing. For example, the duration of a large numerical magnitude was overestimated, whereas the duration underestimation was observed for small numerical magnitudes (Oliveri et al., 2008; Chang et al. 2011; Cai & Wang, 2014; Hayashi et al., 2013b; Rammsayer & Verner, 2014; 2016). In an interesting study, Lu et al. (2009) suggested that number–time interaction can be modulated by contextual information presented with numerical magnitudes. Their study presented identical numerical stimuli with words indicating greater or lesser weight (kilogram or gram). They reported that the effect of numerical magnitude on time estimation appeared only when the higher unit of measurement (kilogram) was associated with the numbers. Their results suggested that the context can modulate the sense of number magnitude, affecting the number–time interaction.

Cross-dimensional magnitude interactions have been observed at both sub-second and supra-second timescales and argued for a common magnitude system (Hayashi et al., 20013b). On the contrary, many studies report an asymmetric interaction effect across different magnitudes (Dormal, Seron & Pesenti, 2006; Dormal & Pesenti, 2007; Bottini & Casasanto, 2010; Tsouli et al., 2019). For example, if a common magnitude system exists, the interaction should be bidirectional – numerical magnitude should affect the processing of duration, and in the other direction, duration should also affect the processing of numbers. However, the lack of such a bidirectional influence of magnitudes has raised questions on the existence of a common magnitude system for space, time, and numbers. Further, a few studies investigating the processing of numbers and time under dual-task conditions assume a common magnitude system and yield a similar influence on the processing of numbers and time. However, the findings suggest a differential influence of dual-task on the processing of numbers and time, indicating a lack of a common magnitude system (Young, Laura, & Cordes, 2013; Hamamouche et al., 2018). More recent studies have argued that attentional mechanisms may modulate such cross-magnitude interactions (Vicario et al., 2008; Di Bono et al., 2020; Shukla & Bapi, 2020, 2021, 2022).

Given the aforementioned findings, it is evident that the results reported for number-time interaction are mixed. In some of the studies, we could see a strong influence of numerical magnitude on temporal processing, but other findings do not follow ATOM's prediction. This raised a fundamental question about what is important in cross-dimensional magnitude interactions. Is it a numerical magnitude or the numerical context that provides the sense of magnitude? In the present paper, we specifically examine whether numerical magnitude (i.e., large and small) affects the perceived duration alone or the numerical context is required to give rise to cross-dimensional magnitude interactions. To test this, we designed a study wherein we presented numerical magnitude (1 and 9) either in a blocked manner (1 and 9, presented in two separate blocks) or in a mixed order (1 and 9, presented randomly within same block). The idea here is to study the effect of magnitude and relative numerical context on duration judgements. According to ATOM, we process magnitudes of different kinds via a common magnitude system, then we should observe the number-time interaction independent of the type of presentation of the number (blocked vs intermixed).

6.1 EXPERIMENT-1: BLOCKED-MAGNITUDE

In this experiment, we examine whether numerical magnitude on its own affects time processing. To study this question, we used a temporal bisection task wherein a numerical magnitude (small and large number) was presented in two separate blocks for varied durations. Participants were asked to judge the duration of the magnitude. We hypothesize that if numerical magnitude alone affects temporal processing, we should observe differential temporal processing for the two numerical magnitudes presented in separate blocks.

6.1.1 METHODOLOGY

6.1.1.1 PARTICIPANTS

Based on the pilot study, twenty-two right-handed university students (participants) (10 females and 12 males, age range = 20-30 years) were recruited. All participants had a normal or corrected-to-normal vision. They had given informed consent before the experiment. All the participants were paid for their participation. The institutional ethics committee approved the study.

6.1.1.2 MATERIALS AND APPARATUS

The stimuli were presented and controlled using E-Prime Standard-2.0 on a 19” Nokia CRT monitor (1024 x 768 resolutions) running at a 100 Hz frame rate. Participants were tested in a quiet room.

6.1.1.3 STIMULUS

We used numbers, i.e., “1” and “9” as stimuli. These numbers were presented in black color against a white background. In this experiment, participants were trained on two anchor durations, 200ms and 800ms, and tested on seven probe durations of 200, 300, 400, 500, 600, 700, and 800ms. Each probe duration was repeated 10 times for each number. Therefore, each number was presented 70 times in a block and 140 trials in total across the two blocks.

6.1.1.4 PROCEDURE

All the participants were taken to a dimly lit experimental room. They were asked to sit comfortably. The distance between the participants and the computer monitor was 57 cm. The instruction was given in both verbal and written format. In the training phase, participants received 10 trials of short anchor duration (i.e., 200ms) and 10 trials for long anchor duration (i.e., 800ms) along with the number “5” to understand what is meant by short and long durations. After the training phase, participants were given a feedback phase where the number “5” was randomly presented either for 200 or 800 ms duration. Participants were asked to identify whether the presented duration was long or short. They were given feedback as ‘correct’ or ‘incorrect’ for their responses. In this phase, we ensured that participants performed with 95% accuracy. Once the participants reached the performance threshold, they were taken to the next phase, i.e., the testing phase. In the testing phase, participants were presented small number and a large number, i.e., “1” and “9” along with probe durations. In this experiment, the small and large numbers were presented in separate blocks. The participants were asked to judge whether the duration of the presented number was closer to small or the long anchor duration and were asked to register their response by pressing a designated key (left-arrow and right-arrow) on the keyboard. The key dedicated for the long and short responses were counterbalanced across participants. The numbers used in experiments were of 2° visual angle. To avoid any order effect, the order of the blocks was also counterbalanced across participants.

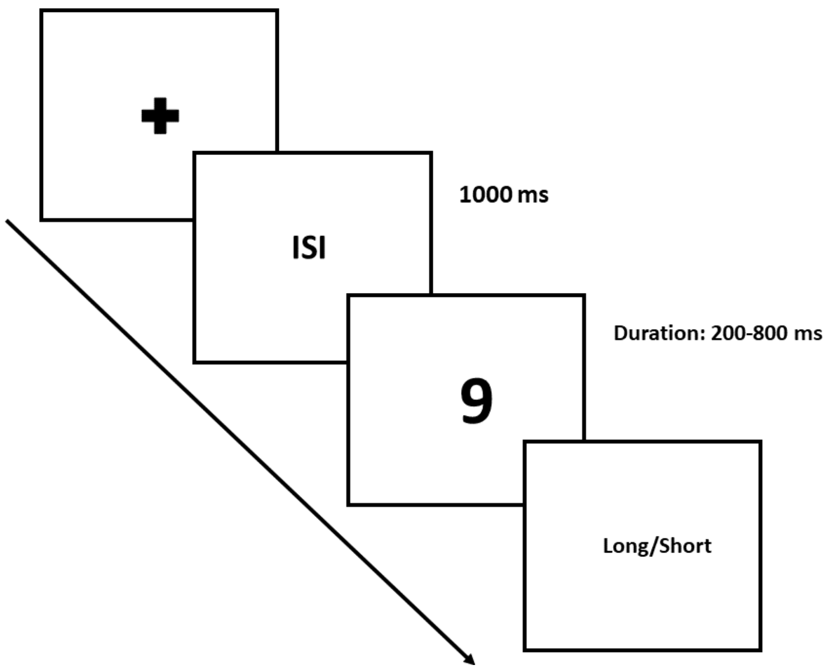

Figure-6.1: Illustration of the Blocked Task: each trial starts with the fixation cross, followed by an interstimulus interval of 1000ms. After the ISI, the numerical magnitude (either “1” or “9” depending on the block) was presented for a varied duration from 200 to 800 ms. Participants were required to judge the duration of the number.

6.1.2 RESULTS

The data were recorded in terms of long and short responses. We estimated a bisection point (BP) for each numerical magnitude condition using a logistic function. The formula for the logistic function is y=a/(1+e)^(-k(x-x_c)) , where xc is the x value of the sigmoid’s midpoint, a is the curve's maximum value, and k is the steepness of the curve. The BP is the point at which 50% of the time participants would have perceived the presented duration to be closer to the short anchor and 50% of the time closer to the long anchor duration (Figure-6.2). The bisection point (BP) is also called the point of subject equality (PSE). Hereafter, we use PSE instead of BP. A higher PSE would be interpreted as an underestimation of duration and a lower PSE as an overestimation of duration.

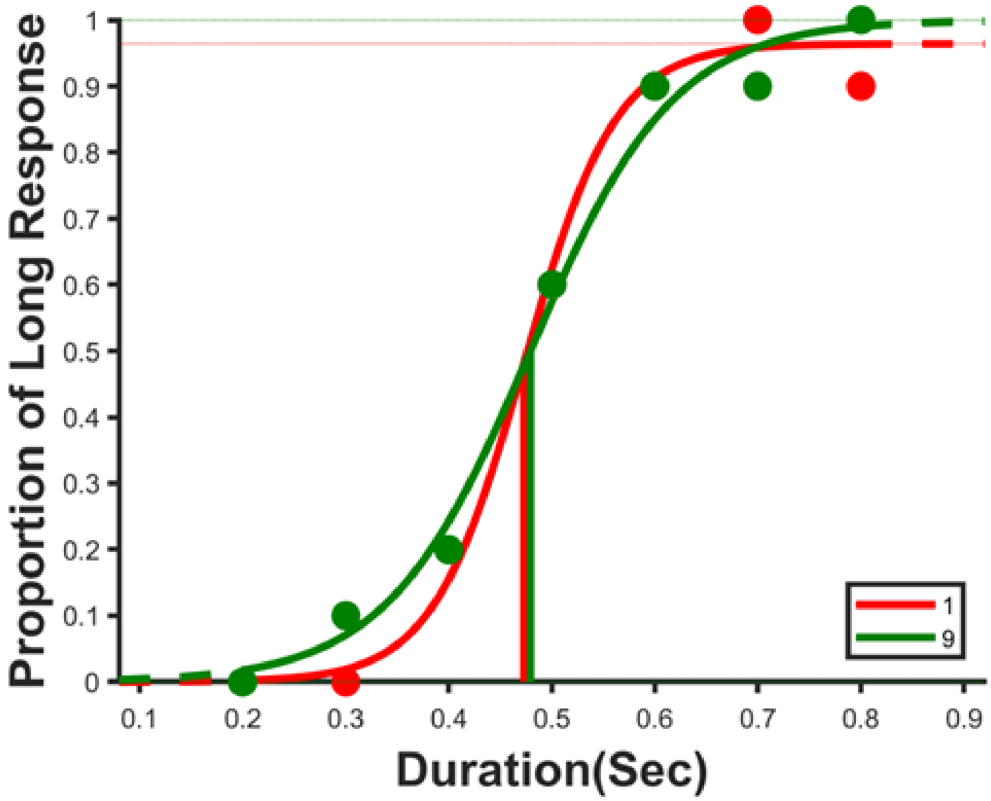

Figure-6.2: A Psychometric fit for the results of a representative participant from a blocked experiment wherein number "1" and "9" were presented in two separate blocks. The red color line represents number "1" and the green color represents number "9".

