SENSORIMOTOR INTERACTION AND TIME PERCEPTION:

AN EMPIRICAL STUDY AND A PHILOSOPHICAL DISCUSSION

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- I am the sole author of this thesis and that I have fully acknowledged and documented in my thesis all sources of ideas and words, including digital resources, which have been produced or published by another person or institution;
- this thesis contains no material that has been submitted or accepted for a degree or diploma in any other educational institution;
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ABSTRACT

Sensorimotor Interaction and Time Perception:

An Empirical Study and a Philosophical Discussion

Time perception is a crucial aspect of experiencing and acting upon the world. This thesis is composed of an empirical part, where the potential interactions between action and visual time perception are studied using psychophysical methodologies and a discussion part, where the results are discussed within a philosophical framework. The general procedure of the experiments includes a comparison between the visuomotor and passive visual observation conditions. The findings show that the perceived durations in the visuomotor conditions are underestimated. It is also demonstrated that the action induces a reduction in the perceived speed. It is claimed that the effects reported here might be modulated in the dorsal route. In fact, it is demonstrated that action-induced duration compression disappears using isoluminant stimuli. This provides further evidence that the locus of these effects should be somewhere, where the neurons are sensitive to luminance-modulation and temporal change. In a final control experiment, it is shown that color discrimination performance is not influenced by the execution of a concurrent motor act, which together implies that attentional factors cannot explain our main results. Broader indication of empirical studies is that the dorsal route has a principle role in the timing of visuomotor sequences. These results support the current philosophical stand that temporal consciousness is both (i) embodied; the body's actions and states have an influence on the perceived time, and (ii) extended; the external information has direct contributions to the perceived time.

ÖZET

Duyu-motor Etkileşim ve Zaman Algısı:

Deneysel Bir Çalışma ve Felsefi Tartışma

Zaman algısı dış dünyayı algılama ve çevreden gelen sinyallere göre eylemde bulunmanın önemli bir unsurudur. Bu tez çalışması, motor hareket ve görsel zaman algısı arasındaki potansiyel etkileşimin psikofizik metodolojilerle çalışıldığı bir deneysel bölüm ile ampirik sonuçların felsefi bir çerçevede ele alındığı bir tartışma bölümü içermektedir. Deneylerin genel prosedürü, görme-motor ve pasif görsel gözlem koşullarının karşılaştırılmasını içermektir. Bulgular öyle göstermektedir ki görme-motor koşullarında algılanan sürede kısalma olmaktadır. Ayrıca eylem, görsel uyaranların algılanan hızlarında da azalmaya neden olmaktadır. Bulunan bu etkilerin dorsal yolakta modüle edildiği öne sürülmektedir. Öyle ki, bir başka deneyde eylemin neden olduğu zamansal kısalmanın eşit lüminanslı uyaranlar kullanıldığında ortadan kalktığını gösterilmektedir. Bu bulgu, bahsedilen etkilerin gerçekleştiği anatomik alanın lüminans karşıtlıkları ve temporal değişime hassas sinir hücrelerinin bulunduğu bir yerde olması gerektiğine dair destekleyici bulgu sunmaktadır. Renk ayrımsama performansının eş zamanlı motor eylemden etkilenmediğini gösteren diğer kontrol deneyi, dikkat faktörlerinin ana sonuçlarımızı açıklayamayacağına işaret etmektedir. Dolayısıyla deneysel çalışmaların genel çıkarımı, dorsal yolağın görme-motor uyaranların zamanlanmasında öncelikli bir rol oynadığıdır. Bu sonuçlar, temporal bilinçliliğin hem (i) somutlaşmış (embodied); bedensel eylemlerin ve durumların algılanan süreye etki etmesi, hem de (ii) genişletilmiş (extended); dışsal bilginin algılanan süreye direkt katkıda bulunması, olduğu tezini desteklemektedir.

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To Uğur,

CHAPTER 1

INTRODUCTION

Many of our daily activities, such as driving a car, riding a bike, reaching a glass of water or playing a ball, require the coordination of the visual and motor systems in our brains. Take a driver for instance, while s/he processes the visual information coming from the road, they also employ certain force to operate gas and brake pedals. These actions, in turn, increase or decrease the car's speed, which consequently change the information coming through the driver's eyes. In this example, we may assume that it is a kind of a fine tuning that takes place in the sensorimotor system. This sensorimotor tuning is affected by both the action of pushing the car pedal and the duration of the push, the two variables which together impact the car's speed and the related visual feedback. How the intensity (i.e. the force employed on the pedal) and the duration for which this force is employed pose a change in the driver's subjective time and speed of the visual events, though, is a question yet to be discovered. The aim of this thesis is to investigate the effect of motor act on the perception of speed and duration in the context of a sensorimotor interaction. Therefore, time perception is the main theme of both the empirical study and the philosophical discussions.

Perception of time lies at the center of our experiences. Processing temporal information is critical for the representation of many features and phenomena, including agents, actions, events and the causal relationships. Due to its central position in the phenomenal experience, time has been the topic of philosophical investigation for centuries. The main foci of these investigations have been diverse with respect to the important questions about *temporal consciousness*. Temporal

consciousness is a term that emphasizes the centrality of time in overall consciousness. The meaning of the term comes from these two statements; (i) our conscious states do occur in time and (ii) time could only be experienced with consciousness. One of the important questions about temporal experience is about the relationship between subjective and objective time. It is an important aspect whether our sense of time is also like a mechanized clock with accurate and reliable mechanisms. Inquiries made to answer this question help us in terms of conceptualizing our temporal experience. A second line of discussion on time consciousness is about the question of whether there is a single or multiple temporal frameworks. Multiple frameworks could refer to either different time scales (millisecond, second, hours, days, seasons, etc.) or different modalities (visual, auditory, motor, etc.). If there is a unity in subjective time, this would possibly require a central timing mechanism which mediates connections carrying sensory and motor information.

Assuming the unity in subjective time, there is another important discussion in philosophy with regards to whether timing is based on internal or external processes. Internal-based timing means that temporal experience is intrinsic and that it first originates in the agent and then mapped onto the outer world. External-based timing, on the other hand, requires certain changes in the external environment to trigger experience of time in the observer. Yet, another group of endeavors on time consciousness is about its causal role. It is true that we have a feeling of time, however, the question is whether it really has a causal role in any process or it is rather *epiphenomenal.* If timing is epiphenomenal, it means that it does not play a role in other processes and it is almost like a byproduct of the brain's processing. Standing a position in answering this question requires an analysis of how time

perception feeds cognition, action, memory, etc. For instance, when we consider millisecond scale, it is possible to attribute a causal role to time perception in action planning and execution. However, one may claim that while timing has a causal role for organisms, time consciousness is epiphenomenal. In order to use time, one does not need to be conscious of it. These are sound claims and direct solution to this debate cannot be given in this thesis study. Because, time perception is empirically studied here with a supposition that it has a causal role and interactions with other processes. Still, this thesis is skeptic about whether being conscious of time is necessary for an organism's functioning.

Our study has the general stand that subjective time is prone to biases and mechanisms which makes it different than an objective clock time. Therefore, we have a general way of answering the first question about temporal consciousness. Similarly, the second question about the unity of subjective time is addressed via a series of experiments we conducted using psychophysical methodologies. We implicitly assume that time consciousness is modality-specific or that there are domain specific modules for interval timing. Parameters and processes involved in this modality specific time perception effects will be discussed in detail in the incoming chapters. Another question that we aim to answer in this thesis study is whether time consciousness is based solely on the internal or external factors. After reviewing the literature on duration perception, there will be a section devoted to the detailed discussion of philosophical questions, the frame of which are given so far.

Before delving into the literature on visual time perception, it is necessary to make it clear that our approach in this study could be classified under the *embodied cognition* approaches. Embodied cognition asserts that cognitive processes in the brain and bodily actions are not separate in terms of functioning and structure. One

way this connection takes place is in the example of sensorimotor processing that underlies many of our actions and perceptions. Sensorimotor account relies on the basic connection between sensory and motor mechanisms. For instance, vision offers significant information to plan and coordinate motor behavior (O'Regan & Noe, 2001). Another related account to sensorimotor view is the Gibson's affordances theory. The word "*affordance*" signifies the possible actions which an object offers. In Gibson's account, objects are directly perceived in the scheme of possible actions through vision. Although some accounts have milder versions of sensorimotor interactions, it is getting more acceptance each day that perception and action are in a constant exchange of information (Noe, 2004; Creem-Regehr & Kunz, 2010)

Embodied perception is a specific term which implies that the goal of perception is to offer organisms with possible actions and costs of these possible actions (Proffitt, 2006). Therefore, the one between perception and action is not a coincidental interaction but rather a one which carries evolutionary utility. Apart from the economy of actions, embodied views are also discussed in terms of concepts and representations. Barsalou (2008) uses the term "*grounded cognition*" in the sense that not only bodily states but also a variety of external stimulations multimodally enable what we call "cognition". Memory, language, perception and aspects of social cognition all follow similar principles of the grounded cognition in which the total experience of the present moment give way to cognitive functions. This total experience includes perception, bodily state, affective state, external conditions, etc. Grounded cognition view is one of the theories which brought attention into the importance of the body in the context of cognition.

With the help of rich literature on embodied and sensorimotor mechanisms in perception and cognition, it is logical to expect a certain interaction between

perceived time and our actions. One way this interaction could be working is by actions' potential to change the visual properties that we perceive, such as body action impacting the perception of motion and speed. In general, there is a strong statistical regularity between action and vision. For instance, optic flow information changes as the body or head moves, therefore creates a route which enables to pick regularities in one domain to the other. Similarly, perception of limbs feeds information for the successful employment of actions. The aim of this study is to look at whether the interaction between visual perception and action is also reflected in the perception of time. However, to give you the scientific background of the paradigm and methods we used here, I will first provide a brief summary of the visual time perception literature. Then, I will combine it with the literature that supports the possible sensorimotor effects on duration perception.

1.1 Motion and visual time perception

It is known that the subjective duration of a visual stimulus is directly influenced by the motion signal it carries. A moving stimulus, for example, is perceived to be longer than a steady stimulus which has the same physical duration (Brown, 1995; Kanai, Paffen, Hogendoorn, & Verstraten, 2006). To better express these deviations in time perception, perceived duration is also called as subjective or apparent duration. Apart from the mere existence of motion, speed or temporal frequency may also have an impact on perceived duration. It has been found that from two visual stimuli which have equal durations, the one with a higher temporal frequency is perceived to be longer than the one with a lower temporal frequency (Kanai, et. al., 2006). Kanai, et al. (2006) proposed that it is the number of changes that influence the subjective duration of a visual event. This view claims that changes are treated as

time markers by the brain and since faster stimuli includes more changes, they are also perceived as longer in duration (Kanai, et al., 2006). To test this view, Kaneko and Murakami (2009) conducted a study in which they systematically measured participants' duration judgments as a function of different speeds, temporal frequencies and spatial frequencies. Their results have shown that it is speed rather than temporal- or spatial frequency of the stimuli that has stronger influence on perceived duration, which contradicts the Kanai et al. (2006)'s change-based model. Despite the discussions on which feature impacts duration perception more significantly, all scholars above would agree on that transient signals might be the *modulators* of duration perception. *Transient* in this sense underlies the temporality of external input, so examples to transient signals are motion, speed, acceleration or temporal frequency of external objects.

In physics, the derivative of velocity is acceleration. Recently, Bruno, Ayhan & Johnston (2015) investigated the impacts of acceleration on apparent duration using a grating-stimuli set. The researchers compared the perceived duration of accelerating and decelerating visual stimuli to that of those with constant velocity. Their results showed that the linear increase of speed decreases the perceived duration by 30%, whereas the linear decrease of speed shows the opposite trend, although with a smaller effect size (Bruno, Ayhan, & Johnston, 2015). Bruno, et al. (2015) have also found that the impact of the change rate of the speed on subjective duration is directly proportional to the range of speed, which together demonstrate that there might be an interaction between the mechanisms underlying speed and duration perception.

