Advancing the Understanding of the Visual Saltation Illusion from investigating the second flash to novel presentation modes

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Advancing the Understanding of the Visual Saltation Illusion

From investigating the second flash to novel presentation modes

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I would like to dedicate this thesis to my mom.

Declaration

I hereby declare that this thesis titled “Advancing the Understanding of the Visual Saltation Illusion," submitted to fulfill the requirements for the degree of Doctor of Philosophy (PhD) in Design, of the Graduate School of Design, Kyushu University, Japan, represents my own work. No part of this dissertation has been previously presented for another degree at any other institution.

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February 2025

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Abstract

The visual saltation illusion (VSI), or reduced visual rabbit illusion, is a notable phenomenon in visual perception where a series of flashes appears equidistant across the visual field, even if some flashes occur at the same location. This dissertation investigates the VSI through four interrelated studies, each employing different experimental paradigms to delve deeper into its cognitive and neurological mechanisms. Collectively, these studies enhance our understanding of the VSI by examining its occurrence under various conditions, the role of attention, the impact of stimulus characteristics, and its manifestation in non-linear presentations. The first study revisits the traditional linear presentation of the VSI, introducing a novel approach by altering the position of the second flash. This study presented the second flash at the position of the third flash, out of sequential order, or at the midpoint between the first and last flash but not aligned linearly. Experiments showed that participants consistently misperceived the second flash as being near the midpoint between the first and third flashes, regardless of its actual position. This finding highlights the robustness of the VSI and suggests a specific neurological process that underlies this perceptual anomaly, setting the stage for further exploration of the VSI's underlying mechanisms. Second, the VSI is explored in two novel modes: expansion and contraction. Participants fixated on a central point while three stimuli flashed below the fovea in either an expanding or contracting sequence. Despite the actual size of the stimuli, observers consistently misperceived the second flash as medium-sized compared to the first and third flashes. Further analysis investigated whether stimulus duration or interstimulus interval (ISI) influenced the VSI. Results indicated that the VSI was observed regardless of these parameters, as long as the stimulus onset asynchronies were less than 317 ms. This finding suggests that VSI extends beyond linear presentations and opens avenues for exploring the illusion under various conditions. Together, these studies provide a comprehensive exploration of the VSI

from multiple perspectives. They suggest that the VSI is not merely a perceptual anomaly but a complex phenomenon involving both low-level sensory processing and high-level cognitive interpretation. The occurrence of the illusion across different paradigms in this research implies how certain neural mechanisms may mediate the perception of continuity in VSI stimuli that may carry on in other transformation modes or novel approaches to the VSI. The study also highlights the importance of stimulus duration and ISI in shaping the VSI's strength and nature. Future research could utilize neuroimaging techniques to identify specific brain regions and networks involved in VSI perception. Additionally, exploring VSI in populations with visual or neurological impairments could provide further insights into its neural and cognitive mechanisms.

Table of contents

List of figures

List of tables

List of Abbreviations

ANOVA	Analysis of Variance
cd/m^2	candela per square meter
CRE	cutaneous rabbit effect
deg	degrees (visual angle)
FLE	flash lag effect
ISI	interstimulus interval
ITD	interaural time difference
Hz	Hertz
MIPS	motion induced position shifts
mm	millimeters
ms	milliseconds
MSRBP	Shaffer's Modified Sequentially Rejective Bonferroni Procedure
PS1/2	Participant subject 1/2
SOA	stimulus onset asynchrony
VSI	visual saltation illusion

Chapter 1

General Introduction

> "All perceiving is also thinking, all reason is also intuition, all observation is also invention."

Rudolf Arnheim [1], a perceptual psychologist and an art theorist, once expressed this idea that the perceptual process is not passive. His thoughts suggest an interplay between objective and subjective processes in our human cognition which manifests as one's reality. There is no neutral way one observes the world; mental frameworks and personal experiences have an impact on how people report what they perceive. The following text and chapters will touch on this idea of the complexity and at times subjective nature of perceptual experiences through the examination of a visual phenomenon known as the visual saltation illusion (VSI).