To examine whether numerical magnitude by itself affects temporal processing, we calculated PSEs for small and large numerical magnitude for each participant and submitted them to paired t-test. The result of the paired t-test indicates that the PSEs between the two numerical magnitude conditions does not differ significantly from each other [$t(21) = 0.228$, $p = 0.821$, Cohen's $d=0.049$], suggesting that the perceived duration for the small numerical magnitude (460.811 ms) did not differ from the large numerical magnitude (454.117 ms). Further, to test the magnitude of the null effect, we carried out a Bayesian paired t-test. The Bayes factor analysis yielded a value of B10 = 0.22. Considering that it is below 1, we can conclude that there is favorable evidence for rejecting the alternative hypothesis (in other words, the results are 4.54 times more likely to have occurred under the null model). The overall results suggest that the numerical magnitudes (small and large) did not modulate the perceived duration when presented in two separate blocks.

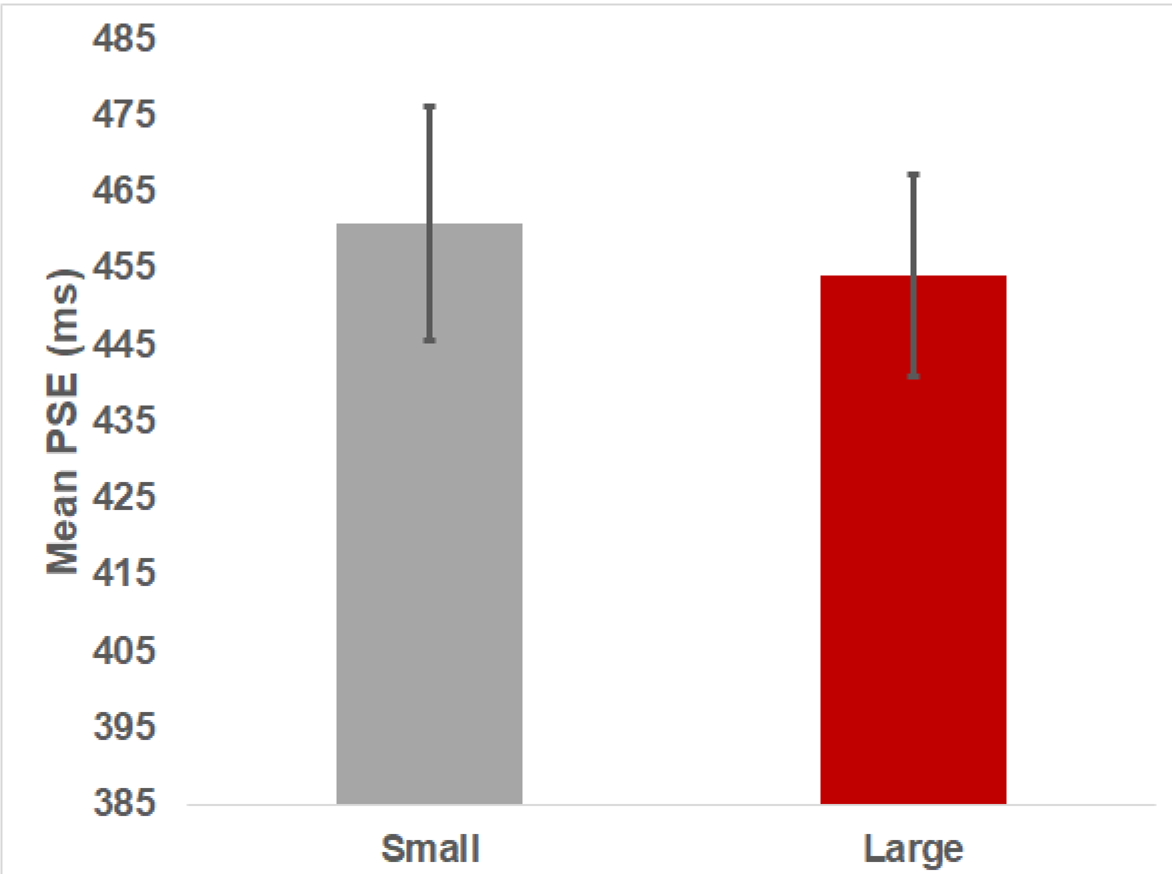

Figure-6.3: Mean PSE for small and large numerical magnitude conditions. The error bar represents the standard error.

6.2 EXPERIMENT-2: MIXED-MAGNITUDE

The null results of experiment-1 motivated us to conduct another experiment wherein we present the numerical magnitudes in an intermixed manner and see whether numerical magnitude affects perceived duration when the two numerical magnitudes are presented randomly in the same block.

6.2.1 METHODOLOGY

6.2.1.1 PARTICIPANTS

Based on the pilot study, twenty-three right-handed university students (participants) (9 females and 14 males, age range = 20-30 years) were recruited. All participants had a normal or corrected-to-normal vision. They gave informed consent before the experiment. All the participants were paid for their participation. The institutional ethics committee approved the study.

6.2.1.2 MATERIALS AND APPARATUS

The stimuli were presented and controlled using E-Prime Standard-2.0 on a 19” Nokia CRT monitor (1024 x 768 resolutions) running at a 100 Hz frame rate. Participants were tested in a quiet room.

6.2.1.3 STIMULUS

The durations and numerical magnitudes used in this experiment were identical to experiment-1.

6.2.1.4 PROCEDURE

All the participants were taken to a dimly lit experimental room. They were asked to sit comfortably. The distance between the participants and the computer monitor was 57 cm. The instruction was given in both verbal and written format. In the training phase, participants received 10 trials of short anchor duration (i.e., 200ms) and 10 trials for long anchor duration (i.e., 800ms) along with the number “5” to understand short and long duration. After the training phase, participants were given a feedback phase where the number “5” was randomly presented either for 200 or 800 ms. Participants were asked to identify whether the presented duration was long or short. They were given feedback as correct or incorrect for their response. In this phase, we ensure that participants perform with 95% accuracy. Once the participants were reached this performance threshold, they were taken to the next phase, i.e., the testing phase. In the testing phase, participants were presented a small and a large number, i.e., “1” and “9” along with probe durations. Unlike in experiment-1, here the small and large numbers were presented randomly within the same block. Rest of the protocols were identical to experiment-1.

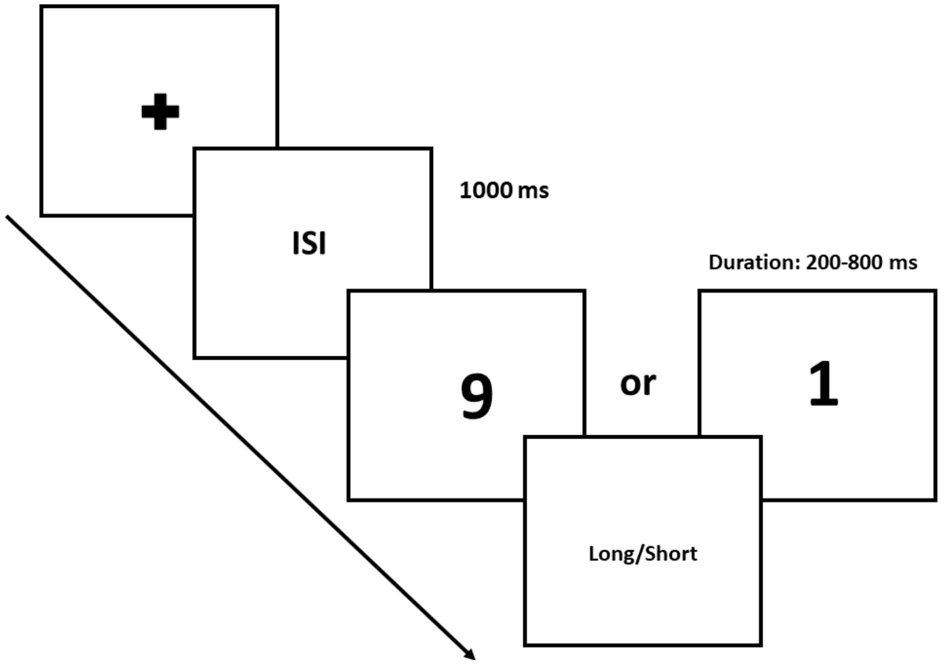

Figure-6.4: Illustration of the Mixed Task: each trial starts with the fixation cross, followed by an interstimulus interval of 1000ms. After the ISI, the numerical magnitude either "1" or "9" was presented randomly for a varied duration from 200 to 800 ms. Participants were required to judge the duration of the number.