Another facet of Bruno, Ayhan & Johnston (2015)'s study is that they have used accelerating and decelerating stimuli with the same average speed. Therefore,

they have challenged Kanai et al. (2006)'s account of number of changes view by using stimuli with the same number of changes (i.e. average speed) yet with different speed profiles. Their results have shown that it is not the number of changes in the external stimulus that affects the visual system's detection of duration. There is an alternative view that duration perception of visual events is related to the changes in the temporal impulse function of magnocellular cells (Johnston, 2010). This view is also called "*predict and compare*" model and assumes that when the prediction of the visual system regarding an interval is matched with the current sensory signal, a tick is generated in the accumulator. So, any deviation in time perception in this system would be due to the accumulation of the effects of phase-shifts in the temporal impulse function of magnocellular cells. Because magnocellular cells do function with band-pass filters (processing certain frequencies and disregarding other range of frequencies), they are suggested as a candidate to enable forward predictions. For instance, when the prediction in the magnocellular signal does not match the current signal in the parvocellular track due to a phase advance, the accumulator creates fewer ticks, therefore triggers a perceptual temporal compression (Johnston, 2010). Magnocellular cells are also known to process motion information and send information to dorsal pathway (Maunsell, Nealey, & DePriest, 1990). Therefore, this view has a potential to answer motion-related changes in duration perception.

To understand how vision may have specific interactive mechanisms with duration perception, temporal modulations due to spatial adaptation need to be mentioned. Johnston, Arnold, and Nishida (2006) have implemented a study, where they asked participants to compare the duration of two sequentially presented stimuli in a temporally adapted vs. non-adapted sides of the visual field. They have shown

that after a long-term adaptation in one region of the visual field, the subjective duration of a stimulus presented sequentially in that part of the visual field is compressed. Interestingly, adaptation to a dynamic 10-Hz stimulus did only induce very small changes in perceived temporal frequency, whereas duration compression affect was still present (Johnston, Arnold, & Nishida, 2006). This shows that it is possible to differentiate mechanisms for perceiving visual change (temporal frequency) and duration.

1.2 Visual time perception and motor mechanisms

As well as the effect of speed of visual stimuli as summarized above, the impact of motor mechanisms is also an important one in subjective timing. Two important aspects with regards to the interaction between the motor and the timing systems are that (i) actions themselves have temporal properties and that (ii) actions depend on perceptual fluctuations. Because of this interaction, there has been an intensive debate in the field as to whether motor- and perceptual timing carry similarities. Treisman, Faulkner and Naish (1992), for example, have claimed that similar information and mechanisms are at the service of judging time and controlling motor action as actions have motor programs based on temporal interactions.

The general inquiry about the relationship between motor action and time perception went even further. If the two carry commonalities, it has been hypothesized that there must be anatomical indications as well as the behavioral evidence. In this context, Ivry (1996) has investigated brain structures which may underlie such interaction between perceptual and motor timing. Cerebellum and the basal ganglia were found to be the two structures which are thought to have a role in timing. For instance, it is known that cerebellar lesions end up with inappropriate

timing both in muscle movements and perceptual tasks. Damage to the basal ganglia, on the other hand, results in the underestimation of time and impaired motor movements as in Parkinson's disease. Thus, Ivry (1996), has concluded from these findings that motor and perceptual timing might be dependent on similar brain structures. It is important to note that damage to basal ganglia do show systematic impairments in timing mostly in supra-second and sub-second levels but not in longer scales (Riesen & Schnider, 2001). This indicates that timing abilities which have interactions with motor actions are short-scale timing abilities rather than minutes or hours.

Schubotz, Friederici, & Cramen (2000) have also investigated organizational overlaps between perceptual and motor timing by using functional MRI. They have found that some parts of the dorsal premotor cortex (PMC) are responsible for both time perception and also temporal planning and timing actions.

There are not only studies of brain functioning which let us corroborate on the impacts of action on time judgments. Carlini and French (2014), for instance conducted an interesting experiment, where they looked at the effects of motor action during a time-judgment task. Stimulus in the task was a gray disk which moves from the bottom of the screen to the top in a vertical trajectory. In this task, in one condition, the researchers asked participants to track the position of a visual stimulus by pointing with a hand, whereas in the other condition, participants only made visual observations. They then reproduced the duration of stimulus by pressing a button in each trial. Carlini and French (2014) found that motor action (pursuit by pointing) improved the time reproduction performance, on the basis of which they concluded that action models may be used to calibrate the time perception of visual

motion. Similarly, here, we also compare the performance in the visuomotor sequences to the pure visual sequences.

One seminal theory on the visual processing in the brain is the "two-pathway" theory, which asserts that information coming from the primary visual cortex (V1) is processed through two main channels; namely, dorsal and ventral pathways (Ungerleider, Mishkin, & Macko, 1991; Milner & Goodale, 1995). In Ungerleider and Mishkin (1983)'s initial work, they have called these routes as "*where*" and "*what*" pathways. They associated the function of the dorsal pathway with the question of *where objects are in space*, and that of the the ventral pathway with the question of *what objects are*. However, Milner and Goodale (1995) have shown that "where" and "what" classification does not convey the exact mechanisms of the dorsal and the ventral pathways. They have rather called the dorsal pathway as "how" pathway and emphasized its connection with action perception. Dorsal pathway is a connection route in which the transient features are processed. It is known that speed information, which is processed in the relevant areas of the visual cortex such as primary visual cortex and the area MT+ is also known to be conducted towards higher level parietal lobe areas through this route (Liu & Newsome, 2005).

Recent studies on the two-pathway theory has led to certain changes since Milner and Goodale (1995) introduced their original idea. Rizolatti and Matelli (2003) for instance, have recently claimed that the dorsal pathway proceeds functionally and structurally through two separate pathways. According to their view, dorsal pathway consists of ventro-dorsal (v-d) and dorso-dorsal (d-d) routes. Whereas the d-d route is proposed to be related to the control of actions, v-d route includes the area MT+ and is claimed to be responsible for the action perception and action planning. The implication of this is that there might be a special route in the

visual pathway which underlies the sensorimotor interaction. Rizzolatti and Matelli (2003)'s proposal is also in line with the aforementioned sensorimotor accounts (O'Regan & Noe, 2003; Gibson, 1978). Remember that according to sensorimotor approaches, the processes that are involved in perception and action processing are not mutually exclusive but rather in constant, complex information exchange. Thus, it might be the case that the ventro-dorsal path is the route, where this information exchange takes place via a mechanism integrating action and perception.

As it is explained above, there are reasons to expect that V5/MT+ has a role in temporal processing. In 2008, Bueti, Bahrami and Walsh conducted a study in which they applied TMS over either the area MT+ or the right intraparietal cortex (IPC), while participants performed a temporal discrimination task with subsecond range visual stimuli. They found that, when TMS is used on the area MT+/V5 or on the right IPC, discrimination thresholds were higher, in other words, the task was perceived as being harder. These results imply that the area MT+/V5 is important for the temporal vision, as well as the spatial vision. Significance of the area MT+ on time perception has philosophical implications as well. If motion and spatial changes are quite central in our perception of short intervals, we could claim that we base our time judgments on the external changes. We will discuss this aspect further in the philosophical discussion section.

In summary, there has been accumulating evidence that the brain areas associated with perceiving motion parameters (direction, speed, acceleration) of visual stimuli overlap with those that are involved in creating action plans. The aim of this psychophysical study is to further elaborate on this issue and specifically investigate the impacts of motor action on speed and duration perception in humans.

1.3 Internal clock theory

Internal Clock Theory has a significant importance in the history of time perception studies. It is the most influential account in the literature in terms of scope and explanatory power. The theory claims that the brain has three main structures for the purpose of keeping time. In the Treisman (1963)'s original account, these components are a pacemaker, a counter and a comparator. The pacemaker works like a metronome and produces pulses in the system. The outputs of the pacemaker are then sent to a counter, which keeps the number and the rate of these pulses. Information from the counter is finally conveyed to the comparator, where the final decision is made for a response. Beyond the basic components of the clock mechanism, there are also factors contributing to the functioning of a component. Treisman (1963) and later scientists who developed the theory always granted that arousal has an impact on pacemaker by reducing or increasing the rate of ticks.

Internal Clock views rely on the metaphor of a single clock mechanism which keeps track of the subjective time. However, in the updated versions of the theory, this has been specifically challenged. Treisman (1984) himself has offered the possibility of multiple oscillators and suggested that similar-frequency-oscillators might create connections in a coordinated manner. In fact, this has been supported by the brain imaging data provided by his group that characteristic frequency of the oscillator overlaps with deviated duration judgments. (Treisman, Faulkner, Naish, & Brogan, 1990). Hence, this theory should not be considered as simply offering a single internal clock in its dictionary meaning. Rather, it signifies a model to explain how the brain might be keeping time. In fact, until now, not a single part of brain has been found to be responsible for subjective timing. Accumulating evidence in the field of interval timing allows us to assert that patterns of neuronal activity which is

wide spread in different parts of the brain collaboratively enable the marking of time (Buhusi & Meck, 2005).

1.4 Timing effects of voluntary action

Humans have a strong sense of ownership of their actions. This *sense of agency* necessitates the feeling that they control the planning and execution of actions. Therefore, empirical studies which focus on motor action in humans generally look at the voluntary and intentional action unless they employ a specific method to deter the feeling of volition. In fact, in our daily lives, when there is a motor movement without a felt volition, we might say there is either a twitch, a serious physiological problem or an exerted control by an external force.

Leaving aside the deep discussions on whether there is a free will or not, here, we will only mention how the felt intentionality has an impact on time experience. In a seminal study conducted by Haggard (2005), it has been shown that the duration between the action (i.e. key press) and the following sensory feedback (i.e. auditory tone) is compressed compared to the actual physical interval between the two. This result has been interpreted by Haggard such that participants thought that they caused the sensory event and therefore perceived them as closer to their action in the timeline. In fact, in a follow-up experiment, when TMS was used to get fingers of participants move involuntarily by causing a twitch, this time compression effect has been reported to disappear (Haggard, 2005). The term "*intentional binding*" was coined by Haggard to refer to this compression effect and also to underlie the connection between actions and external changes due to underlying intentionality (Haggard, Clark, & Kalogeras, 2002).

There is a body of studies that replicated the intentional binding results, which together demonstrate that having the sense of intentional action has an influence on perceived time (Buehner & Humphreys, 2009; Cravo, Claessens, & Baldo, 2009; Desantis, Roussel, & Waszak, 2011). Importantly, in our current experiments, we investigate the interaction between voluntary action and perceived duration of visual stimuli. Since the participants were allowed to act at their own will in our study, they had the feeling of *intentional action*. So, the agential control of action was preserved. Note that this is not to say that this work aims at shedding light on the mechanisms of intentionality, though. The reason why we used voluntary action in our paradigm was rather to study temporal experience in the presence of the sense of agency and voluntary control of actions.

1.5 Motivation and summary of the experiments

The aim of the present empirical studies was to reveal any potential influence of motor action on visual time perception. Therefore, time judgments of visuomotor sequences which had concurrent motor action and visual stimulus were compared to passively observed visual sequences in both duration reproduction- and duration discrimination methodologies. Results demonstrated, for the first time in literature (as we are aware of), that concurrently executed motor actions trigger a compression in the subjective duration of visual events while performing a visual duration judgment task. In a series of further experiments, it has also been provided the limits and possible mediating factors of this effect.

The apparent duration of a moving stimulus increases with speed for low to mid-range velocities (Kaneko & Murakami 2009). Relatedly, some temporal effects such as the long-term adaptation induced duration compression has been shown to

disappear when the apparent speed of the two test stimuli are matched (Burr, Tozzi, & Morrone 2007). In order to separate out the potential effects of motor action on perceived duration and speed, here, we first conducted a control experiment to quantify the changes in perceived speed during the execution of a visuomotor task and then measured the duration judgments after having individually matched the subjective speeds of the two stimuli, the visuomotor- and the pure visual sequences. The results still indicated a duration compression effect, which implies that the effect we demonstrate here is not an indirect consequence of the changes in perceived speed, but rather a specific influence on timing mechanisms.

Alertness (Treisman, Faulkner, Naish, & Brogan, 1990; Wearden & Penton-Voak, 1995) and attention (Rose & Summers, 1995; Tse, Intriligator, Rivest, & Cavanagh, 2004) are the known factors that modulate our time perception. The main finding that came out of these studies is that when a participant gives full attention to a temporal task, the perceived duration gets expanded, whereas concurrently conducted secondary tasks draws some of the attentional resources that would be dedicated to the temporal task otherwise and lead to subjective compression of time. In our paradigm, one could claim that for the sequences, where participants executed a motor act while observing the visual stimulus, some of the attentional resources were drawn from the temporality. In a control experiment, however, we demonstrated that color discrimination performance is preserved even while executing a concurrent motor act, which implies that attentional factors might not be the potential explanations of our main results.