Vision is one of the utmost important senses in how people see and perceive the world. When people recall memories or dreams, what they imagine is usually based on the visual information they received in the past. People also judge whether something is awful or pleasant through visual appearances. But vision is more than "seeing." While the eyes see, the brain perceives. There are many instances where what a person sees does not match actuality. A popular debate arises from this on the reliability of eyewitnesses. There is an argument that witnesses' intention is not to misinform the jury, but rather that such testimony is inaccurate because too many factors influence what a person believes they perceived.

Another case where perception does not match reality is in the realm of illusions. Illusions, whether haptic, visual, or auditory, can give insight into how our brain processes information. Discovering how to break such illusions can create a full circle understanding of this process as well. The amount of an illusion can be measured by how much what is reported diverges from what was presented. As Richard Gregory [2] put it, illusions are considered a "departure from reality." If the color green is presented, but if observers report seeing pink, one can argue that the illusion can be strong. What is reported can also give insight into which part of the sensory process the discrepancy lies. In the case of the previous example, investigators would look at the areas related to color perception, such as the eyes' cones. If the answer does not lie there, they would continue to work their way along the visual pathway till they reach the occipital lobe.

Specifically for vision, some illusions might be due to a manipulation of the information presented, or caused by a physiological part of the visual system [3]. Optical illusions that play with colors, angles, such as the Ames Room or the Adelson Checker Shadow Illusion are examples of physical alterations made to deceive the eyes. One example of the latter would be the blind spot, a part on the retina where no photoreceptors exist. This area goes unnoticed in daily life but has been subject to many experiments where people report to see color, or other images occur in their blind spot. This is just an example of how the brain compensates for the visual system and a small wonder why this field is worthwhile to investigate.

Humans are not the only creatures who perceive illusions. Aside from other primates [4], dolphins [5], cats, and even bees are susceptible to visual illusions [6]. When similar traits across species are present, it is important to understand why. Although this thesis does not delve deeply into the evolutionary aspects of vision, this factor is considered. One can argue that the ability to experience illusions has some adaptive value that was carried across time and species.

Another proof of the adaptive nature of illusions are the differences based on environmental upbringing. Certain cultures with mostly circular or curved surroundings, such as the Zulu people, are relatively resistant to perceiving linear illusions, such as the Müller-Lyer illusion [7]. This discrepancy between cultures or physical surroundings is highly relevant because it supports that vision, and therefore reality is shaped by what one is exposed to. Also, it addresses a limitation of most perceptual research, where data is gathered solely from those of linear cultures, as this thesis.

Events that occur later in a person's life can also have an impact on their reality and their vision. Patients who develop physical diseases such as glaucoma, psychological disorders such as schizophrenia, or even a substance abuse disorder, are likely to report changes in their vision. A comprehensive review of patients who have schizophrenia found that in some illusions, there were discrepancies between patients and the control group [3]. A few alcoholic drinks can temporarily cause blurry vision, while long-term abuse can lead to abnormal eye movement or even permanent vision loss [8]. A study on the visual tilt illusion found those with alcohol use disorder were less prone in reporting angular differences in certain conditions versus those of healthy subjects [9]. For this case, being immune to the illusion is a factor of decaying vision.

Despite the vast number of studies, there is no single decisive reason why illusions occur. However, the complexity of illusions has and will continue to merit investigation, especially alongside the development of technology. This dissertation aimed to contribute to the field of perception and visual sciences through a series of experiments conducted on the visual saltation illusion. This chapter will give a background of this illusion, the objectives of this research, and the structure of this dissertation.