6.2.2 RESULTS

We estimated a Bisection Point (BP) for each numerical magnitude condition using a logistic function. (Figure-6.5). Hereafter, we use PSE instead of BP.

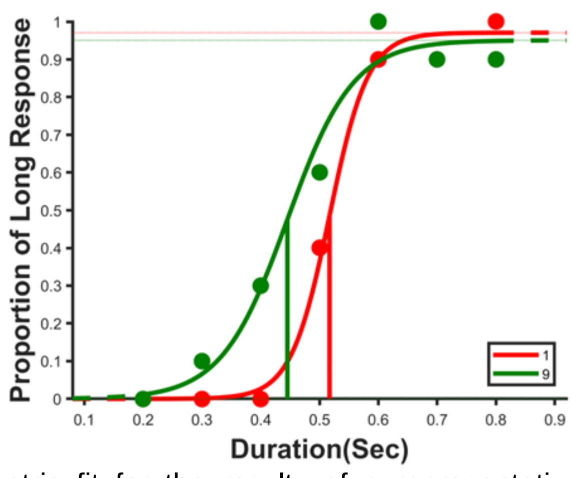

Figure-6.5: A Psychometric fit for the results of a representative participant from a mixed experiment wherein number "1" and "9" were presented randomly within the same block. The red color line represents number "1" and the green color represents number "9".

To examine whether numerical magnitude affects temporal processing when presented in an intermixed manner, we calculated PSEs for small and large numerical magnitudes for each participant and submitted them to paired t-test. The result of the paired t-test indicates that the PSEs between the two numerical magnitude conditions differ significantly from each other [$t(22) = 2.691$, $p = 0.013$, Cohen's $d = 0.561$], suggesting an underestimation of duration for the small numerical magnitude (470.488 ms) and a relative overestimation of duration for the large numerical magnitude (438.053 ms) (Figure-6.6).

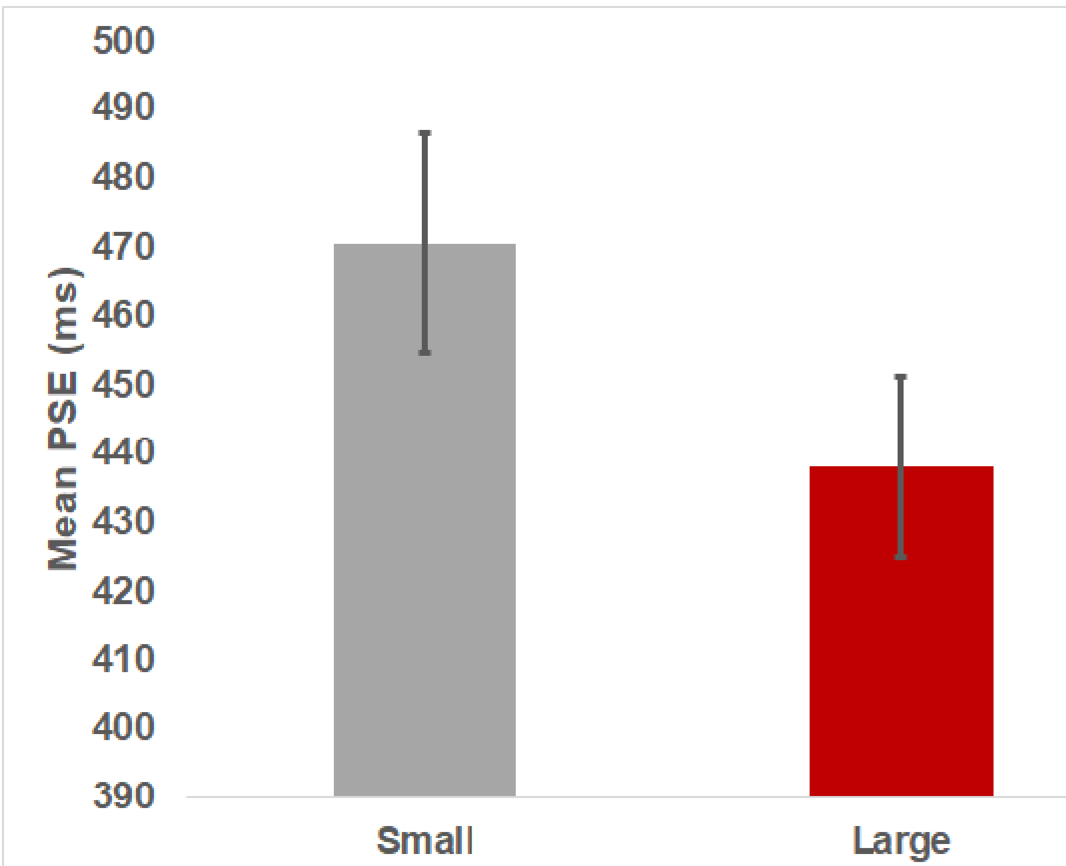

Figure-6.6: Mean PSE for small and large numerical magnitude conditions. The error bar represents the standard error.

6.3 DISCUSSION

In the present study, we examined whether numerical magnitude on its own affect temporal processing or the number-time interaction emerges from a numerical context. We used a temporal bisection task wherein we presented numerical magnitudes for varied durations, and participants were asked to judge whether the presented durations were long or short as compared to previously memorized short and long anchor durations. We hypothesized that if number and time share a common magnitude representation, the common magnitude system automatically engages whether the numerical magnitudes (numbers) are presented in individual blocks (experiment-1) or in intermixed in the same block (experiment-2). Our results from the two experiments suggest that the numerical magnitude affects temporal processing only when the number magnitudes are presented within the same block. No temporal processing differences were observed when the large and small numerical magnitudes were presented in two separate blocks. Previous studies investigating the influence of numerical magnitude on the processing of time have argued in favor of a common magnitude system and supported ATOM's predictions (Hubbard et al., 2005; Xuan et al., 2007; Bueti & Walsh, 2009; Srinivasan & Carey, 2010; Hayashi et al., 20013a; Cai & Connell, 2015; Schwiedrzik, Bernstein, & Melloni, 2016; Yamamoto, Sasaki, & Watanabe, 2016; Skagerlund, Karlsson & Träff, 20016). However, the findings of the present study seem interesting and point toward a relative numerical context effect. In other words, numerical magnitude affects temporal processing only when large and small numbers are presented in the same block.

Interestingly, the same numerical magnitudes (in fact, the same numbers 1 and 9) affect time perception differently in different experimental setups. The current findings replicate the number-time interaction (Experiment-2, see figure-6) and suggest that such cross-dimensional magnitude interactions may emerge from cognitive factors like attention. Further, the results also point out that the mere presentation of numerical magnitude may not lead to temporal bias. For example, the numerical magnitudes (large and small) when presented in a blocked manner do not lead to differential temporal processing (see experiment-1, figure-1). In contrast, the same numerical magnitudes (large and small) affect duration judgments when presented together, suggesting that the relative sense of magnitudes is crucial for cross-dimensional interactions. The findings from the two experiments indicate that the number and time magnitude may not be processed by a common magnitude system as posited in the ATOM framework. If these magnitudes required common processing mechanisms, then numerical magnitude would have affected temporal processing equally in both the experiments. Our present results indicate that a sense of numerical magnitude is crucial for cross-dimensional interactions. Presentation of numerical magnitude in separate blocks may not raise a relative sense of large and small numerical magnitudes. Thus, the number did not interact with temporal processing in the blocked experiment. However, the moment both the numbers were presented within the same block, it evoked the relative sense of magnitude. Thereby, the same numerical magnitudes but presented within the same block affected temporal processing and resulted in an overestimation of time for large magnitude trials and relative underestimation of time for small numerical trials. The present findings are consistent with the recent studies suggesting that numerical magnitude biases temporal processing and such bias may emerge from differential attentional mechanisms required for processing large and small magnitudes (Casarotti et al., 2007; Di Bono et al., 2020; Shukla & Bapi, 2020, 2021). Alternatively, it is possible that since the primary task is duration comparison, numbers are to be ignored. Incidentally, in the blocked experiment, the number might be truly irrelevant as the same number appears throughout the block, perceptual or attentional system might ignore it automatically. Whereas in the intermixed condition, the background is not stable, the numbers associated with durations keep changing between 1 and 9. So the spatial attentional processes might get engaged and connect this to the magnitude processing system (Fischer et al., 2003; Vicario et al., 2008).

6.4 SUMMARY

Several studies have reported that numerical magnitudes biases temporal judgments, i.e., large numerical magnitude, were perceived to last longer than small numerical magnitude. However, these predictions have been predominantly verified only when the large and small numerical magnitudes were presented in an intermixed fashion where numerical magnitudes varied randomly from trial to trial. We have shown that the temporal judgments were affected when small and large numbers were randomly presented in an intermixed manner. However, such effects disappeared when the number magnitudes were presented separately. These results indicate the modulation of attention in number-time interaction, and such crosstalk may not require a generalized magnitude system.

Previous studies (including ours) investigating number-time interaction have used only one task-irrelevant magnitude dimension and have studied its influence on task-relevant magnitude dimension. Thus, such a design does not allow us to tease out whether the task-irrelevant magnitudes are processed and therefore, we assume that such interaction does not pose attentional resource demands on the cognitive system. Therefore, in the next chapter, we shall examine whether the task-irrelevant numerical magnitude is processed actively and thus affects the processing of the other magnitude dimension.

Chapter-7

Is Task-Irrelevant Magnitude in Number-Time Interaction Really Irrelevant?

7.0 INTRODUCTION

Previous research has shown that magnitudes like space, time, and numbers are processed through a generalized magnitude system. Thus, we see the influence of task-irrelevant magnitude dimension on the processing of task-relevant magnitude. Such cross-domain influence has been termed as magnitude interaction. For example, we often misjudge the distance of an object depending on its size. Large objects are perceived closer compared to small objects.