A growing body of evidence suggests that chromatic and achromatic luminance signals are carried in separate pathways in the visual system (De Valois, Abramov, & Jacobs, 1966; De Valois, Cottaris, Elfar, Mahon, & Wilson, 2000;

Derrington, Krauskopf, & Lennie, 1984; Hubel & Wiesel, 1966). In a final experiment, we used isoluminant background and stimuli in the same visuomotor duration judgment paradigm and found that motor action dependent duration compression disappears with the equiluminant setup. This experiment excludes all possible explanations with regards to memory getting involved in the tasks we conducted here, as the same memory effects would have been expected to be observed with the isoluminant stimuli.

In sum, the results fit well to the relevant literature, where the dorsal route is suggested to play the principle role in the interaction of visual and motor areas. We propose that this dorsal route might also be involved in the domain-specific timing of visuomotor events.

CHAPTER 2

GENERAL METHODOLOGY

2.1 Participants

Two of the participants were the authors of this thesis and her supervisor. The rest of the participants were naïve observers who were graduate and undergraduate students at Boğaziçi University. In Experiment 1, five of the participants were recruited by posting adverts on the Psychology Department's board, who received 2 course credits in exchange of their participation. Others attended the experiments on a voluntary basis without a compensation or an award. Nine observers (DO and 8 naïve observers) participated in the duration reproduction (Experiment 1) experiment. Thirteen observers (DO, IA and eleven naïve observers) participated in the experiments on perceived duration (Experiment 2A) and perceived speed (Experiment 2B). Ten observers (DO, IA and eight naïve observers) participated in the perceived duration with matched speed (Experiment 2C) experiment. Six participants (IA and five naïve observers) participated in the perceived color (Experiment 3), perceived duration with isoluminant stimuli (Experiment 4A) and perceived speed with isoluminant stimuli (Experiment 4B) experiments. The study was compliant with the university research ethics requirements (i.e. approved by Boğaziçi University Social Sciences Institute Ethics Coordinating Committee). All participants read and signed the consent form and agreed to participate in the study. The names of participants were only mentioned on the consent forms and the experimental data were kept in a separate folder with initials of the participants. Those who completed the experiments had either normal or corrected-to-normal (i.e. glasses or contact lenses) vision. Apart from the consent form, verbal instructions

were given before the start of experiments. These instructions were in Turkish since all participants spoke Turkish as their native language.

2.2 Stimuli and apparatus

In all experiments, stimuli were presented on a CRT Monitor (Samsung Syncmaster 753 DF with a refresh rate of 100 Hz and pixel resolutions of 1024 x 768). For the execution of the experimental tasks, MATLAB software was used on an iMac Retina 4K Late 2015 computer. The control of the visual stimuli in the study was executed with a function coded on PsychToolBox, MATLAB (Brainard & Vision, 1997). Responses were made using Apple Keyboard. To avoid observers using auditory signals (i.e. sound of a key press) participants wore sound absorber earbuds while performing the experimental tasks.

Visual stimuli in the experiment is commonly called as *circular dot presentation*, which consists of little dots spreading from the center to the periphery of the visual field in an expanding manner. This type of stimuli is intensively used in the field to model the optic flow on the retina of a moving person (i.e. walking or driving). The idea of optic flow was mentioned by Gibson (1950) to explain motion parameters in the optic array in relation to the organism's movement in the environment. Later on, the first mathematical calculations for optic flow were given by Lucas and Kanade (1981). In general, optic flow stimuli contain a central focus point and image elements moving outwards for forward motion models and inwards for the backward motion. In the experiments, though, we have used dots moving linearly towards the periphery to model a forward motion which is a more intuitive action in natural environments. Dot speeds were also not assigned a gradient to

simulate optic flow but rather kept the same to prevent speed gradient having an additional effect on subjective time.

The radius of dots was kept at approximately 0.5 degrees of visual angle and in each frame of the animation, there were 2000 dots. They were presented on a grey background with a central fixation spot where subjects were informed to fixate throughout the experiment sessions. Dots in the array were hueless and were produced in grayscale except for Experiment 3, where green-to-blue isoluminant chromatic dots were used and Experiment 4, where an isoluminant grey and a blue hue were used.

In Experiments 1 and 2B, the speed of the circular dots either linearly increased from 1°/sec to 9°/sec (acceleration condition) or decreased from 9°/sec to 1°/sec (deceleration condition). In a control condition, we also tested participants, where the speed of dots was kept constant at 5°/sec. In the following experiments, (Experiments 2A, 2C, 3, 4A and 4B), the speed was always kept at 5°/sec.

2.3 Procedure

Before the beginning of each experimental session, participants received verbal and written instructions and signed a consent form to ensure their voluntary participation. Experiments were designed using visual psychophysical methodologies. All participants were tested in the same set-up, in front of a computer screen in a dark, quiet cubicle in Vision Lab at Boğaziçi University. To make the viewing distance (approximately 57 cm) fixed across conditions and participants, a chinrest was used. This was critical to standardize the parameters (i.e. the speed and size of the dots) of the stimuli and to avoid artifacts due to the head movements of the participants.

The main procedures we used were either the duration reproduction (Experiment 1) or the two-alternative forced choice (2AFC). The duration reproduction methodology consists of a stimulus presentation and a reproduction period, which involves a certain action to indicate the duration of a stimulus with a continuous action. In our experiment, we asked participants to reproduce an interval by pressing the space key and holding it down. In the duration discrimination methodology, on the other hand, there are two consecutive visual stimuli with a temporal gap between them, and participants are asked to respond by indicating which one seemed to last longer. Whereas the standard stimulus is presented for the same duration across trials, the comparison stimulus varies in duration to allow a psychophysical function fit. Similarly, in the speed discrimination methodology, two consecutive visual stimuli were judged in terms of their subjective speed.

In the experiments, each experimental session took around 15 to 20 minutes. After each session, participants were allowed to give a short break. A typical participant was tested for approximately 6-hours on average, where within-subject data was collected for the main and the following control experiments.

2.4 Data analysis

Except for Experiment 1, we used a 2AFC paradigm. Thus, the data analysis was based on the psychometric function plots for each condition and each participant, separately. Calculations in the data analysis were executed using MATLAB. First, the individual psychophysical data were modelled using a General Linear Model (GLM) to derive the Point of Subjective Equality (PSE) values. In the duration discrimination experiments (Experiment 2A, 2C, 4A, and 4B), comparison durations were produced by participants and took variable durations ranging from 0 ms to 1500

ms. These values were binned into 5 groups of similar-range stimuli levels. In the x axes of psychometric functions were these 5 binned duration levels. The y axes indicated the proportion of comparison stimulus perceived as longer responses. After the individual functions for the visuomotor and the pure visual conditions have been plotted for each condition separately, %50 value on the y axes were taken as the PSE values. These individual PSE values were then averaged and used for the statistical analyses. Paired-samples t-test analysis was run to test if PSEs for the two different conditions differ significantly. Statistical analyses were run in the SPSS program. In experiment 1, production and reproduction data were taken as the source of analysis. Their difference was treated as the amount of compression or dilation. These difference values were then compared using a repeated-measures analysis of variance (ANOVA) by using SPSS statistics program.

CHAPTER 3

EXPERIMENTS

3.1 Experiment 1: Visuomotor duration reproduction paradigm using arrays with accelerating, decelerating or constant speed dots

Using a behavioral paradigm, Bruno, et al. (2015) showed that for acceleration, progressively increasing the speed of a visual stimulus decrease the perceived duration, whereas decelerating stimuli trigger only a mild expansion effect. Neurophysiological evidence indicates that these types of speed context effects are processed in the motion area MT+ (Schlack, Krekelberg, & Albright, 2007), which is also known to be a component of the dorsal *how* pathway, where the visuomotor interaction takes place in the brain (Milner & Goodale, 1995). In this experiment, using psychophysical methodologies, we aimed at studying the effects of motor action on the perceived duration of visual stimuli with different speed profiles (accelerating, decelerating, stable). The method of duration reproduction was used as an indicator of participants' perceived duration judgments (For the experimental procedure, see Figure 1). Reproduction performances in the visuomotor and passive visual conditions were then compared to acquire the effects of motor action on subjective duration.

3.1.1 Visuomotor conditions

The visual stimulus in the first experiment was a 2D circular array of dots (light grey, X cd/m^2), moving from center to the periphery in a fixed annular patch ($radius_{inner\ circular\ aperture}$ = 15 deg, $radius_{outer\ annulus}$ = 1 deg) on a gray background (40.95 cd/m^2). The array was composed of 2000 dots with limited lifetimes (%5 of dots were killed

in each frame); thus, for any specific dot disappearing from the screen, there was one appearing at a random position so that the density remained relatively constant. Limited-lifetime-dots prevented any afterimages following the visual presentation. In 3 different speed conditions, dots moved linearly either in an accelerating (from 9°/sec to 1°/sec), decelerating (from 1°/sec to 9°/sec) or at a constant speed (5°/sec) profiles.

In the visuomotor condition, participants were first asked to produce a visual stimulus (circular array of moving dots) by pressing the space bar of a keyboard at an intended onset and holding it as pressed for a brief interval (from 0 to 1500 ms, varied in each trial) while dots kept moving. If a participant pressed the button for longer than 1500 ms, they were presented with a warning message that the interval had been too long and were asked to try it over. Following a successful stimulus production, where participant pulled their finger from the key at the end of an interval within the specified range, they were then asked to press the same space bar for as long as they thought the visual stimulus (that they had just observed) lasted on the screen. During this reproduction phase, they were visually presented with a blank screen. There were 200 trials in each speed conditions, making a total of 600 trials per participant. Order of the sessions were randomized across participants. Note that because participants initiate the next trial on an intended moment, sessions in this condition were all self-paced. A typical average session, though, seemed to take around 15 minutes.

3.1.2 Passive visual observation conditions

Performances in the passive visual observation conditions served as baselines for the visuomotor conditions in Experiment 1. Here, in a standard duration reproduction

paradigm, participants first made passive visual observations of the stimuli they produced in the visuomotor condition and then reproduced their subjective duration of these intervals by pressing the space bar in a similar manner described above. Note that the paradigm we used here was slightly different than the traditional duration reproduction approaches, where participants are presented with a series of constant stimuli and asked to reproduce their felt durations. Unlike the traditional approaches, in our paradigm, participants were both the producers and reproducers of the intervals. Thus, the intervals were all different in each trial across blocks.

The same stimuli, produced by the participant in the visuomotor condition were presented in a randomized order in the passive viewing condition. Following the reproduction phase, the next stimulus appeared on the screen after a second-long wait. Passive visual observation conditions were conducted for all 3 speed regimes (accelerating, decelerating, stable) included in the visuomotor conditions. Each block took around 15 minutes to complete.

3.1.3 Results of Experiment 1

Firstly, we analyzed each participant's data individually. This analysis included the calculation of differences between the reproduced durations and their corresponding physical values. This difference metric was an index of the change (compression or expansion) in apparent durations. Reproduced durations with 3 standard deviations far from their actual values were tagged as outliers and not included in the analyses. The means of these difference values were then compared across 6 different conditions (acceleration x visuomotor, acceleration x visual, deceleration x visuomotor, deceleration x visual, constant x visuomotor, constant x visual) by plotting graphs.

In order to assess the duration judgments in relation to different speed profiles (1- 9°/sec accelerating, 9-1°/sec decelerating and constant at 5°/sec) and motor control (visuomotor and passive visual) conditions, a repeated-measures ANOVA was executed. Here, the aim was to assess the factors (i.e. speed type, task type or their interaction) having an impact on perceived duration. The analysis procedures included Bonferroni corrections and assumption checks, as well as the main tests. It was found that the main effect of speed change on duration reproduction is significant, $F(2,7) = 15.034$, $p = .003$, $\eta_p^2 = .811$. As shown in Figure 2 (see Appendix), pairwise comparisons showed that the duration of accelerating stimuli is perceived significantly shorter than decelerating and constant speed stimuli ($p=.003$, $p=.001$ respectively).

The second independent variable, motor control, was also found to have a significant effect on duration judgments, $F(1,8) = 25.539$, $p = .000$, $\eta_p^2 = .761$ (see Figure 3, Appendix). This indicates that motor act causes a compression in the perception of duration.