1.1 The visual saltation illusion

1.1.1 Cutaneous Rabbit Effect

Expounding on the visual saltation illusion would not be complete without mentioning the illusion it originated from. The cutaneous rabbit effect (CRE) also known as the cutaneous rabbit illusion, was discovered by Geldard and Sherrick[10]. The original experiment administered taps at around three locations on the forearm, between the wrist and the crook of the elbow. The locations of the taps were equidistant to each other, the number of taps at each location were the same, and the timing of and between each tap were also uniform. Instead of feeling taps solely at the stimulated locations, subjects reported feeling the taps traveling down them from the first tap location up to the final tap location. They likened it to a small rabbit hopping across their skin, which is how the illusion was aptly named.

Geldard and Sherrick [10] emphasized the importance of uniformity in administering tap stimuli, along with short interstimulus intervals (ISI), and a balanced number of taps at each point. If these conditions are met, the taps are felt as a train of continuous motion, similar to the phi phenomenon. A reduced version of the illusion (Figure 1.1) was found to produce the same effect with fewer stimuli locations and taps, and researchers cited the low sensory acuity of the forearm as a factor for the illusion's success. The saltation effect arises when stimuli are presented rapidly along a linear path, with the duration and the ISI being uniform. The stimuli, which could be taps, flashes, or beeps, are sometimes presented in the same location, leading subjects to perceive subsequent stimuli at a point further from their true location. Reduced versions of saltation illusions use three stimuli with two stimulus locations, creating the perception of a new intermediate location under optimal conditions.

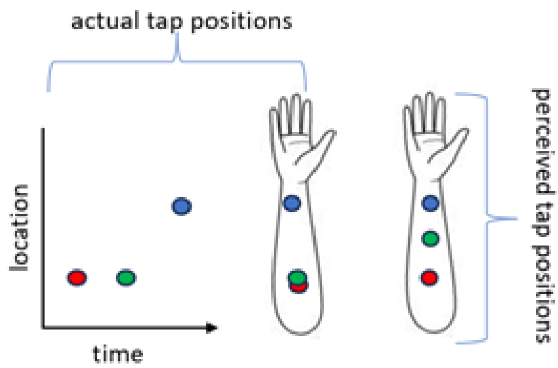

Fig. 1.1 Reduced cutaneous rabbit effect. Colored circles indicate taps. The red indicates the first, the green circle indicates the second, while blue indicates the third tap.

While this thesis is based on the reduced CRE, it is worth noting that Geldard and Sherrick [11] also produced a similar effect with what they called the utterly reduced CRE. This version uses only two stimuli at two locations. If the second tap is far in distance and time from the first tap, mislocalization does not occur. However, if the second tap follows the first tap rapidly, a person may perceive the taps as being close together, even when they are physically not. Typically, the second tap becomes the "attractant," with the first tap (attractee) perceived as occurring near it. Under certain conditions, the utterly reduced CRE can even produce an illusory third tap, usually following the first or second tap.

Geldard [12] later found that the effect only arises in areas innervated by adjacent spinal nerves and that the hopping effect does not cross the body midline. This implied that perceived illusory points would also be reflected on the body's somatosensory brain map. This was later supported by a study using functional magnetic resonance imaging [13, 14].

These studies verified that the saltation phenomenon was indeed a perceptual illusion, in which what a person reports is also what their brain perceives as having “felt.”

Subsequent experiments that presented the CRE across the forehead [15] and abdomen [16] contradicted Geldard’s original findings that the CRE does not occur when presented across the body’s midline. Eimer et al. [17] also discovered that the "rabbit" can traverse the forearms when positioned side-by-side (e.g., right wrist behind left elbow, left wrist in front of right elbow). If two taps were administered at a location (L1) on the right arm, and one tap on the left arm (L3), an illusory tap was reported at a location on the right arm (L2), approximately central between L1 and L3. Martel et al. [18] later observed the same effect across arms and legs, challenging the notion that attentional effects solely account for the saltation phenomenon [17] and suggesting that prior experience influences tactile perception [18].

1.1.2 Saltation in other modalities

The CRE has also been successfully projected "out of body" [19, 20] and explored in virtual reality [21]. These innovative approaches demonstrate the impact of technological advancements on the investigation of this phenomenon. In these experiments, visual attention was directed to the locations where the phantom taps would occur. This emphasizes the role that visual attention plays in perceiving saltation stimuli, potentially affecting the overall perception of the illusion.