Similarly, more numerous displays are perceived to last longer in time compared to less numerous displays. These cross-domain magnitude interactions have been explained using a theory of magnitude (ATOM) (Walsh, 2003). According to ATOM, space-time and numbers are processed by a generalized magnitude system, and therefore, they interact with each other even though one of them is task-irrelevant. Previous studies have provided support to the idea of a common magnitude processing system (Srinivasan & Carey, 2010; Cai & Connell, 2015; Schwiedrzik, Bernstein, & Melloni, 2016). The locus of such cross-domain magnitude interaction is prefrontal and parietal cortices in the brain (Hubbard et al., 2005; Bueti & Walsh, 2009; Hayashi et al., 2013a; Skagerlund, Karlsson, & Traff, 2016). Despite these pieces of evidence favoring a common magnitude system, more recent studies have provided evidence against ATOM (Dormal, Andres, & Pesenti, 2008; Agrillo, Ranpura, & Butterworth, 2010; Winter, Marghetis, and Matlock, 2015; Anobile et al., 2018; Tsouli et al., 2019). Thus, whether such cross-domain magnitude interaction emerges from a generalized magnitude system or is the result of the involvement of cognitive mechanisms like attention and memory processes is still an unsettled question. Therefore, in the present study, we would specifically test the role of attention in cross-domain magnitude interaction.

Studies investigating the magnitude interactions have shown that task-irrelevant magnitudes have affected the judgment of task-relevant magnitude dimension. In the context of duration judgments, the overestimation of duration was observed for a visual stimulus that is more bright, more numerous, or larger in size than that of the visual stimuli that were less bright, less numerous, or shorter in size, respectively (Xuan et al., 2007, Oliveri et al., 2008; Wutz et al., 2015). Similar findings have been reported for the temporal reproduction task when participants reproduced longer durations for large magnitude compared to that of small magnitude (Chang et al., 2011; Vicario, 2011; Rammsayer & Verner, 2014, 2015). These findings are intriguing as the presented magnitude dimension was task-irrelevant, yet it affected the processing of task-relevant magnitude dimensions. These results were attributed to a generalized magnitude processing system proposed under the ATOM framework.

Further, previous studies have also reported that the generalized magnitude system operates at different ranges of timescale (Hayashi, Valli, & Carlson, 2013b; Gilaie-Dotan, Rees, & Butterworth, 2014; Yamamoto, Sasaki, & Watanabe, 2016) as well as in different contexts (Lu et al., 2009; Vicario, 2011). In addition to these findings, studies based on concurrent tasks have provided evidence against a common magnitude system. For example, when participants were required to judge the duration or numerosity under the dual-task condition, it was observed that participants underestimated the numerosity whereas overestimated the duration under dual-task conditions (Hamamouche et al., 2018). Similar results were observed when participants performed a duration judgment and numerosity judgments task under the influence of emotion (Young & Cordes, 2013). Since the influence of dual-task and emotion were found to be different for the numerosity and duration judgment task, it is suggested that the two magnitude dimensions may not be processed by a common magnitude system and might indicate domain-specific processing. In a similar spirit, an adaptation study has observed a unidirectional influence of adaptation to the duration on numerosity judgments task but not the adaptation to numerosity on duration judgment tasks (Tsouli et al., 2019).

Apart from the above studies, a handful of studies have documented the role of visuospatial attention on cross-dimensional magnitude interaction. To understand the role of visuospatial attention, number and time magnitude were presented in the left and right visual space. The authors noted an expansion of time on the right and contraction of time in the left visual space, regardless of the numerical magnitude. However, numerical magnitude biased temporal estimation only when the numbers were presented at the center (Vicario et al., 2008). In a more recent study examining the influence of visuospatial attention on number-time interaction, the number format (positive and negative) was manipulated and presented with varying durations. Participants were asked to judge the duration of the number. The results indicated that numerical magnitude affects duration judgment when durations were paired with positive numbers but not with negative ones (Shukla & Bapi, 2021b). Further, it is observed that numerical magnitude selectively affects the accuracy but not the precision of temporal judgments (Shukla & Bapi, 2021a). It is important to note that all the above studies have primarily used two magnitude dimensions where one of them was task-irrelevant. The influence of task-irrelevant magnitudes has been studied on the task-relevant magnitude dimension and the findings have been either interpreted in favour or against the ATOM framework. The fundamental assumption of such a common magnitude processing system is that the task-irrelevant dimensions sneak in while processing the task-relevant magnitude dimension. Such implicit influence of one magnitude on the processing of another magnitude has given strength to ATOM-like framework. However, such assumptions raised a fundamental question as to whether in fact, task-irrelevant magnitude dimensions are processed actively or not. We have a limited attentional capacity to process information and if in fact, the task-irrelevant magnitude dimensions are processed actively and they in turn affect the processing of the task-relevant magnitude dimension, then we can argue that this points to issues related to attentional effect. So far, studies investigating the cross-dimensional magnitude interactions have used only one task-irrelevant and one task-relevant magnitude dimension. Thus, it is difficult to ascertain whether the task-irrelevant magnitude dimension was processed actively or not. Consequently, such a design (single task-irrelevant magnitude setting) makes it impossible to tease out the effect of cognitive factors like attention in cross-dimensional magnitude interactions. Therefore, to dissociate the role of cognitive processing in cross-domain magnitude interactions, we have used three magnitude dimensions (size, number, and time). In this study, we have manipulated size and number together, creating Size-Number Congruent and Size-

Number Incongruent combinations and have studied their influence on temporal processing. We hypothesized that if the task-irrelevant magnitude dimensions are processed and cognitive factors like attention modulate cross-domain magnitude interactions, we would see the influence of large/small Size-Number Congruent combination on temporal processing compared to large/small Size-Number Incongruent setting. Specifically, we predict overestimation of time when large size and large number magnitude dimensions are presented together compared to small size and small number magnitudes as the attentional mechanism will act as a glue to combine the congruent magnitude dimension and give raise to a sense of large or small congruent magnitudes. However, when we present the size and number magnitudes incongruently, attentional resources might be diverted in processing these two different magnitude dimensions. Therefore, we would expect to observe no differences in processing temporal information for the incongruent conditions. At the outset, we would like to state that we do not assume any equivalence across the three magnitude dimensions. We are studying the relative influence of size-number congruency and incongruency on the processing of duration information.

7.1 METHODOLOGY

7.1.1 PARTICIPANTS

Thirty-two right-handed participants (12 females; age range: 22-27 years) were recruited from the International Institute of Information Technology, Hyderabad, India. The participants have either normal or corrected to normal vision. Informed consent was obtained from the participants at the beginning of the experiment. The experiment reported in the present study was approved by the Institute Review Board (IRB), International Institute of Information Technology, Hyderabad, India.

7.1.2 APPARATUS

The stimuli were presented and controlled using OpenSesame stimulus presentation software on a laptop with a 15.6” monitor (1024 x 768 resolutions) running at a 60 Hz frame rate.

7.1.3 STIMULUS

We used three magnitude domains (e.g., size, number, and time). The size and number magnitude were presented together to make Number-Size Congruent and Number-Size Incongruent conditions. Further, we presented Large-Size with Large Number (LS-LN) and Small-Size with Small-Number (SS-SN) to obtain combined-large and combined-small magnitude settings as part of the congruent condition. Similarly, in the incongruent condition, we combined Large-Size with Small-Number (LS-SN) and Small-Size with Large-Number (SS-LN) [see figure 7.1]. These combinations were presented to participants, and they were asked to judge the duration of the presented combinations.

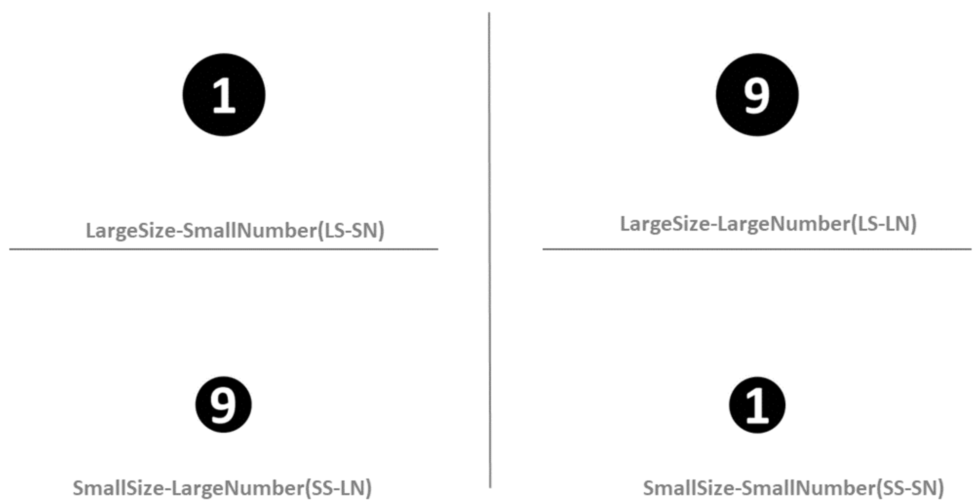

Figure-7.1: Stimuli: The figure represents different combinations of Size-Number magnitude. The left panel (top and bottom) shows incongruent combinations of Size-Number magnitudes. In contrast, the right panel represents Size-Number congruent combinations. Particularly, the top right panel shows LargeSize-LargeNumber (LS-LN) “congruent large,” and the bottom right panel presents SmallSize-SmallNumber (SS-SN) “congruent small”.