Results have shown that both speed profile and motor control have significant main effects on duration reproduction task. Although there are significant effects of speed change and motor control, no interaction effect has been found as significant $F(2,7) = .042$, $p > .05$, which may indicate that the two variables (speed change and motor control) might impact duration perception via different mechanisms.

3.2 Experiment 2A: Visuomotor duration judgments in a 2AFC paradigm

In the previous experiment, the act of pressing the key was used for both the stimulus presentation and the duration reproduction. Since the same action was executed for both, motor memory could have brought an impact within the context of sequential

action repetition. In fact, when we checked the correlations between the physical veridical values of the produced and the reproduced durations in the visuomotor and the passive visual observation blocks individually in Experiment 1, we found that the correlations are higher in the visuomotor conditions than those in the pure visual blocks (see Appendix, Figure 4), indicating a potential motor memory boost. Thus, here, in Experiment 2, we investigated the effect of motor act on the perception of temporal features using a 2AFC task, where the reporting phase of the experiment did not require a reproduction by motor action. Thirteen students from Boğaziçi University participated in this experiment. Experimental procedure and stimuli can be seen in Figure 5 (see Appendix).

3.2.1 Visuomotor conditions

Here, stimuli were almost the same as in the previous experiment. In Experiment 1, participants were asked to reproduce the duration of the stimulus they produced during the production phase. In Experiment 2A, though, we rather used a 2-AFC paradigm, where participants made duration judgments between two sequentially presented visual stimuli and reported which they thought lasted longer on the screen (i.e. the former or the latter) by using left and right arrows on a keyboard. The first visual stimulus (0-1500 ms), produced by pressing the space bar by participants, was an array of circular dots moving at a constant speed (5°/sec) along linear trajectories elongating from the center to the periphery of an annulus. After 1 second the participant stopped pressing the button and the first visual stimulus disappeared, a similar standard stimulus (dot speed of 5°/sec), this time observed passively, was presented centrally for a fixed duration of 750 ms. Following the presentation of the stimuli, the participant indicated which of these stimuli were longer in duration by

pressing left (first stimuli) or right (second stimuli) arrows. The next trial was initiated by the participant by pressing the space bar. There were 200 trials in each condition and each session took around 20 minutes.

3.2.2 Passive visual observation conditions

Data from the passive visual observation conditions were used as baseline values for each subject individually. Observers were presented with the same stimuli they produced in visuomotor condition as comparison stimuli, but here, distinctively, no action was executed during the stimulus presentation phase. They were then asked to make duration judgments between the two stimuli (a comparison and the standard) presented with an inter-stimulus interval of 1 sec.

In the visuomotor condition of Experiment 2A, actively produced comparison stimulus would always come before the visually presented standard. Temporal order in a sequence, though, is known to influence perceived duration (Jamieson & Petrusic, 1975). In order to control for temporal order effects, the comparison (with variable durations across trials) was always presented as the first stimulus in sequence in the passive visual observation condition, as well as in the visuomotor condition, so any effect caused by the ordering would cancel each other out.

3.2.3 Results of Experiment 2A

Since this was a 2AFC task, responses made for each stimulus level were plotted on a psychometric function and PSE values were obtained. Then, in order to make a comparison between the perceived durations in visuomotor and passive visual observation conditions, a paired-samples t-test was conducted. The results indicated that there was a significant difference between the visuomotor (M = 940.6, SD =

83.8) and passive visual (M = 862.8, SD = 71.13) conditions; t(12) = 6.705 , p = .000, d = 1.86. Higher PSE values indicate that visuomotor comparison sequence had to be longer (for about 190 ms) to be perceived as equal to the passive visual standard stimulus of 750 ms. Hence, the original duration compression effect we found in Experiment 1 was also observed in a 2-AFC paradigm here, which implies that perceived duration of visuomotor sequences is shorter than pure visual sequences.

Steepness of a psychometric function is an indicator of a task's difficulty. Harder tasks are expected to yield shallower slopes since it means that larger differences in stimulus intensity are required for discrimination. In order to check whether high PSEs observed in the visuomotor condition is due to task difficulty, we conducted a paired-samples t-test between the steepness values in two conditions. Results showed that visuomotor (M = 156.5, SD = 35.1) and pure visual conditions (M = 164.03, SD = 54.1) did not differ significantly in steepness of psychometric functions; t(12) = -0.549 , p > .05, which provides evidence for a true experimental effect.

In both Experiment 1 and Experiment 2A, participants produced visual stimuli with their own action, therefore they had the control over the duration range they were presented with. Therefore, it was important to check if the mean or the standard deviation of the produced durations were correlated with the magnitude of the duration compression effect; which would indicate a response bias rather than a genuine visuomotor effect. As shown in Figure 6 (see Appendix), however, the mean and the SD of produced durations were not correlated with duration compression neither in Experiment 1 (r = .018; r = .054) nor in Experiment 2A (r = -.11, r = .53).

As we have summarized in Chapter 1, visual duration perception is highly influenced by the perceived speed. Thus, to rule out any potential effect of changes in subjective speed during action execution, we implemented the similar procedure we used here into a speed judgment task as a next step.

3.3 Experiment 2B: Visuomotor speed judgments in a 2AFC paradigm

Temporal change (Kanai et al., 2006) and speed (Kaneko & Murakami, 2009) are known to influence the perceived duration of visual stimuli. To understand if the concurrent motor action has any impact on the perceived speed, as well as the perceived duration in our paradigm, we have implemented a speed discrimination task with the same stimuli set we used above. The same 13 participants who had attended to Experiment 2A also took part in Experiment 2B. Task and procedure are shown in Figure 7 (see Appendix). In both the visuomotor and the pure visual conditions, the speed of the comparison stimulus took a random value between 1°/sec - 9°/sec across trials, while the speed of the standard stimulus was kept constant at 5 °/sec.

3.3.1 Visuomotor conditions

Similar to the experimental paradigm of Experiment 2A, trials in this condition also started with the execution of a key press by the participant, which triggered the presentation of an array of circular dots moving at a speed randomly assigned from a specified range (1°/sec - 9°/sec). Visual stimulus being contingent upon the key press, the comparison stimulus disappeared as soon as the participant stopped pressing the space bar. After a 1 second interval, the second stimulus (standard stimulus), which had a fixed speed (5°/sec) across trials appeared on the screen. The

duration of the standard stimulus was equal to that of the comparison stimulus the participant produced at that specific trial (between 0-1500 ms). At the end of the stimulus presentation phase, subjects had to respond which stimulus seemed to be faster by pressing either left (first one was faster) or right arrow (second one was faster) key. Following the response, the participant initiated the next trial by pressing a button. A session of this task took around 20 minutes.

3.3.2 Passive visual observation conditions

In this condition, each participant was presented with the same stimuli they were presented with in Experiment 2A, except that they passively observed the stimuli during the stimulus presentation phase. They then indicated which stimulus seemed to move faster by pressing arrow keys on a keyboard.

3.3.3 Results of Experiment 2B

Here, to analyze the results, data points had to be binned first. Since speeds in the comparison stimuli ranged from 1°/sec to 9°/sec, speed values were grouped into 5 categories of stimuli levels with equally spaced intervals. We plotted psychometric functions using these 5 speed groups on the x-axes and proportion of faster responses for the comparison stimuli on the y-axes individually for each condition. After the psychometric functions of the visuomotor and pure visual conditions were plotted, %50 values on the y-axis were taken as the PSE values. Individual PSE values of the participants were then used for the statistical analyses. A paired-samples t-test was run to test if the PSEs for the visuomotor and the pure visual conditions differed significantly. The result of the analysis showed that the perceived speed in the visuomotor condition ($M = 5.79$, $SD = .534$) was less than that in the pure visual (M

= 5.23, SD = .417) condition; t(12) = 4.533 , p = .001, d = 1.26. It is plausible to deduce from these results that motor action has a way of interacting with the perceived speed, as well as the perceived duration. However, the result of this experiment is not enough to conclude that the duration effects we observed in Experiment 2A are mediated by the alterations in perceived speed during action execution as it might be that motor action has differential impacts on speed and duration perceptions, separately.

3.4 Experiment 2C: Visuomotor duration comparison with matched speed stimuli

From a series of studies that investigated the long-term temporal adaptation effects on perceived duration and perceived speed in the literature, we know that the manipulations that change the temporal tuning of the units in the dorsal pathway might have dissociated effects on either feature (Johnston et al., 2006; Ayhan et al. 2009). Thus, the main aim of this experiment was to check whether the motor action induced duration compression effect we observed here would still be present even when the perceived speed of the comparison and the standard stimuli would have been perceptually matched. 10 participants who had attended in the previous two experiments have also participated in Experiment 2C. Experiment procedures were exactly the same with those in Experiment 2A. There were two conditions again; the visuomotor and the passive visual observation. In the visuomotor condition, the comparison stimulus was coupled with a motor action whereas in the pure visual conditions, observers observed both stimuli passively. The only difference from Experiment 2A was the speed of the standard stimulus. Whereas in 2A, both the comparison and standard stimuli had a constant speed of 5 °/sec, in this experiment,

the speed of the standard stimulus was individually adjusted according to the PSE values of the subjects in the speed discrimination experiment (Experiment 2B).

3.4.1 Results

Data analysis process was exactly the same as was in Experiment 2A. Firstly, psychometric functions were calculated for each participant. Then, a paired-samples t-test was run to compare PSE values in two conditions. The result of the analysis showed that the point of subjective equality differed significantly between the visuomotor (M = 894.9, SD = 92.2) and the pure visual (M = 834.8, SD = 69.2) conditions; in particular, the PSEs in the visuomotor conditions were higher ($t(9) = 2.683$, $p = .025$, $d = 0.85$). This indicated a duration compression effect for the sequences presented in the visuomotor condition. Although the strength of the significance was less than that in Experiment 2A (p = .000), the effect was still significant in Experiment 2C (see Figure 8, Appendix). This shows that the effect of action on perceived speed and duration are dissociable, thus there might be domain-specific sensorimotor timing mechanisms in the system.

3.5 Experiment 3: Color discrimination paradigm

The results of Experiments 2A, 2B, 2C all manifested a similar trend of response. In all of these experiments, the visuomotor stimuli were judged as shorter or slower. This brings up the question of whether there is an attentional cost of doing a motor action simultaneously with a visual task as attention is known to be a common factor that modulates time perception (Rose & Summers, 1995; Tse, Intriligator, Rivest, & Cavanagh, 2004). To check this possibility, we have designed a color discrimination experiment. Our hypothesis here was that if there would be no difference in the color

discrimination performances in the visuomotor and the passive visual observation sequences, then one could claim that the temporal changes induced by motor action are observed not because a secondary task (i.e. motor execution) draws attentional resources per se but are rather due to a modulation in a genuine timing mechanism. Procedures were the same as those in Experiment 2A, 2B and 2C with the visuomotor and the pure visual conditions. Unlike the previous tasks, though, this time the chromaticity of the expanding dots in the comparison stimulus (the one that is contingent upon a key press) was changing from green (xyY = 0.26, 0.37, 40.75) to blue (xyY = 0.21, 0.25, 40.75) across different trials, with that of the standard stimulus always kept at a light blue (xyY = 0.23, 0.31, 40.75). Participants' task was to judge which of the two test stimuli was bluer. Isoluminant green-blue colors have been used in order to rule out luminance being used as a cue. RGB values were taken from the isoluminant color map developed by Peter Kovesi (2015) on the basis of CIELAB space and adapted to our experimental screen after having the CRT monitor calibrated. Six participants took part in this experiment.

3.5.1 Results of Experiment 3

After having calculated the PSE values of each subject in both conditions, a paired-samples t-test was run to compare the mean PSEs of the visuomotor and the pure visual conditions. PSEs in the visuomotor (M = 83.04, SD = 1.54) and the pure visual (M = 86.1, SD = 3.43) conditions did not differ significantly ($t(5) = -2.206$, $p = .08$). The p value is in the range to consider the effect as marginal. So, there is a trend that pure visual conditions are judged to be more blue. Even if this effect was significant, the direction of the effect is the opposite of the previous experiments.

Thus, we could rule out a possible confounding effect of an attentional cost due to motor execution.