In the related field of haptics, the CRE was also found to occur in temperature and pain detection, suggesting that similar neural mechanisms may be involved across different sensory modalities [22]. In Trojan et al.’s [22] experiment, a laser beam was emitted on the forearm at different temperatures and varying locations utilizing the reduced CRE paradigm. The distance between the second beam and the third beam was fixed at 105 mm. The ISI between the first beam and second beam was fixed at 1000 ms, while the ISI between the second beam and third beam varied between 60 and 516 ms across trials. The second beam was observed to be displaced farther from the first beam as the ISI between the second and third beams decreased. Interestingly, there was a correlation between the overall perception of the beam locations and the absolute position of the subject’s forearm. Stimuli presented closer to the wrist were more accurately perceived than those presented closer to the crook of the elbow.

Referring to the same experiment, visual attention was not given to the beam locations; subjects used a three-dimensional (3D) tracker to mark the beam locations on their skin. The stimuli parameters were groundbreaking as, unlike the original CRE, they were not presented uniformly. The ISI between the first and second beams was fixed, but the latter ISI altered between trials; yet saltation of the second beam occurred. This study reemphasized Geldard and Sherrick's [10] claim on the importance of ISIs and also aligned with the tau effect [23, 24], explicitly showing how the timing of stimuli affected the subjects' perception of the beams' locations on their skin.

Bremer et al. [25] first investigated saltation in hearing by presenting a variety of click trains from three different speakers hidden from subjects. Clicks had a duration of 20 ms, with at least three clicks being presented by each speaker, with the first clicks sounding from the left speaker and ending in the right speaker. The interval between clicks from adjacent speakers was about three times longer than the interval between clicks within the same speaker. Just as in the original CRE, they found that for both naïve and experienced subjects, low ISIs of 20 ms were favored to produce a saltation effect, with ISIs of 75 ms being sufficient as well. The number of clicks emitted from each speaker was also an important factor, just as the number of taps were in the original CRE.

A related experiment conducted by Hari [26] presented eight binaural clicks to subjects with an interaural time difference (ITD) of 800 μs using headphones and found that at short ISIs of 120 ms, misjudgment of click locations occurred. Subjects observed the clicks jumping from the left to the right ear, with an ISI range of 30 to 90 ms being ideal. In monaural click conditions, saltation did not occur. Shore, Hall, and Klein [27] built on these two auditory experiments by applying an additional ITD of 300 μs as a condition. The results were consistent with Hari's, where differences between ITDs of 800 and 300 μs at low ISIs were not significant, and saltation did occur; subjects perceived clicks to occur smoothly between both ears. However, at ISIs of 120 ms, saltation was less likely to occur at ITDs of 800 μs, but ISIs of 150 ms were sufficient at ITDs of 300 μs.

Saltation in the auditory modality is fascinating, in the sense that it is difficult to link sound to a precise physical location. In the previously mentioned experiments, at short ISIs, the clicks are not perceived as isolated events, but are integrated as a whole, indicating how sounds are temporally processed under rapid presentation speeds. Hari [26] and Shore et al. [27] suggested that neurons of the brain process sounds in overlapping patterns under rapid stimuli presentation, meaning the brain is unable to process a click before the next one arrives, resulting in saltation.

Understanding the saltation effect across the senses and how they compare with the VSI is necessary to understand the VSI as a whole. The remainder of this chapter will focus on saltation in the visual domain.

1.1.3 Visual Saltation Illusion

Geldard [28] first conducted a reduced VSI using flashing lights in a dark room. The first two flashes were presented at one point, and the third at a distance; subjects perceived an illusory flash to occur at the center of the first and third flash. Timing between the stimuli were equal, as well as the timing of the stimuli presentation, just like the original CRE. As hypothesized, the second flash hopped from its original location to be perceived at a place where it never existed. Thus, began the idea that perceptual input might undergo the same processing tendencies across the senses.