7.1.4 PROCEDURE

Participants were tested in a quiet room. They were asked to sit comfortably. The distance between the participant and the computer monitor was 57 cm. The instruction was given in both verbal and written format. The study took part in 3 phases—training, feedback, and testing phases. In the training phase, the stimulus (a black disc of 5 degrees and number “5” of 2 degrees was embedded in the disc) was presented for 100 ms and 900 ms as short and long anchor durations, respectively. To get a sense of the long and short durations, participants received 10 trials of short and 10 trials of long anchor durations along with the training stimulus on the computer screen. After the training phase, participants were given a feedback phase wherein the training stimulus was randomly presented either for 100 ms or 900 ms duration on the screen. They were asked to identify whether the stimulus presented corresponded to the long anchor or the short anchor duration. Participants were required to respond by pressing the dedicated key for the long/short on the keyboard.

Once the response was made, the feedback as correct or incorrect was presented on the computer screen. In this phase, we ensured that participants performed the duration judgment task with 90% accuracy. Once the participants reached this performance threshold, they were taken to the next phase, i.e., the testing phase. In the testing phase, participants were presented the Size and Number magnitude as LS-LN, SS-SN, LS-SN, and SS-LN composites with varying probe durations from 100 ms to 900 ms in steps of 100 ms. Participants were asked to judge whether the presented stimulus (LS-LN, SS-SN, LS-SN, and SS-LN) was closer to the small anchor or the long anchor duration they memorized earlier in the training phase. They were asked to press the button “L” on the keypad if they felt the duration was closer to the long anchor duration and the button “S” if it was closer to the short anchor duration. Participants were instructed to judge the stimulus durations without being influenced by the combination of size and numerical magnitudes. Each participant presented with 4 (Number-Size: LS-LN, SS-SN, LS-SN, and SS-LN) × 9 (Durations: 100–900 ms in steps of 100 ms), and each duration was repeated 8 times. Therefore, a total of 288 trials were presented to each participant.

7.2 RESULTS

The responses were recorded in terms of long and short responses. We used Psignifit-4 MATALB version to fit a logistic function to estimate the bisection point for each size-number congruent and incongruent conditions. The bisection point (here onwards called, the point of subjective equality or PSE) is the point on the psychometric curve on which participants produced 50% of time long responses. Thus, we computed a total of four PSE values for each participant (see Figure-7.2).

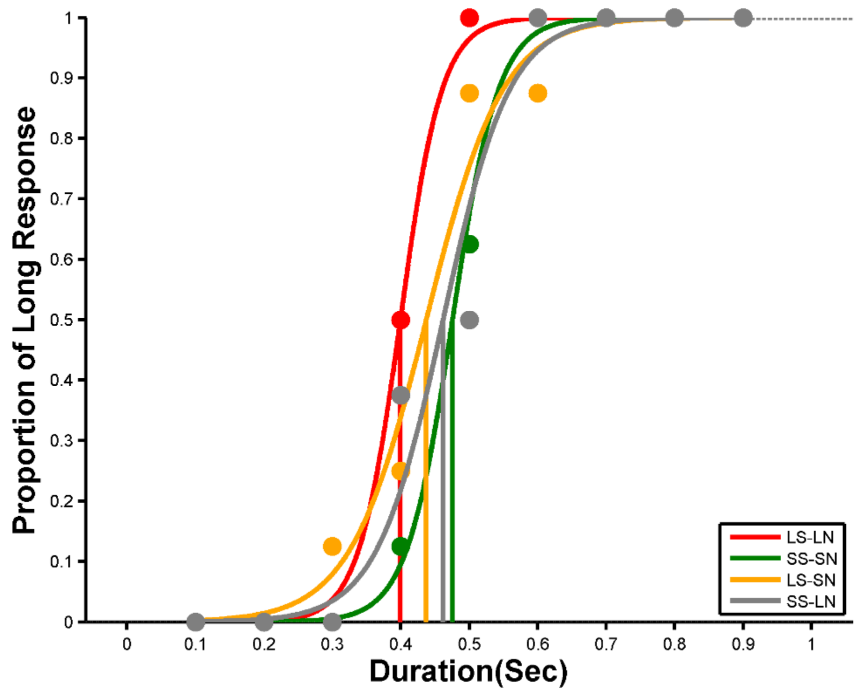

Figure-7.2: Example psychometric plot of a representative subject. The red line represents a fit for LargeSize-LargeNumber (LS-LN) condition and green line shows a fit for SmallSize-SmallNumber condition. Yellow line and gray lines represent a fit for LargeSize-SmallNumber and SmallSize-LargeNumber conditions, respectively.

A Friedman ANOVA was used to test whether the PSEs computed for the different conditions were statistically different. The results of the Friedman ANOVA suggest that the PSEs are statistically different from each other [$\chi^2(3) = 22.349$, $p = 0.001$], indicating that the temporal perception varied across different number-size. Further, the post hoc tests with Bonferroni correction suggest that in the LargeSize-LargeNumber (LS-LN) congruent magnitude condition, participants significantly overestimated the duration (420.42 ± 84.47 ms) as compared to that in SmallSize-SmallNumber (SS-SN) congruent condition (484.89 ± 85.17 ms) [Z = 4.311, P = 0.001]. On the contrary, no significant difference was observed when comparing LargeSize-SmallNumber (LS-SN) incongruent (439.45 ± 78.23 ms) with SmallSize-LargeNumber (SS-LN) incongruent conditions (461.39 ± 79.01 ms) [Z = 1.877, P = 0.384] (See Figure-7.3).

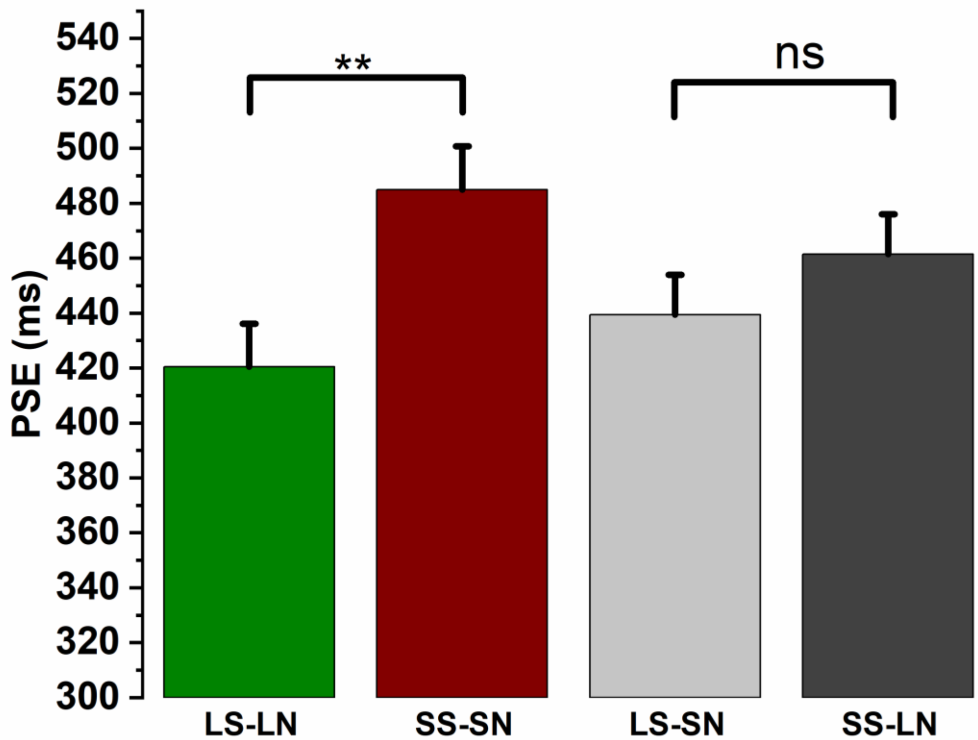

Figure-7.3: PSE across different Size-Number conditions. The green bar shows the average PSE for the LargeSize-LargeNumber condition, whereas the red bar indicates the average PSE for the SmallSize-SmallNumber condition. Similarly, the gray bar represents the average PSE for the LargeSize-SmallNumber condition, and dark gray indicates the average PSE value for the SmallSize-LargeNumber condition. The error bar shows the standard error of the mean. ** represents the significant difference at $p < 0.05$.

Apart from the simple congruent and incongruent combinations, our post hoc analysis also provides an opportunity to evaluate the effect of single magnitude dimensions on temporal processing. Therefore, to evaluate the influence of numerical magnitude-only on temporal processing, we controlled for the size magnitude so that only the numerical magnitude varied between large and small magnitudes in a particular combination. For example, LS-LN/SS-LN is compared with LS-SN/SS-SN. The result yields non-significant differences between LS-LN (420.42 ± 84.47 ms) and LS-SN (439.45 ± 78.23 ms) [Z = 1.065, P = 1]. Similarly, a non-significant difference was observed between SS-LN (461.39 ± 79.01 ms) and SS-SN (484.89 ± 85.17 ms) [Z = 1.369, P = 1]. On the other hand, we observe a significant effect of size magnitude when we control for number magnitude, for example, when LS-LN/LS-SN is compared with SS-LN/SS-SN. The result shows that large size is perceived to last longer than small size when controlling for the number magnitude: LS-SN (439.45 ± 78.23 ms) versus SS-SN (484.89 ± 85.17 ms) [$Z = 3.246$, $P = 0.01$] and LS-LN (420.42 ± 84.47 ms) versus SS-LN (461.39 ± 79.01 ms), [$Z = 2.942$, $P = 0.025$], indicating a duration overestimation for the large size (irrespective of number magnitude). Interestingly, these results suggest that when number and size magnitudes are presented together, the size magnitude seems to influence the processing of time differentially than that of number magnitude.