3.6. Experiment 4A: Visuomotor duration judgments using isoluminant stimuli in a 2AFC paradigm

There are strong evidence that chromatic and achromatic luminance signals are carried via separate anatomical pathways in the visual system (De Valois, Abramov, & Jacobs, 1966; De Valois, Cottaris, Elfar, Mahon, & Wilson, 2000; Derrington, Krauskopf, & Lennie, 1984; Hubel & Wiesel, 1966). Thus, the rationale of this experiment was to check whether the duration compression effect which was found in Experiment 2A could also be replicated using equiluminant grey background and chromatic dot colors. Color values were taken from the same map we used in Experiment 3 (Kovesi, 2015). As shown in Figure 5 (see Appendix), the procedure was the same with that of Experiment 2A, so there were both the visuomotor and the pure visual conditions. Six participants, who had already completed Experiment 2 have also completed Experiment 4.

3.6.1 Results of Experiment 4A

A paired-samples t-test has shown that the PSEs in the visuomotor (M = 927.6, SD = 58.7) and the pure visual (M = 900.9, SD = 58.4) conditions did not differ significantly ($t(5) = 1.108$, $p = .318$, $d = .45$). As shown in Figure 9 (see Appendix), the duration compression which was found in Experiment 2A and Experiment 2C decreased considerably when the luminances were equalized on the background and the dots. This means that luminance contrast is necessary for the duration compression effect in the visuomotor sequences. Note that this experiment has also

ruled out any sensorimotor memory-related accounts of the action-induced duration compression, as the same memory effects would have been expected to be observed with the isoluminant, as well as the achromatic stimuli.

3.7 Experiment 4B: Visuomotor speed judgments using isoluminant stimuli in a 2AFC paradigm

Similar to Experiment 4A, in this experiment, speed judgments were investigated using isoluminant background and stimuli colors. Procedures were the same with those used in Experiment 2B. Five subjects have participated in this experiment.

3.7.1 Results of Experiment 4B

In order to compare the speed perception in two conditions, a paired-samples t-test was run. Results have shown that the visuomotor (M = 5.16, SD = .313) and the pure visual (M = 5.11, SD = .54) conditions did not differ significantly ($t(4) = .333$, $p = .756$, $d = .15$). It can be seen in Figure 10 (see Appendix) that the difference in perceived speed has almost disappeared in this experiment compared to Experiment 2B. These results imply that the effect of motor action on both speed and duration judgments relies upon the same luminance-contrast sensitive motion pathway in the brain.

3.8 General conclusion

Since our experiments here mainly deal with sensorimotor interactions in the visual time perception, results are expected to offer some mechanisms for the infrastructure of this sensorimotor interaction. We think that the dorsal pathway in the brain potentially has important roles in the timing of visual and sensorimotor time

perception. It is known that temporal properties like motion, speed and frequency are processed via this route and then used for motor planning. Thus, we claim that the neural units in the dorsal route might also function as a modulator for the action-related alterations in time perception. In fact, the results of Experiment 4A (isoluminant duration judgment task) supports this claim by showing that the duration compression in the visuomotor sequences disappear with isoluminant stimuli. This is a strong support for the underlying communication between motor areas and the dorsal visual areas in terms of how to calculate the passage of time.

CHAPTER 4

GENERAL PHILOSOPHICAL DISCUSSION

Experiments have shown that duration perception of short intervals are subject to effects of motion, speed and motor action. It is aimed in this section to build a philosophical framework based on the experimental results and procedures. In this perspective, it is necessary to discuss relevant philosophical questions, but firstly it will be beneficial to think about how to conceptualize empirical methods that are used.

4.1 Conceptualization of current experimental paradigms

One important aim of this thesis was to ground the empirical results into a philosophical domain and develop a theory of the nature of our experience of time. For this purpose, we need to conceptualize the empirical methodology in the study. In the experiments, time judgments were taken as the indicators of the time perception. However, we need to clarify that there is a difference between judging the time and experiencing the time or using the time for action and planning. Using the time for action or planning does not necessitate a conscious judgment, it rather relies on implicit processes. The explicit judgments about the time, on the other hand, require a sort of decision making mechanism. We can also apply *personal vs subpersonal* levels of description into this distinction between judging the time vs. using the time. We judge time in a personal level, however experience of time or usage of time may occur in a subpersonal level. Therefore, the two might depend on different structures and processes. However, it is claimed here that judging or using time information are not mutually exclusive. Our judgements of time are based on

and correlated with our implicit perception of time, although they are not the same phenomenon. This differentiation is quite necessary in the handling of our empirical results, because in all of the experiments, participants did judgments about the duration of intervals.

Deciding which stimulus took longer or reproducing the duration by pressing a button require representations of the perceived time. Temporal representations, therefore get manifested in our discussions. Similar to all representations, temporal representations require formation and retrieval processes to be addressed later. The scope of this study has more to do with the formation part. How our perceptions must be like to pave the way for temporal judgments and representations. In this line of thought, our aim is to infer about the nature of the perceived time from the knowledge we gained through studying duration judgments of visual events.

4.2 Relationship between subjective time and objective time

With the initial presupposition of the time's existence, we choose to discard the ontological discussions of time. This is convenient and plausible for the purposes of this thesis as well. Subjective judgments of durations are more significant in this set of experiments. "Subjective" implicitly indicates the "objective" time which is endowed in the nature. The objective time in this sense is reliable, consistent and agreed on. It is represented by clocks, stop-watchers, etc. and assumed to follow certain universal rules. Although there are philosophical accounts which deny the existence of the objective time or the time in general, existence of the objective time is widely accepted in philosophy as well as in psychology. To be fair, time has not always been thought with the dichotomy of subjective and objective, but rather conceived as a whole. Therefore, views of thinkers consisted of attributions to time

in general. However, drawing a line between time and experience of time imposed the dichotomy between objective and subjective distinction. For instance, in ancient discussions of time, it was not as common to think about deviations in the perception of time since the dichotomy was not strong yet.

Although subjective vs. objective dichotomy was not common to philosophical discussions of time perception in ancient times, philosophers still discussed how humans process temporal information. For instance, Aristoteles was interested in time and in his conceptualization, time experience was dependent on the changes in the environment (Annas, 1975). Aristoteles indirectly implied that the time consciousness is not consistent and is not an intrinsic property of to the organism. Thus, with various scientific evidence and accumulation of philosophical views, it is generally accepted now that our time experience or time consciousness is subject to variety of effects which makes it "subjective". This is the general standing point of this thesis as well. Behind the experimental paradigms, there was the premise that time perception is subject to deviations which makes it completely different than the objective time. What is meant with "deviation" is any kind of changes in the perceived duration which is distorted compared to the clock time.

4.3 Unity of subjective time

Time is continuous and one-directional, this makes it unstoppable and unlimited. Is time consciousness also uniform and continuous? Unity in this sense can be thought both in terms of different time scales and different modalities. *In Critique of Pure Reason* (Guyer, 2009), Kant, shows a strong stand on this regard:

> For there is only one time, in which all different times must not be places simultaneously but only one after another. (p.303)

Although, Kant's position makes sense with regards to our phenomenal experience, we can still ask whether the representation of milliseconds range of durations might be different than the representation of hours or days? Time perception studies have answered this question with affirmation. Days and milliseconds are found to be processed and judged differently (Mauk & Buonomano, 2004). One implication of this difference is that the long-term memory has more impact on longer duration representations than milli-second ranges (Fraisse, 1984). Additionally, time perception follows Weber law to a certain extent, which means that as duration range increases, the deviation of the perceived time from actual time increases (Getty, 1975). At the very least, this shows a lack of uniformity in functioning of different time scales.

The parameters corresponding to certain time-scales are strong indicators of different mechanisms for time perception. For instance, the millisecond range of time perception has more to do with the perceptual properties in certain modalities, whereas longer durations are impacted more from the memory mechanisms (Fraisse, 1984). For example, judgments of hours are under the influence of how well one remembers the details of the past duration. It is the general presupposition of the current experiments that short and long durations are processed and experienced differently. In the experiments, millisecond range of durations were used with the aim of shedding light on the possible impacts of motor action on duration perception. The choice of short durations enabled us to be more precise and able to control emotional and motivational differences between the subjects. In addition, perceiving short durations is thought to be connected with motor regions in the brain, such as supplementary motor area (Lewis & Miall, 2003). Therefore, the usage of the psychophysical methodology was a suitable way to conceptualize philosophical

questions in a measurable way and also to incorporate the sensorimotor interaction debate.

In addition to different time scales, evidence suggests that temporal information is processed differently by different sensory modalities, which suggests existence of multiple temporal frameworks. This question deals with the interpretation of, let say a tone versus an image, a touch versus a smell. Different sensory modalities come up with different range of possible changes and action possibility maps. For instance, the way you plan your actions based on a sound is different than a sight of a predator. In the precise planning of actions, modalities have unique roles and connections. This can be taken to offer that temporal properties of modalities are different with respect to their interaction with action planning. If this is really the picture, then these differences might plausibly be reflected in the temporal experience.

In the previous paragraphs, scale-specific and modality-specific timing mechanisms are described. Although there are multiple frameworks for temporal *processing* in the brain, this does not entail that our *experience* of time is not unitary. Dissociations in mechanisms mainly imply the organizational interactions within time experience. However, phenomenologically, *single and continuous* time is a strong sense in humans. Therefore, despite multiple mechanisms behind subjective time, experience of time may still be in unity.

Time perception is a component of our overall consciousness. However, there are also unique temporal interactions between the visual information and action. This empirical work is focused on the visual time consciousness and therefore can answer some questions about the specific interactions between vision and action. For instance, it is possible to conclude that action interferes with the duration judgments

of visual stimuli. This result definitely has implications for the general temporal consciousness, however it is necessary to assert that the vision's unique connection with action may be the source of the compression effect. Therefore, the timing of visual events is always bound to the general interval timing mechanisms as well as it is bound to properties of visual events such as speed, motion, temporal and spatial frequency. It is suggested that time perception has a general mechanism, on top of modality specific temporal mechanisms.

4.4 Inner sense vs. outer sense

It is for sure that humans experience time. However, it is an important question that what do we base our time experience on? This question deals with the source of temporal "calculation". Do we possess a clock like mechanism in our brain which keeps track of the time by itself or do we use the external information as the basis of our time consciousness? For empiricists, it is rather straightforward that perceptions are all based on internal mechanisms. Similarly, time perception is also based on internal processes. John Locke (1689)'s view on time perception is a great example to the empiricist picture:

> It is not then motion, but the constant train of ideas in our minds whilst we are waking, that furnishes us with the idea of duration; whereof motion no otherwise gives us any perception than as it causes in our minds a constant succession of ideas. (p.171)

As we see from the quote, Locke (1689) argues that our idea of time is not based upon motion and he suggests that duration can be thought of as the distance between ideas. For him, external changes are not enough for perceiving time, rather the idea of those changes is necessary for sensing durations:

> First, by observing what passes in our minds, how our ideas there in train constantly some vanish and others begin to appear, we come by the idea of

> succession. Secondly, by observing a distance in the parts of this succession, we get the idea of duration. Thirdly, by sensation observing certain appearances, at certain regular and seeming equidistant periods, we get the ideas of certain lengths or measures of duration, as minutes, hours, days, years, &. (p.180).

We can speculate from this quote that Locke consider time perception as depending on the number of changing ideas. This resembles Number of Changes view which was supported by some scholars in time perception literature (Kanai, et. al., 2006). Because, both entail the positive interaction between number of changes and perceived time. Hume also holds an empiricist account of time perception. So, for Hume (1738) perception of changes is also a necessary condition:

> Wherever we have no successive perceptions, we have no notion of time, even tho' there be a real succession in the objects. From these phenomena, as well as from many others, we may conclude, that time cannot make its appearance to the mind, either alone, or attended with a steady unchangeable object, but is always discovered some *perceivable* succession of changeable objects. (p.24)

A complete opposite account to this kind of an empiricist view may be to assert that external information is the direct property which we base our time judgments on. In this explanation, external sense has the principle role, therefore it contradicts the empiricist account in many aspects. This contrast between empiricist and externalist descriptions is clearly visible in Hume and Kant's conception of time perception. Hume holds an empiricist view of time perception. In a way, he follows Locke's idea that time is based on the succession of ideas rather than the succession of external changes (Falkenstein, 2017). This is highly compatible with having an internal base for time perception as well. Kant's ideas on temporality and time consciousness, on the other hand, stands on a completely different ground. In *Critique of Pure Reason* (Guyer, 2010), Kant clearly explains that external objective appearances are the basis of time perception:

> Now time cannot be perceived by itself. Consequently, it is in the objects of perception, i.e. The appearances, that the substratum must be encountered that represents time in general and in which all change or simultaneity can be perceived in apprehension through the relation of the appearances to it. (B225, First Analogy, *Critique of Pure Reason*)

It is clear that Kant places external objects as the basis of time perception. Moreover, Kant thinks that succession of ideas is not enough for experiencing time and that external objects form the perception of time through change. Another facet of his conceptualization is that he also thinks that experience of motion is central to our capacity for what he calls "time determination":

> I am conscious of my existence as determined in time. All time-determination presupposes something persistent in perception. This persistent thing, however, cannot be something in me, since my existence in time can first be determined only through this persistent thing. Thus the perception of this persistent thing is possible only through a thing outside me and not through the mere representation of a thing outside me. Consequently, the determination of my existence in time is possible only by means of existence of actual things that I perceive outside myself. (B276, Refutation of Idealism, *Critique of Pure Reason*)

By "*time determination*", I think Kant means our capacity to make judgments about specific durations – how long an event lasted, and then he states that this is based on motion. If we remember the results of Experiment 1, where acceleration was shown to reduce the perceived time, Kant's idea of "time determination" makes more sense. In our experiment, we showed a large role for motion, speed and acceleration in duration judgments or what would Kant call "time determination". Therefore, our study has a way of approving Kant's account on time perception.