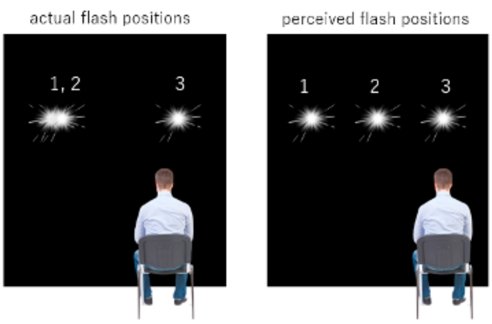

Fig. 1.2 Reduced visual saltation illusion. Depiction of what the first VSI experiment conducted may have looked like

In terms of vision, Geldard's [28] study emphasized the importance of retinal position relative to stimuli and the fixation point, describing the ideal visual eccentricity for stimuli at a position 25 to 30 deg from the fovea, while a visual eccentricity of 50 deg could still induce the illusion but with more difficulty. Geldard also reinforced saltation illusions' feature of favoring short ISIs, where ISIs below 100 ms can cause a flash to “leap” at longer distances from the first flash position (L1) to the midpoint (L2). ISIs approaching 300 ms would induce only leaps of 10% or none at all [28]. The constraints on retinal eccentricity and timing are reminiscent of the fact that this phenomenon is based on lower-level processing.

In line with the points made above, unlike the CRE, Geldard (1975) did not find a straightforward linear correlation between ISI and the saltatory leap of the target stimulus in the VSI. Although saltation may be shared among the senses, the manner in which distance or the timing between stimuli is processed by the brain might vary. This brings to mind the classic tau and kappa effects. The tau effect demonstrates that the perceived spatial distance between successive stimuli can vary depending on the temporal intervals between them. Stimuli presented with shorter time intervals are often perceived as closer together, irrespective of their actual spatial distance [23, 24]. The kappa effect illustrates how temporal intervals between stimuli are perceived to be shorter or longer based on their spatial separation; greater physical distances tend to lengthen the perceived time interval [29, 30]. The reliance on ISIs for producing the saltatory leap in vision would align with these effects, as both point to the nonlinear processing of spatiotemporal cues by the brain.

Short ISIs were enough for subjects to perceive a tap or a beep to do a full leap from one stimulation point to another in the CRE and auditory saltation, an outcome Geldard termed “coincidence.” In Geldard’s (1975) original experiments, he was unable to produce an outcome of coincidence with the VSI. He measured the furthest leap from the first flash location to the subsequent one at 80%, but these distances were rarely reported by subjects.

This might also be related to the fact that the eyes must be oriented at a particular point for the illusion to be perceived, while the skin does not require any type of adjustment to perceive the illusion. The VSI only arising in the periphery can be viewed as a limitation of saltation in vision as opposed to other senses. This limitation can be reduced if paired with stimuli in other modalities, such as auditory beeps. Stiles et al. [31], presented VSI stimuli as close as four degrees from the fixation point and successfully produced saltation when paired with synchronized audio stimuli. Because of the need for a fixation point in vision, Geldard [11] found that a locator stimulus (the first pulse in the CRE and the first flash in the VSI) was not necessary to produce saltation. The utterly reduced VSI appeared to be more robust than its CRE counterpart in this aspect.

Bowen [32] found a phenomenon similar to the utterly reduced VSI where the rapid presentation of two flashes produced an illusory third flash. However, unlike the CRE or VSI, these flashes are presented in the same location. Earlier, Ikeda [33] found the opposite effect, where two flashes presented extremely rapidly dampened the perception of the second flash, and only one flash was reported. In Ikeda's experiment, two flashes could be perceived as a single flash when the interflash interval was at 0.07 s or less. Subjects reported seeing three flashes when the interflash interval ranged between 0.05 and 0.17 s in Bowen's experiments, with 0.11 s being the highest instance of three flashes being spotted. These outcomes provide clues on how temporal intervals can affect visual perception and the mechanics behind the VSI.