Further, we also analysed the PSE data while collapsing the LS-LN, SS-SN as congruent and LS-SN, SS-LN as incongruent conditions. The computed average congruent and average incongruent bisection point was tested using paired sample t-test. The paired sample t-test suggested no difference in the temporal perception across congruent and incongruent condition [$t(28) = 0.347$, $p = 0.731$]. This suggests that when we collapse the magnitudes (small and large) into one, temporal perception differences across congruent and incongruent conditions disappear (see Figure-7.4).

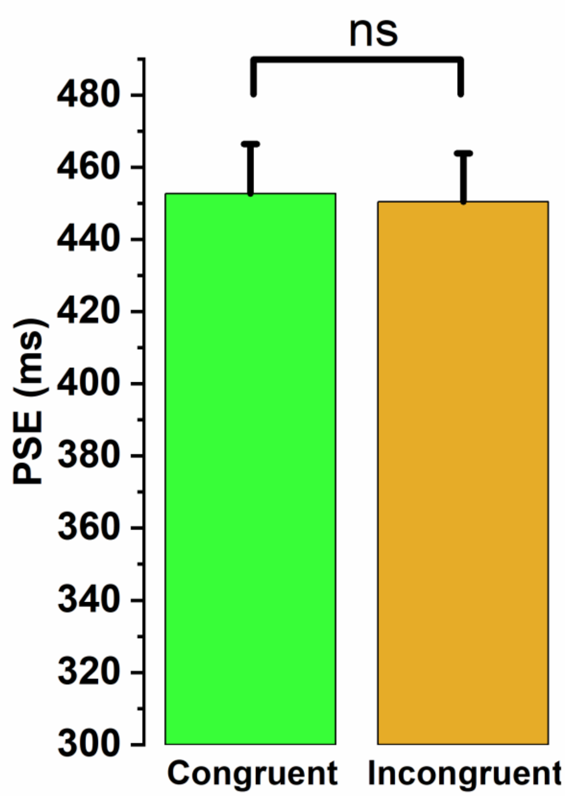

Figure-7.4: Shows the Mean PSE for Congruent and Incongruent conditions. The green bar shows the congruent mean PSE computed from the LS-LN and SS-SN congruent combinations, and the orange bar represents the Incongruent mean PSE computed from the LS-SN and SS-LN incongruent combinations. The error bar represents the standard error of the mean.

7.3 DISCUSSION

In the present study, we examine the direct influence of attentional mechanisms in cross-dimensional magnitude interaction. We have manipulated magnitudes of size and number together to create Size-Number congruent and Size-Number incongruent conditions. Further, within congruent and incongruent conditions, we have four different Size-Number combinations such as LargeSize-LargeNumber (LS-LN), SmallSize-SmallNumber (SS-SN), LargeSize-SmallNumber (LS-SN), and SmallSize-LargeNumber (SS-LN). These four different conditions are presented to the participants, and they were asked to judge the duration of the presented Size-Number combinations. We hypothesized that the processing of task-irrelevant number-size magnitude combinations would pose differential attentional processing demands for number-size congruent and number-size incongruent combinations and that would mediate the influence of combined magnitude on temporal processing. Specifically, we would observe temporal processing differences when size and number magnitudes are combined in a congruent manner to give rise to a sense of combined large or small magnitude versus when they are combined incongruently. Further, when the size and number magnitudes are combined incongruently, attentional mechanism would be diverted to process the incongruent magnitude. Thus, it may lead to no differences in the temporal processing with the size-number incongruent combinations. Our results seem to indicate that temporal processing is different for the congruent large when compared with congruent small, and no differences were observed when compared to size-number incongruent combinations.

Previous studies have suggested that a common magnitude system processes the magnitude domains such as space, time, and numbers. Therefore, task-irrelevant magnitude dimensions interact with the task-relevant magnitude dimension. For example, large numerical magnitude tends to be perceived longer in time compared to small numerical magnitude. Such cross-dimensional magnitude interactions have been attributed to ATOM. However, more recent studies have challenged the idea of a generalized magnitude system proposed under the ATOM framework and argued that the cross-domain magnitude interactions might arise from cognitive processes like memory (Cai et al., 2018) and attentional mechanisms (Vicario et al., 2008; Shukla & Bapi, 2020, 2021; Di Bono et al., 2020). In the present study, we specifically tested whether attentional mechanisms modulate the cross-domain magnitude interactions. Our experimental data suggest that the duration is overestimated for the large-congruent (LS-LN) compared to small-congruent (SS-SN) conditions.

In contrast, no temporal processing differences were observed when the dimensions of size and number magnitudes were combined incongruously (LS-SN vs SS-LN). This indicates that when the size and number magnitudes are presented congruently, participants perhaps processed the combined magnitude dimension that in turn gave an internal sense of combined large/small magnitudes. Thus, it may have evoked visuospatial processing, resulting in overestimated duration for combined-large (LS-LN) compared to combined-small (SS-SN) magnitudes. On the contrary, when the size and number magnitude are combined incongruently, i.e., LS-SN and SS-LN, the participants perhaps processed incongruent combinations as well and attentional resources may have been diverted to process these combined-incongruent magnitude dimensions. Thus, it did not affect the processing of duration judgment. These results are particularly interesting because the ATOM framework does not account for the attentional modulation of cross-domain magnitude interactions. We provide direct evidence by directly manipulating the attentional mechanisms (without asking participants to process the task-irrelevant number-size magnitude combinations) and investigating its effect on duration judgments across different combinations.

In addition to the combined magnitude effect, our design also evaluated the effect of size and number on temporal processing individually. Interestingly, when we examined the effect of size on temporal processing while controlling for the number magnitude, our results show that size influences the judgment of durations. Whereas we did not observe the influence of number magnitude on temporal processing when we controlled for the size magnitude. There could be two possible explanations for such asymmetric influence. One of the possibilities is that size (could be seen as space) is more fundamental and intuitive compared to number magnitude and thus has affected duration processing significantly. The second reason for the asymmetric finding could be the saliency effect. Since the disc size was varied as large and small, it might be the case that such changes have altered the attentional processing differently for small and large size, and such size variations must have invoked the visuospatial processing of attention, in turn affecting the processing of duration differently than the number magnitude.

Given the asymmetric effect, one might argue that the present results are only driven by size-magnitude. However, this is not true. A closer look at our data suggests that the results observed in the present study are not merely due to the overwhelming influence of size alone. If it indeed is the case, then the manipulation of size-number congruency and size-number incongruency should not have worked, and we would have observed the temporal processing differences arising from size alone, independent of how size and number were combined (congruent or incongruent). Our results indicated overestimation for large-congruent (LS-LN) than that in small-congruent (SS-SN) but not for the incongruent (LS-SN and SS-LN) combinations. Therefore, this can be taken as evidence that the manipulation of congruency and incongruency has worked for us. The observed results cannot be simply attributed to size magnitude only. Instead, it reflects the combination of both magnitudes.

The proponents of ATOM can argue that the present results are consistent with the ATOM's prediction, i.e., the magnitude dimensions like space, time, and number are converted into a common metric and therefore interact with one another. Given that the task-irrelevant number-size magnitude can also be converted into a common dimensionless currency and thereby lead to magnitude interaction. However, we argue that such a scenario would be possible only when the two task-irrelevant magnitude dimensions are presented sequentially or separated from one another so that ATOM can sense the two different magnitude (number and size) signals and convert them into a common currency that can then be mapped on to the task-relevant magnitude dimension. Since we presented the number and size magnitudes conjointly, it may not be feasible for an ATOM-like framework to dissociate (segment) the two magnitude domains (especially when the magnitudes are task-irrelevant) and then convert them into a common metric to obtain a sense of large or small magnitude. An attentional account for such cross-dimensional magnitude interactions is a parsimonious explanation for the current data.

Further, it can also be argued that the observed cross-domain magnitude interaction arises from the bias in the response system. One can argue that the response effects lead to the differences in time processing for congruent-large and congruent-small but not in the case of incongruent combinations. However, our results cannot be attributed to the bias in the response system. If this were the case, we should have observed a significant difference in temporal processing when we combined the small- and large-congruent magnitudes into average-congruent and compared them with the average-incongruent condition. We did not observe any change in temporal perception across average congruent and average incongruent conditions (See figure-7.4). Thus, the lack of difference suggests that the present results should not be interpreted as effects from the response system. We suggest that these effects arise from the conceptually represented large- and small-congruent and incongruent magnitudes and are mediated by attentional mechanisms.

7.4 SUMMARY

The present chapter examined the role of attention in cross-dimensional magnitude interaction while using two task-irrelevant magnitudes (number and size) and their influence on temporal processing. The idea was to test whether the task-irrelevant magnitude dimensions are processed and whether such processing affects the concurrent duration judgment. The findings of the present study clearly show that the task-irrelevant magnitude dimension (i.e., number-size combinations) are processed and lead to differential temporal processing for different number-size combinations. Specifically, the large number-size congruent magnitude is perceived to last longer in time compared to small number-size congruent magnitudes. Conversely, the temporal processing was not affected when these magnitude combinations were presented in an incompatible manner. Thus, this clearly shows that the task-irrelevant magnitude affects the processing of the task-relevant magnitude dimension because they are processed actively. Such active processing of task-irrelevant magnitudes and their influence on task-relevant magnitude dimension do not necessitate the proposal of an explanatory device like common magnitude processing system. Therefore, we suggest that the cross-dimensional magnitude interactions emerge from the modulation of cognitive factors like attention.