Comparison of empiricists' and Kant's views is interesting, because both sides think that time perception has close connections with "change". The difference between the two sides though is where they position the "change". If external changes are perceived directly, Kant must be right. That is why, objective realists

would be closer to the Kant's idea of time perception even though Kant himself is against the idea of objective realism. This is the present position of the thesis as well. Similar to the general scientific community, this study is based on the view that we can have a direct access of the external world. Since we have direct access to it, we use it to determine and experience time. One implication of this is how time perception is modulated by the motion of visual stimuli. As it is previously noted, moving visual stimulus is perceived to be longer than a steady stimulus with the same physical duration (Kanai et al., 2006). The results of Experiment 1 also present that the perceived duration of accelerating stimulus is compressed. This means that there is a strong connection between external changes and our sense of time.

Kant was a proponent of the idea that the time perception is principally extended to the outer world (B 276). If we leave his metaphysical world behind, we can still trace similar ideas in various philosophical disciplines. For instance, the *extended mind* view asserts that the brain and body tend to outcast the processing power of representations to the external world (Clark & Chalmers, 1998). If some information is externally available, the system uses it to form related representations rather than keeping abstract and precise information. General principles of the extended mind view can be thought in terms of time perception as well. External visual cues are used as strong predictors of the perceived time. Therefore, we can mention about the systematic outcast of so called internal clock to the environment. Rather than tracking time like a stopwatch, it is more efficient to make some isomorphism between the changes in the world and the possible time that might have passed. It would have been costly to have a timer in the body which is systematic and reliable at all times. Hence, the time perception is extended from the body to the world. I suggest that this view can be called as *extended time cognition* and it is

theoretically related to extended mind theories. As it is well shown, motion, speed and acceleration cause biases in terms of time perception. The brain seems to use a lot of external visual cues to represent and experience time. Therefore, although there are intrinsic mechanisms that enable humans to experience and keep time, external changes have the essential role in time consciousness. This makes the current empirical work in line with the Kant's views which are briefly mentioned above.

4.5 Time perception and action

As it is expressed previously, the central point of this study is sensorimotor interactions. So, the principle premise is that there are strong links between sensory and motor processing mechanisms in the brain, and in the body. One influential approach to the sensorimotor interaction is of O'Regan and Noe (2001)'s. O'Regan and Noe (2001) apply the general theme of the sensorimotor interaction into visual consciousness. According to them, vision is for action and therefore the two are merged more than previously thought in cognitivist approaches. Perceiving edges, colors, distances, etc. have manifestations in our actions towards them. Similar ideas have been suggested by different scholars under the general theme of *embodied cognition.*

According to the embodied cognition approach, cognitive mechanisms are embedded in the body and not in separate realm from the physical nature of the organism, and also not stuck in the brain. Although embodied cognition has a wide range of aspects that it deals with from language to memory, what interests us here is the perception part. Embodied perception asserts that the perception's principle role is informing actions and calculating costs associated with those actions (Proffitt,

2006). In the same light, what this study has focused on has direct implications for such an interaction between vision and action.

In the last couple of decades, embodied views have taken surge. However, when we look closely, we realize that most of these works or models describe how the perception gives information about edges, distances, colors or height. For instance, Gibson's affordances theory asserts that perception is for receiving the action possibilities in the environments. Most of the examples Gibson gave in his works focuses on object size, distance and other spatial properties. Although spatial properties are highly important, perceiving temporal structures are also necessary for committing an action successfully. Imagine you are trying to catch a prey. You need to plan your movements precisely in time to success. A group of scholars who uses the term "*embodied time cognition*" claims that sensorimotor states and emotional states have strong influence on temporal judgments (Droit-Volet et al., 2013). They ground their view on examples of deviated time perception in affective disorders and during particular action states. This group of scientists claim that only by including emotions and other bodily states, we can have a better theory of time perception.

The main argument of our study is that time perception and therefore time judgments are embodied and closely linked with our actions. The general duration compression effect of visuomotor events that we have found in the experiments, signifies the sensorimotor influences on time perception. The shortening of the perceived time during a motor action supports the embodied accounts with its emphasis on the connection between the body's movement and the perception of visual events. The embodied principles are not themselves enough to conceptualize the full frame of our time perception since the external cues still offer strong biases to the perception of time. In this perspective, another aspect of this study is that even

with visuomotor sequences, there is still the impact of the speed of the visual motion on duration judgments. Speed and motion parameters in general have strong contributions to visual time perception and duration judgments.

4.6. Conclusion

In our phenomenal experience, time has an underlying role. Events happen in time, perceptions depend on time related changes in the external world and bodily processes occur in the temporal dimension. Current experimental findings provide evidence for that our actions do have an effect on the perceived duration of visual events, while the effects of stimuli speed are still present. This result has a potential to answer couple of important questions about temporal consciousness. Firstly, our empirical approach and results support the subjective vs. objective distinction in time. Secondly, found duration and speed effects support modality-specific frameworks for temporal consciousness. Thirdly, the effect of stimuli speed on perceived duration suggests an answer to the question that whether time consciousness is fundamentally based on internal or external processes. Fourthly, the impact of motor action on time perception offers an embodied account for temporal consciousness. The conclusive argument as a result of the philosophical discussions is that visual time consciousness is both embodied and extended.

APPENDIX FIGURES

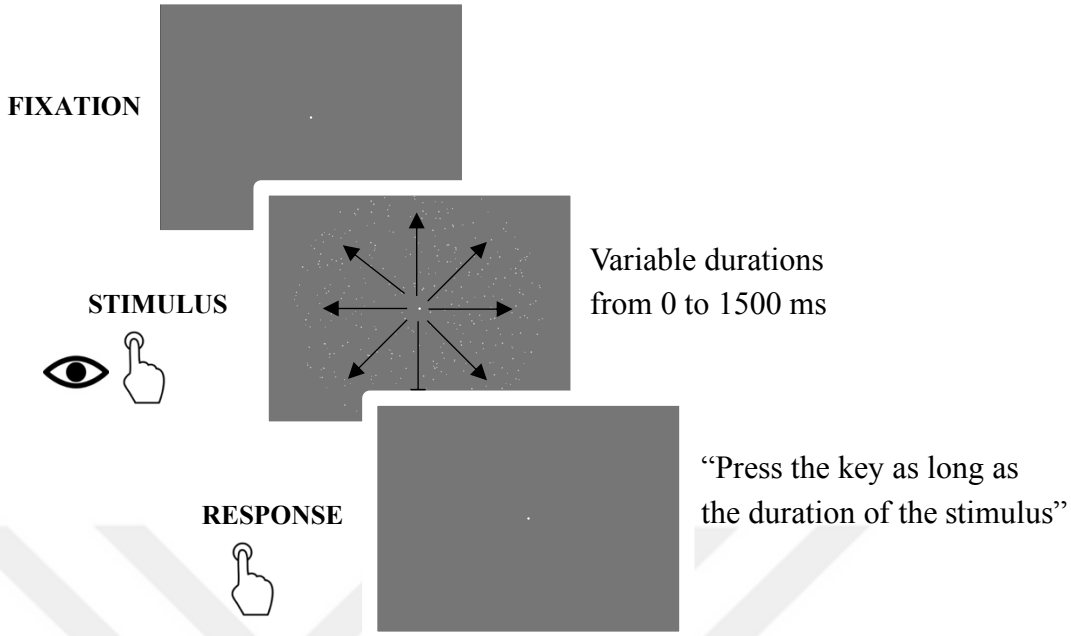


Figure 1. Outline of Experiment 1
In the visuomotor conditions, there was not a fixed interval before the stimulus presentation since participants initiated the visual presentation of the stimulus themselves and determined for how long it would remain on the screen by pressing the space bar. During this production phase, they were asked to press the space bar for no more than 1500 ms. In the following reproduction phase, however, they were presented with a rather blank screen and were asked to press the same space bar for as long as they thought the previous visual stimulus lasted on the screen.

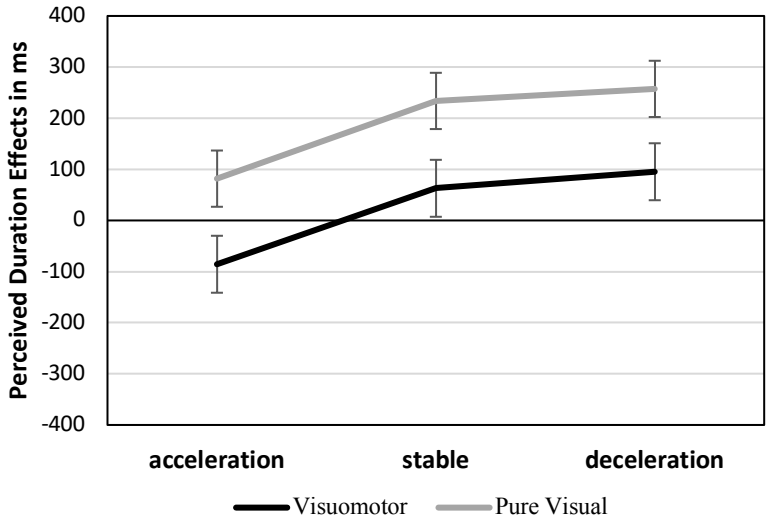


Figure 2. Overall results of Experiment 1
On the x-axis, the three conditions of speed change are shown (acceleration, stable speed and deceleration). On the y-axis, the perceived duration effects in terms of reproduced intervals minus the stimulus duration are shown. The dark line represents the visuomotor condition and the light line represents the passive visual observation conditions. The negative values imply that the perceived duration is shorter than the veridical duration of stimuli. Error bars indicate the standard errors of the mean (SEMs).

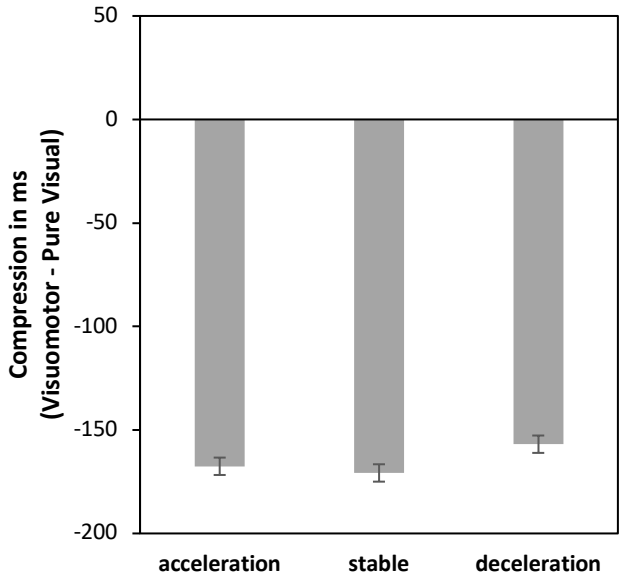


Figure 3. Compression in each speed change conditions
On the x-axis, the three conditions of the speed type are shown. On the y-axis, compression in ms is indicated. Compression is calculated by subtracting the reproductions in the pure visual conditions from the reproductions in the visuomotor conditions. Duration compression in all of the three conditions were significant. The error bars illustrate standard errors of the mean (SEMs).