Chapter-8

Conclusion & Future Directions

8.0. CONCLUSION

In daily life, we are constantly engaged in quantifying varieties of magnitude, for example, space, time, and quantities. However, how we process these magnitude dimensions and represent them is still a matter of debate. Some attempts have been made to explain. For example, Gallistel & Gelman (2000) suggested that these (space, time & number) magnitudes are represented as “mental magnitudes”. In 2003, Walsh extended the idea of mental magnitudes and proposed a theoretical framework called “A Theory of Magnitude (ATOM)”. According to ATOM, space, time and quantities are converted into a common internal currency and represented. Thus, these magnitude dimensions have a shared representational format. Because of the shared representational format, there is a likelihood that these different magnitude dimensions interact with one another. For example, larger objects are perceived to be closer than relatively smaller objects kept at the same distance. Such interactions are the result of a common magnitude system posited by ATOM. Numerous studies have supported the idea of a common magnitude system (Srinivasan & Carey, 2010; Cai & Connell, 2014; Schwiedrzik, Bernstein, & Melloni, 2016). However, more recent studies have shown contradictory findings and argued against the ATOM (Dormal, Seron, & Pesenti, 2006; Dormal, Andres, & Pesenti, 2008; Agrillo, Ranpura, & Butterworth, 2010; Young, Laura, & Cordes, 2013; Hamamouche et al., 2018). A major concern with the ATOM-like framework is the problem of lack of symmetry of interaction of these dimensions — for example, the way number-magnitude affects the processing of durations should be the same as how duration-magnitude affects numbers. But in reality, this is not the case. Further, it has also been observed that different tasks affect different magnitude dimensions differently (Laura, & Cordes, 2013; Hamamouche et al., 2018). Therefore, it is hard to understand when there is a common magnitude system that processes all sorts of magnitude dimensions (independent of the physical dimension), why should different magnitude dimensions give rise to differential effects when tested in different contexts. Such mixed results led us to investigate whether such cross-dimensional interactions arise from the common magnitude system or due to modulation effects of related cognitive factors (i.e., attention, memory).

In the present thesis, we conducted a series of investigations to evaluate whether the number-time interaction arises from a generalized magnitude system as posited by ATOM or the result of the modulation in cognitive factors such as attention and memory. In chapter 3, we have shown that the numerical magnitude affects temporal accuracy but not the precision of temporal judgments. Further, we have also shown that the bias in temporal accuracy for the large and small numerical magnitudes is relative in nature. For example, the perceived duration for the large numerical magnitude was overestimated compared to the small numerical magnitude. However, no absolute over- or under-estimation of duration was observed as a function of numerical magnitude when compared to the PSEs for the large and small numerical magnitudes against the standard duration (i.e., 550ms). This perhaps indicates that the influence of numerical magnitude on temporal processing results from “bias” (i.e., results from differential attentional engagements) and does not necessarily reflect the role of the generalized magnitude system. Similarly, in chapter 6, we have shown that the numerical magnitude affects temporal processing only when the numerical magnitudes (small and large) are presented within the same block but not when presented in two separate blocks. This indicates that the same large numerical magnitude did not yield an overestimation of time when presented independently, i.e., separated from the small numerical magnitude and vice-versa. Such an influence clearly suggests that the number and time do not require a common magnitude system. Perhaps, the number-time interaction is modulated by cognitive factors like attention. Number processing literature has shown that numerical magnitudes have the potential to modulate visuospatial attention (Fischer et al., 2003). More specifically, a large numerical magnitude induces a right shift of attention, whereas a small numerical magnitude induces a left shift of attention in the mental space. We suggest that the magnitude-based covert shift of attention plays a crucial role in number-time interaction. Therefore, such a shift in attention can result in differential duration processing and bias temporal judgments. The results of chapter 4 substantiate the idea that visuospatial processing of attention modulates number-time interactions in the human mind. We have shown that the large numerical magnitude affects duration judgments only when the presented numbers were positive (i.e., 1 and 9). However, no modulation in temporal judgments was observed when the numbers were negative (i.e., -1 and -9). Although the participants were well aware of the largeness and smallness of numerical magnitudes of negative numbers, yet that did not interfere with the processing of time. This indicates that the presence of large and small numerical magnitudes appearing in the negative number block did not modulate the temporal processing. Further, when positive numbers (i.e., 1 and 9) and negative numbers (i.e., -1 and -9) were presented against a common reference “0” within the same block, the influence of numerical magnitudes (small and large) disappeared for the positive number as well. The overall results suggested that the positive numbers (independent of the numerical magnitude) overestimated the duration compared to negative numbers. Such an effect raises a fundamental question as to what is important in number-time interaction -- is it the numerical magnitude (small or large) or the polarity of the number (positive or negative)? We argued that if the numerical magnitudes were an important factor in number-time interactions, independent of the number domain (positive and negative), we would have observed an overestimation of duration for the large numerical magnitude compared to the small numerical magnitude. On the contrary, we did not find magnitude-based overestimation or underestimation of duration. This further indicates that the number-time interaction may not emerge from a common magnitude system but could result from an attentional mechanism. Perhaps the processing of the two number domains (positive and negative) engages attention differently, leading to the differential effect of the number domain on temporal processing. Apart from testing the ATOM’s prediction in a unimodal setting, we also tested the generality of the common magnitude system in a multimodal setup. Chapter 5 examined the cross-modal number-time interaction by presenting the numerical information (task-irrelevant) in the visual domain. The temporal information in the auditory either simultaneously with the duration judgment task (Experiment-5.1), or before the duration judgment task (Experiment-5.2), and before the duration judgment task but with numerical magnitude also being task-relevant (Experiment-5.3). We observed the influence of visual numbers on auditory temporal judgments only when the numerical information was available while making a temporal decision (Experiment-5.1 & 5.3). However, the visual number did not affect temporal judgments when these two pieces of information were temporally separated. In other words, access to the numerical information at the time of temporal judgment is crucial for number-time interaction in the cross-domain setting. Interestingly, experiment 5.3 has raised an important question as to whether the explicit processing of task-irrelevant numerical magnitude dimension is needed for such cognitive interactions to emerge. Our findings in chapter 5 also hinted that it might be possible that the task-irrelevant numerical magnitude is really not task-irrelevant. It might be the case that participants are processing these task-irrelevant numerical magnitude dimensions, and such explicit processing of task-irrelevant magnitude (in our case, numerical magnitude) might induce a magnitude-based shift of attention (Fischer, 2003). Now, supposing that the task-irrelevant magnitude dimensions are processed along with the task-relevant ones, it could also reflect on the resource allocation issues. Differential attentional resource allocation can lead to biases in our temporal judgments across different numerical magnitudes. We have addressed this in chapter 7, where we designed a conjoint task where two task-irrelevant magnitude dimensions (Size and Number) were combined to create Size-Number congruent (large and small) and Size-Number incongruent conditions. We asked participants to judge the duration of these combinations. The idea was to test whether task-irrelevant magnitude dimensions are processed at all or not. If these conjoint magnitude dimensions are explicitly processed, then LargeSize-LargeNumber combinations should be perceived longer than SmallSize-SmallNumber combinations. We have shown that congruent-large task-irrelevant magnitude is perceived to be longer than congruent-small task-irrelevant magnitude. This perhaps indicates that when the two different task-irrelevant magnitude dimensions conjoin in a congruent manner, then only it affects temporal judgments but not when these task-irrelevant magnitude dimensions are combined in an incongruent manner. This clearly suggests that although the Size-Number combinations were task-irrelevant, it was explicitly processed and affected temporal processing in the congruent conditions. Conversely, the same Size-Number combinations did not modulate temporal processing when presented incongruently. This further strengthens our argument that task-irrelevant magnitudes are indeed processed and do influence duration judgments. These results are significant because these are potentially modulated by the control processes and may not reflect the automatic processing of the combined large magnitude or combined small magnitude conditions. Such cross-dimension magnitude (Size and number) conjointly cannot provide a representation of the “large” or “small” sense of magnitude on its own. One needs to process it actively and represent it conceptually as a “long” or “small” magnitude dimension, thereby affecting the processing of task-relevant magnitude dimension (in this case, temporal processing).

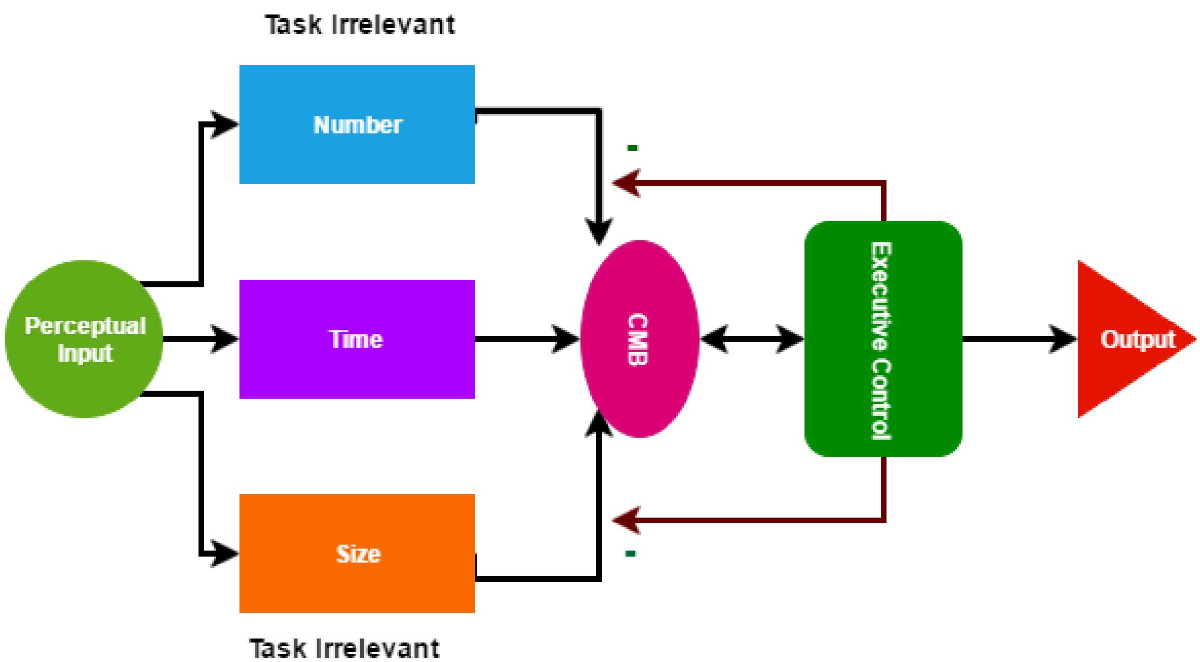

Figure-8.1: Executive Control and ATOM. The schematic presents a conceptual diagram on how various magnitudes arrive at the Common Magnitude Buffer (CMB) where the cross-talk between magnitudes from different stimulus dimensions might take place. The feedback control exerted by the executive control system is hypothesized to be the modulator of cross-dimension magnitude interaction.