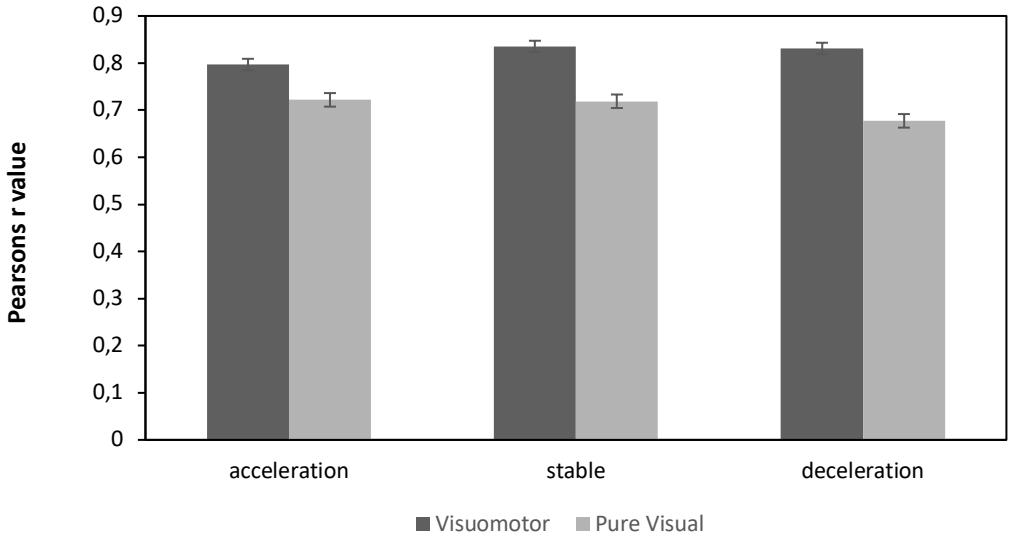


Figure 4. Correlations between the stimuli durations and the reproduced durations Here, correlations of the reproduced and the veridical durations of stimuli are shown for the six conditions. On the x-axis, three speed type conditions are shown. On the y-axis, correlation values from 0 to 1 are illustrated. Dark gray bars indicate the visuomotor conditions, whereas the grey bars indicate the passive visual observation conditions.

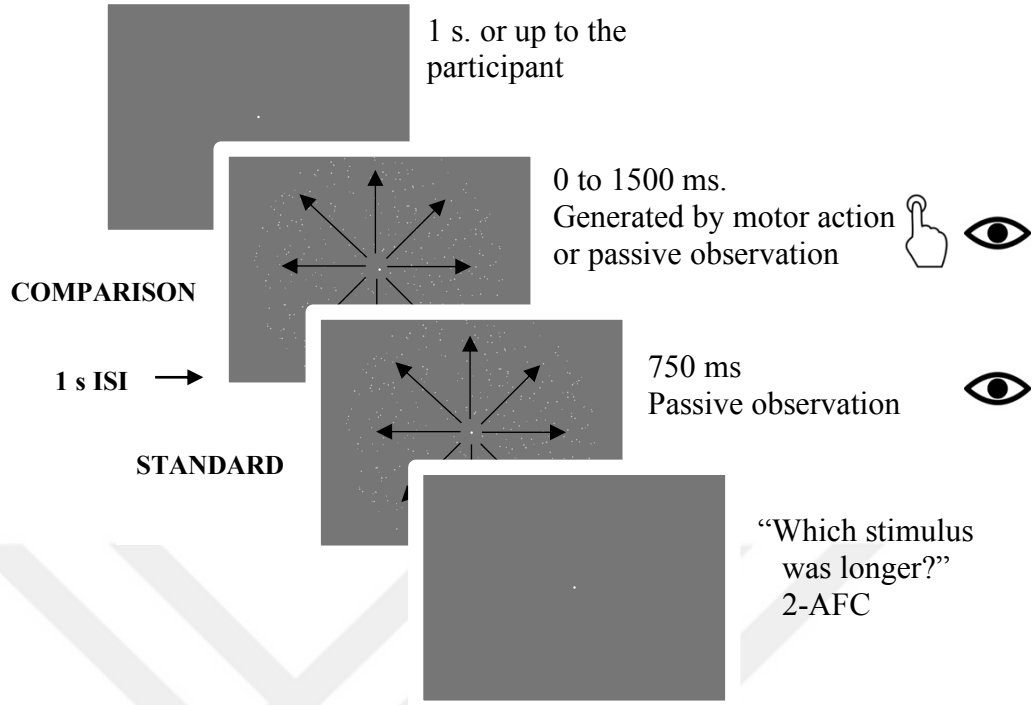


Figure 5. Outline of Experiment 2A, 2C and 4A
Our 2-AFC duration judgment task started with a grey screen with a white fixation dot upon it. In the visuomotor conditions, as soon as the participant started pressing the space bar, the moving dots appeared on the screen and remained as long as the key was pressed down. If the participant had pressed the space bar for longer than 1500 ms, they were told to press again. After the comparison stimulus had disappeared, there was a 1 second inter-stimulus interval and then, the standard stimulus began. The standard stimulus was always observed passively for 750 ms. After the presentation of the stimuli, participants were asked to respond which stimulus remained longer on the screen by pressing the left (comparison) or the right (standard) arrow keys on a keyboard.

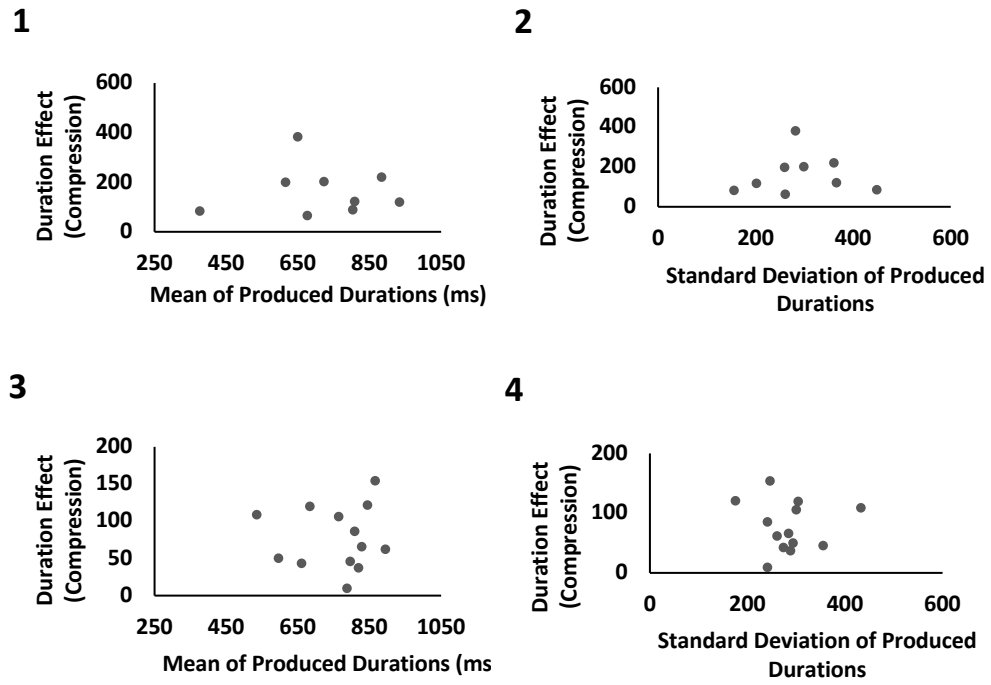


Figure 6. Produced durations vs. duration Effect
Here, mean and standard deviations of the produced durations in two experiments are plotted (In charts 1 and 2 - Experiment 1 and in charts 3 and 4 - Experiment 2A). Each dot represents a participant's performance. On the x-axis, the mean and standard deviations of produced durations are illustrated. On the y-axis, the duration compression effects are illustrated. Mean and/or SD of durations and duration compression effect did not show a systematic relation, as the dots do not show a linear trend.

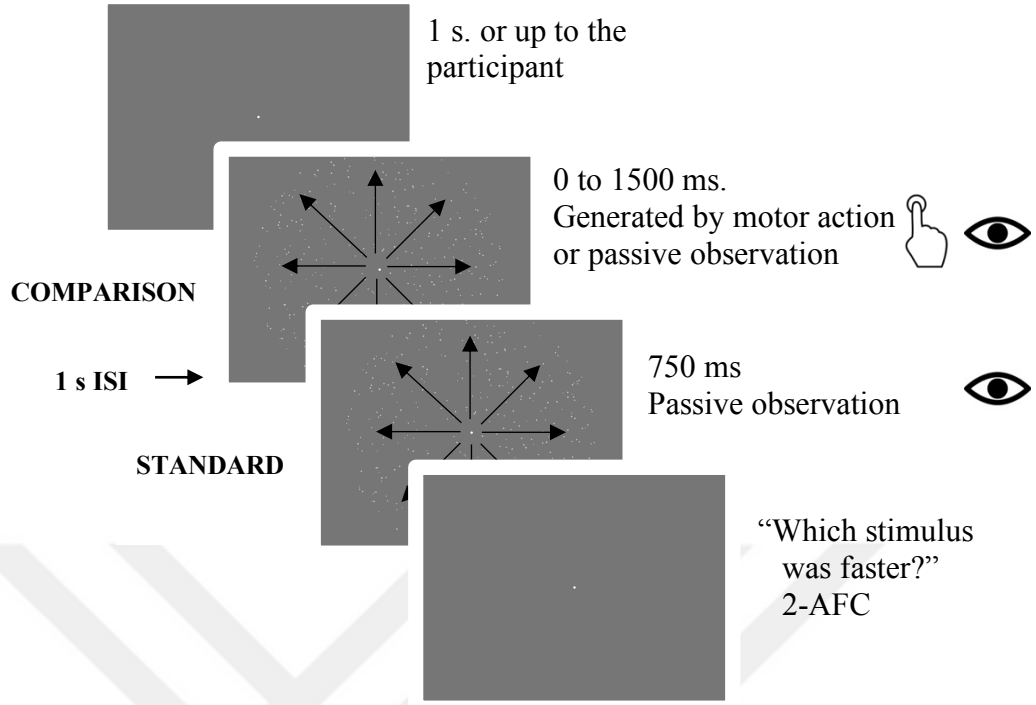


Figure 7. Outline of Experiment 2B and 4B
The speed discrimination tasks in Experiment 2B and 4B consisted of comparison and standard stimuli. In the visuomotor conditions, a comparison stimulus was initiated by the participant's key press. The durations of the comparison stimuli were variable in each trial (between 0 to 1500 ms), while the standard stimuli were always 750 ms. Between the two stimuli there was 1 second inter-stimulus interval. The participants were asked to respond which stimulus dots were moving faster. They indicated their answer by pressing the left (the comparison was faster) or the right (the standard was faster) keys on the keyboard.

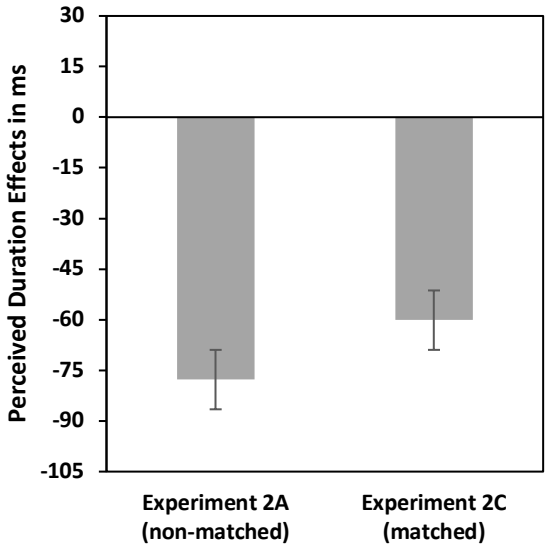


Figure 8. Perceived duration effects in Experiment 2A and 2C
Two experiments are shown in the x-axis, while the perceived duration effects in milliseconds are represented on the y-axis. The perceived duration effects are the differences between mean PSE values of the visuomotor and the pure visual conditions in each experiment. Negative values represent the duration compression and the error bars indicate the SEMs of scores. The perceived duration effects in both conditions were significant.