Overall, the findings of the present work challenge the traditional notion of modularity and the existence of an ATOM module, suggesting that the processing of different magnitudes, such as time, space, and number, is independent and cross-dimensional magnitude interactions are mediated by cognitive factors. These studies provide evidence that different magnitude dimensions are explicitly processed and can interact with each other, possibly due to resource competition in the brain that is linked to attention and working memory. Resource allocation, which is critical to understanding how the brain processes different magnitudes, is influenced by executive control, which involves inhibiting task-irrelevant processing and focusing on task-relevant dimensions. Executive control plays a critical role in time perception, modulating attentional resources allocated to timing. As a result, executive control processes such as attentional shifting and inhibition (Figure 8.1) can affect the allocation of attention to timing when other task-irrelevant magnitude dimensions, such as numerical magnitude, are present along with the task-relevant dimension. These findings suggest that resource competition and executive control processes may impact number-time interactions. It is also possible that the modalities involved in processing various magnitudes are designed to process more general information to perceive the world coherently. However, space, time, and number experiments generally use psychophysical methods where we manipulate the stimulus level by varying the stimulus intensity. Such inherent variability might invoke both automatic and controlled processing. For example, when the two stimuli are clearly distinct (i.e., 100 vs 500ms), then automaticity comes in and helps us discriminate better (independent of the magnitude). However, discrimination becomes difficult when the two stimulus levels are close (i.e., 500 vs 600ms). In such cases, there is competition in the allocation of attentional resources, which can bias judgments based on the magnitude size (small/large). It is possible that the cross-dimensional magnitude interaction is an artifact of such psychophysical procedures and may not necessarily reflect the true cross-dimensional magnitude interaction.

To summarize, with the help of a series of experiments, we have shown that the cross-dimensional interaction (in this case, number and time) may not be contingent on the common magnitude system as posited by ATOM-framework. Such interactions may emerge from cognitive factors like attention (see the summary in Figure-8.1). The present thesis also raises a fundamental question on the idea of a common magnitude system as to whether the task-irrelevant magnitude dimension is processed and then affects the processing of the task-relevant magnitude dimension, or the mere presence of the task-irrelevant magnitude dimension affects the processing of task-relevant ones. Because if the task-irrelevant magnitude dimension is actively processed and subsequently modulates the processing of the task-relevant magnitude dimension, then it may reflect the problem of resource allocation rather than a common magnitude system. As we have limited mental resources to process upcoming information and when the task-load increases, our performance on a particular task is affected. In fact, this has been observed in the dual-task conditions (Chapter 5). So, the broader question is how much the task-irrelevant dimension is task-irrelevant in cross-dimension magnitude interactions. This needs to be investigated further.

8.1 LIMITATIONS & FUTURE DIRECTIONS

As not all the studies are foolproof, there is always a scope for improvement by improving upon the limitations of the existing studies. We feel that in the present investigation, the potential limitation could be the use of one kind of stimulus. For example, in the entire thesis, we have used only one kind of numerical magnitude (i.e., 1 and 9). Also, we have used only numerals across different sets of studies. Future studies could be conducted using a different kind of number format. For example, instead of numerals, one can also use numerosity (for example, see figure 8.1).

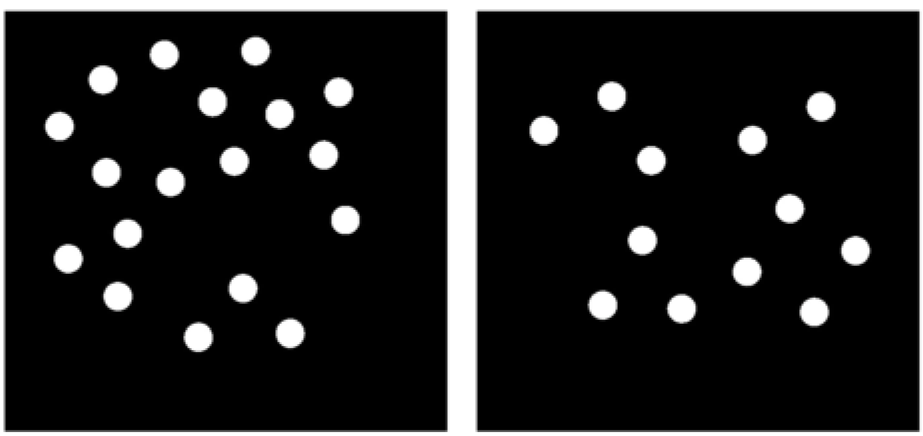

Figure-8.2: Shows an example of numerosity (countable and uncountable number of dots). The left panel shows more numerosity and the right panel represent less numerosity.

Further, another potential limitation could be the use of only one kind of task-irrelevant magnitude dimension (i.e., numbers) and studying its impact on task-relevant magnitude dimension (i.e., duration/time). Future studies can extend to other magnitude dimensions like Size, Brightness, etc. These magnitude dimensions can be used as task-irrelevant magnitude dimensions, and their influence can be studied on task-relevant magnitude dimensions. Although, in Chapter-7, we have tried to include Size (of the enclosing circle) as the third dimension (see Figure. 7.1), but the purpose of such inclusion as a task-irrelevant magnitude dimension was different. For example, we wanted to study the influence of two task-irrelevant magnitudes on temporal processing. In order study this, we combined size and number magnitude to create congruent and incongruent combinations. Therefore, more future investigation is needed to test the influence of different task-irrelevant magnitude dimensions on temporal processing. Apart from stimulus level limitations, the present investigation is also limited to temporal estimation paradigms and predominantly uses temporal bisection and temporal discrimination tasks to study the influence of number on temporal judgments. Although we consciously decided to use only these two paradigms (temporal bisection and temporal discrimination task), we believe that the involvement of motor response might act as a confounding factor (sensory to motor processing) that can directly affect the temporal processing performance. Therefore, future studies should utilize a more diverse paradigm (i.e., temporal generalization, temporal reproduction, verbal estimation) to study number-time interactions. Apart from the common magnitude system posited by the ATOM framework, a more recent model uses a Bayesian account of cross-dimensional magnitude interactions (Cai et al., 2018). The present investigation focuses on testing ATOM's predictions and providing an alternate account for number-time interaction. Therefore, future work should also try to explore Bayesian-based accounts for number-time interactions.

The present investigations are limited to behavioral experiments. Therefore, we could not offer any insights about the neural basis of the current findings. Thus, future studies should design an appropriate experiment that can be ported to various neuroimaging setups such as *Electroencephalogram* (EEG), *Functional magnetic resonance imaging* (fMRI) and *Magnetoencephalography* (MEG). Such an extension would validate the current findings and help us dissociate the brain areas associated with processing numbers and time. Such findings also allow us to generalize the present findings at the brain level and provide strengths against the generalized magnitude system.

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10.0. RELATED PUBLICATIONS

1. **1.** Shukla, A., & Bapi, R. S. (2020). Numerical magnitude affects accuracy but not precision of temporal judgments. *Frontiers in Human Neuroscience*, **14**, 623.
2. **2.** Shukla, A., & Bapi, R. S. (2021). Attention mediates the influence of numerical magnitude on temporal processing. *Scientific reports*, **11**(1), 1-10.
3. **3.** Shukla, A., & Bapi, R. S. (2022). Number-time interaction: Search for a common magnitude system in a cross-modal setting. *Frontiers in Behavioral Neuroscience*, 16, 891311.
4. **4.** Shukla, A., & Bapi, R. S. (2022). Relative Numerical Context Affects Temporal Processing. In *Proceedings of the Annual Meeting of the Cognitive Science Society* (Vol. 44, No. 44).

10.1 RELATED CONFERENCE PRESENTATIONS

1. **1.** Anuj Shukla, Rakesh Sengupta and Bapi Raju Surampudi: Interference in Magnitude domains: differential processing of sub- and supra- second durations in temporal discrimination paradigm, <u>Annual Conference of the Association of Cognitive Science (ACCS) from October 10-12, 2018 at IIT- Guwahati, India</u>
2. **2.** Anuj Shukla, Rakesh Sengupta, Raju S Bapi: Magnitude affects temporal processing in sub-second but not in supra-second time-scale, <u>European Conference on Visual Perception (ECVP)-2018 from August 26–30, 2018 Trieste, Italy</u>
3. **3.** Anuj Shukla, Rakesh Sengupta, Raju S Bapi: Does Congruent/Incongruent Task-Irrelevant Magnitude Information Affect Temporal Processing in Sub- and Supra-Second Duration? <u>(Annual Conference of the Association of Cognitive Science (ACCS) from December 10-12, 2019 at BITS- Goa, India</u>
4. **4.** Anuj Shukla, Raju S Bapi: Number-Time Interaction: Search for a Generalised Magnitude System in a Cross-Modal Setting, <u>43rd European Conference on Visual Perception (ECVP)-2021 from August 22–27, 2021</u>.