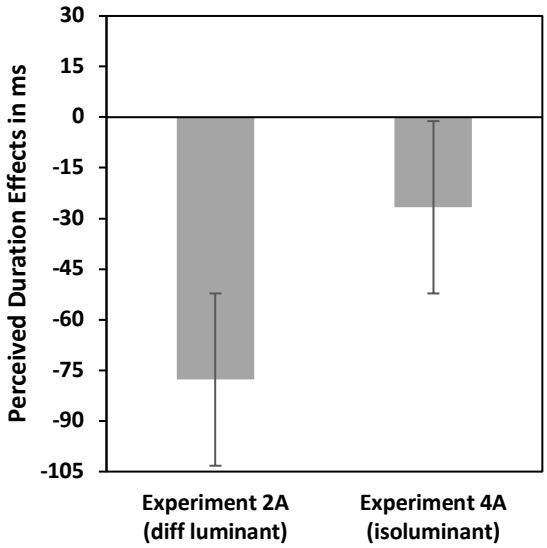


Figure 9. Perceived duration effects in Experiment 2A and 4A
The x-axis indicates the two experiments. The y-axis illustrates the perceived duration effects in milliseconds. Negative values indicate the duration compression. The grey bars represent mean PSE in the visuomotor condition minus mean PSE in the pure visual condition and the error bars represent SEMs. Perceived duration effects in Experiment 2A was significant, whereas in Experiment 4A it was insignificant.

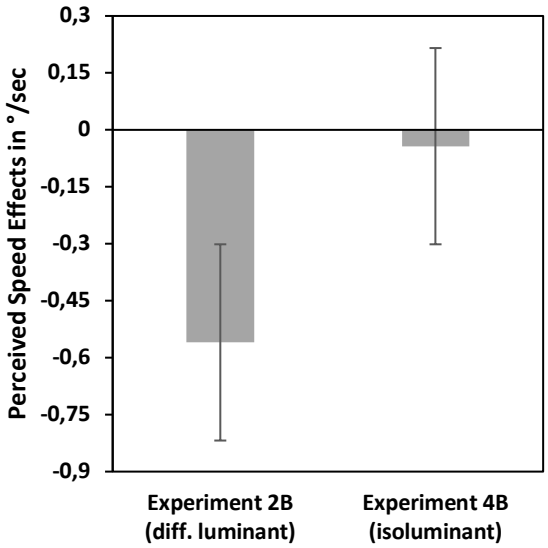


Figure 10. Perceived speed effects in Experiment 2B and 4B
The x-axis illustrates two experiments, the y-axis indicates the perceived speed effects. The error bars signify SEMs. The perceived speed effects are calculations of the difference between PSEs in the visuomotor conditions and the pure visual conditions. Negative value means that the perceived speed is less than the actual speed, so there is a negative effect. The perceived speed effect was significant in Experiment 2B, but not in Experiment 4B.

REFERENCES

Annas, J. (1975). Aristotle, number and time. *The Philosophical Quarterly*, *25*(99), 97-113.

Ayhan, I., Bruno, A., Nishida, S., & Johnston, A. (2009). The spatial tuning of adaptation-based time compression. *Journal of Vision, 9*(11), 1-12.

Barsalou, L. W. (2008). Grounded cognition. *Annual Review of Psychology, 59*, 617-645.

Brainard, D. H., & Vision, S. (1997). The psychophysics toolbox. *Spatial Vision*, *10*(4), 433-436.

Brown, S. W. (1995). Time, change, and motion: The effects of stimulus movement on temporal perception. *Perception & Psychophysics, 57*(1), 105–116.

Bruno, A., Ayhan, I. & Johnston, A. (2015). Changes in apparent duration follow shifts in perceptual timing. *Journal of Vision, 15*(6), 1-18.

Buehner, M. J., & Humphreys, G. R. (2009). Causal binding of actions to their effects. *Psychological Science, 20*(10), 1221-1228.

Bueti, D., Bahrami, B., & Walsh, V. (2008). Sensory and association cortex in time perception. *Journal of Cognitive Neuroscience, 20*(6), 1054-1062.

Buhusi, C. V., & Meck, W. (2005). What makes us tick? Functional and neural mechanisms of interval timing. *Nature Neuroscience, 6*(10)*,* 755-765.

Burr, D., Tozzi, A., & Morrone, M. C. (2007). Neural mechanisms for timing visual events are spatially selective in real-world coordinates. *Nature Neuroscience*, *10*(4), 423.

Carlini, A., & French, R. (2014). Visual tracking combined with hand-tracking improves time perception of moving stimuli. *Nature Scientific Reports, 4*, 1-6.

Cravo, A. M., Claessens, P. M., & Baldo, M. V. (2009). Voluntary action and causality in temporal binding. *Experimental Brain Research, 199*(1), 95-99.

Creem-Regehr, S. H., & Kunz, B. R. (2010). Perception and action. *Wiley Interdisciplinary Reviews: Cognitive Science*, *1*(6), 800-810.

De Valois, R. L., Abramov, I., & Jacobs, G. H. (1966). Analysis of response patterns of LGN cells. J*ournal of the Optical Society of America*, *56*(7), 966-977.

De Valois, R. L., Cottaris, N. P., Elfar, S. D., Mahon, L. E., & Wilson, J. A. (2000). Some transformations of color information from lateral geniculate nucleus to striate cortex. *Proceedings of the National Academy of Sciences*, *97*(9), 4997-5002.

Derrington, A. M., Krauskopf, J., & Lennie, P. (1984). Chromatic mechanisms in lateral geniculate nucleus of macaque. *The Journal of Physiology*, *357*(1), 241-265.

Desantis, A., Roussel, C., & Waszak, F. (2011). On the influence of causal beliefs on the feeling of agency. *Conscious Cognition, 20*(4), 1211-1220.

Droit-Volet, S., Fayolle, S., Lamotte, M., & Gil S. (2013). Time, emotion and the embodiment of timing. *Timing & Time Perception, 1*(1)*,* 99-126.

Falkenstein, L. (2017). Hume on temporal experience. In Phillips, I. (Ed.), *The Routledge handbook of philosophy of temporal experience* (pp. 42-52), Oxford: Routledge.

Fraisse, P. (1984). Perception and estimation of time. *Annual Review of Psychology, 35,* 1-37.

Getty, D. J. (1975). Discrimination of short temporal intervals: A comparison of two models. *Perception and Psychophysics, 18*(1), 1-8.

Gibson, J. J. (1950). *The perception of the visual world.* Oxford: Houghton Mifflin.

Gibson, J. J. (1978). The ecological approach to the visual perception of pictures. *Leonardo*, *11*(3), 227-235.

Gibson, J. J. (1979). *The ecological approach to visual perception*. Boston: Houghton Mifflin.

Guyer, Paul (ed.) (2010). *The Cambridge companion to Kant's critique of pure reason*. Cambridge: Cambridge University Press.

Haggard, P. (2005). Conscious intention and motor cognition. *Trends in Cognitive Sciences, 9*(6), 290-295.

Haggard, P., Clark, S., & Kalogeras (2002). Voluntary action and conscious awareness. *Nature Neuroscience, 5*(4), 382-385.

Hagura, N, Kanai, R., Orgs, G., & Haggard, P. (2012). Ready steady slow: Action preparation slows the subjective passage of time. *Proceedings of the Royal Society B, 279,* 4399-4406.

Hume, David (1738). *A treatise of human nature*. Oxford: Oxford University Press.

Ivry, R. B. (1996). The representation of temporal information in perception and motor control. *Current Opinion in Neurobiology, 6*(6), 851-857.

Jamieson, D. G., & Petrusic, W. M. (1975). The dependence of time-order error direction on stimulus range. *Canadian Journal of Psychology*, *29*(3), 175.

Johnston, A. (2010). Modulation of time perception by visual adaptation. In A.C. Nobre & J. T. Coull (Eds.), *Attention and time*, (pp. 187-200). Oxford: Oxford University Press.

Johnston, A., Arnold, D. H., & Nishida, S. (2006). Spatially localized distortions of event time. *Current Biology*, *16*(5), 472-479.

Kanai, R., Paffen, C. L. E., Hogendoorn, H., & Verstraten, F. A. J. (2006). Time dilation in dynamic visual display. *Journal of Vision, 6*(12), 1421–1430.

Kaneko, S., & Murakami, I. (2009). Perceived duration of visual motion increases with speed. *Journal of Vision, 9*(7), 1-12.

Kovesi, P. (2015). Good color maps: How to design them. *Arxiv*.

Lewis, P. A., & Miall, R. C. (2003). Distinct systems for automatic and cognitively controlled time measurement: Evidence from neuroimaging. *Current Opinions in Neurobiology, 13*(2), 250-255.

Liu, J., Newsome, W. T. (2005). Correlation between speed perception and neural activity in the middle temporal visual area. *Journal of Neuroscience, 25*(3), 711-722.

Locke, J. (1975). *An essay concerning human understanding* (ed. Nidditch, P.). Oxford: Oxford University Press.

Lucas, B. D., & Kanade, T. (1981). An iterative image registration technique with an application to stereo vision. In *Proceedings of the 7th International Joint Conference on Artificial Intelligence,* (pp. 674-679). San Francisco: Morgan Kaufmann Publishers.

Mauk, M. D., & Buonomano, D. V. (2004). The neural basis of temporal processing. *Annual Review of Neuroscience, 27,* 307-340.

Maunsell, J. H. R., Nealey, T. A., & DePriest, D.D. (1990). Magnocellular and parvocellular contributions to responses in the middle temporal visual area (MT) of the macaque monkey. *The Journal of Neuroscience, 10*(10), 3323-3334.

Milner, A. D., & Goodale, M. A. (1995). *The visual brain in action.* Oxford: Oxford University Press.

Mishkin, M., Ungerleider, L. G., & Macko, K. A. (1983). Object vision and spatial vision: Two cortical pathways. *Trends in Neurosciences*, *6*, 414-417.

Noë, A., & Noe¨, A. (2004). *Action in perception*. Cambridge, MA: MIT Press.

O'Regan, J. K., & Noe, A. (2001). A sensorimotor account of vision and visual consciousness. *Behavioral and Brain Sciences*, *24*(5), 939-1031.

Proffitt, D. R. (2006). Embodied perception and economy of action. *Perspectives On Psychological Science, 1*(2), 110-122.

Riesen, J. M., & Schnider, A. (2001). Time estimation in Parkinson's disease: Normal long duration estimation despite impaired short duration discrimination. *Journal of Neurology, 248*(1), 27-35.

Rizolatti, G., & Matelli, M. (2003). Two different streams form the dorsal visual system: Anatomy and functions. *Experimental Brain Research, 153*(2), 146-157.

Rose, D., & Summers, J. (1995). Duration illusions in a train of visual stimuli. *Perception*, *24*(10), 1177-1187.

Schlack, A., Krekelberg, B., & Albright, T. D. (2007). Recent history of stimulus speeds affects the speed tuning of neurons in area MT. *Journal of Neuroscience*, *27*(41), 11009-11018.

Schubotz, R.I., Friederici, A. D., & Cramon, D. Y. (2000). Time perception and motor timing: A common cortical and subcortical basis revealed by fMRI. *Neuroimage, 11*(1)*,* 1-12.

Treisman, M. (1963). Temporal discrimination and the indifference interval: Implications for a model of the "internal clock". *Psychological Monographs: General and Applied, 77*(13), 1-31.

Treisman, M., Faulkner, A., Naish, P. L. N., & Brogan, D. (1990). The internal clock: Evidence for a temporal oscillator underlying time perception with some estimates of its characteristic frequency. *Perception, 19*(6)*,* 705-743.

Treisman, M., Faulkner, A., & Naish, P. L. N. (1992). On the relation between time perception and the timing of motor action: Evidence for a temporal oscillator controlling the timing of movement. *The Quarterly Journal of Experimental Psychology, 45*(2), 235-263.

Tse, P.U., Intriligator, J., Rivest, J., & Cavanagh, P. (2004). Attention and the subjective expansion of time. *Perception & Psychophysics*, *66*(7), 1171-1189.

Wearden, J. H., & Penton-Voak, I. S. (1995). Feeling the heat: Body temperature and the rate of subjective time, revisited. *The Quarterly Journal of Experimental Psychology Section B*, *48*(2b), 129-141.

Wiesel, T. N., & Hubel, D. H. (1966). Spatial and chromatic interactions in the lateral geniculate body of the rhesus monkey. *Journal of Neurophysiology*, *29*(6), 1115-1156.