Lockhead et al. [34] built on the VSI following the parameters of Geldard and Sherrick (1972) and showed that subjects perceived flashes to occur within their blind spot, an area where visual stimuli should not be detected. This gave further insight into how the brain processes VSI stimuli. Visual saltation can extend into the filling-in phenomenon, showcasing the brain's adaptive mechanisms in perception. Like the CRE, this experiment verified the illusion arises from temporal processing and that the reconstruction of information does not occur at the level of retinal activity.

Geldard [11] also found that color misperception occurs in the VSI. If flashes at the first location presented are presented as one color, and flashes in the next location are different, the subject perceived the mislocalized flash to be a mixture of the two colors. Physical yellow (L1) and blue flashes (L3) resulted in a perceived white flash (L2), while green (L1) and red (L3) resulted in a perceived yellow flash. Lewis and Khuu [35] built on this study and found that manipulating the background color when the target flash is presented can also influence what color is reported.

Since then, different visual aspects have been examined under the VSI, such as using animal-shaped flashes to see their effect on subjects' emotions [36]. Using Kanizsa-type subjective contours as flash stimuli can produce the illusion and that incorporating inducers with real shapes can enhance the saltation effect [37]. These studies revealed that the illusion still holds strength even if the physical aspects of stimuli increased in complexity.

The reasons why and how the VSI occurs warrants investigation. Geldard [11] hypothesized that the CRE and other saltation illusions occur due to brain's tendency to integrate sensory inputs over time and space to create a continuous perceptual experience. The following effects have been cited as contributing to misperception in the VSI:

Motion Induced Position Shifts

Motion-based phenomena have been used as explanations for the VSI. The Fröhlich effect [38] causes the perceived shift of the starting position of a moving object in the direction of its motion. MacKay [39] found that putting slight pressure on the eyeball can cause a viewer to observe disparity in apparent motion between self-luminous and stroboscopically lit surroundings. Nijhawan [40] re-discovered Mackay's phenomenon, which has become well known as the flash-lag effect. That is, a moving object is perceived to go ahead of a flashed object even though both stimuli were physically aligned when the flash appeared. In the motion drag illusion [41], the position of a flash is misperceived, shifting to the direction of nearby motion. The flash drag effect is caused not only by real motion but also by bistable apparent motion [42]. When an object's background moves back and forth in the flash grab effect, it can also produce a stronger shift of an object's position when attention is modulated [43].

In the case of VSI, apparent motion between the first (or second) flash and the third flash could be hypothesized. The motion-based position-shift phenomenon generally shifts the perceived position of a flash to the forward direction of motion. This matches the perceived shift of the second flash position in VSI. However, motion induced position shifts (MIPS) would not be sufficient to explain the effect when the last two stimuli are presented in the same spot in the VSI.

Perceptual Grouping

Another explanation for the VSI is not based on motion signals. When a train of clicks are presented in the same manner as taps in the CRE, instead of hearing clicks distinctly in illusion conditions, subjects reported hearing a blur of clicks. With each click being perceived to be equally spaced in time, the researchers cited perceptual grouping to be responsible[27]. The perceptual system seems to prefer a simple interpretation for ambiguous or complicated stimuli, according to the principles of Gestalt psychology. Perceptual grouping gives individuals sense to the random chaos presented daily. This is why certain patterns appear when the eyes are presented with rows of dots (dots grouped horizontally, vertically, or even diagonally), or why people see images in clouds.

Since swift presentation of flashes makes it difficult for observers to exactly perceive the positions of the flashes in the VSI, they may select the simplest interpretation of the spatial relationship of the stimuli. Khuu et al. [44] also cited perceptual grouping as responsible for the VSI when stimuli such as flashes moving across a screen, appear as real motion. This mechanism is hypothesized to occur in a consciousness level, and not in the retinal representation level [45].

Postdiction

Later events have the ability to affect the interpretation of an earlier event in the hypothesis of postdiction [46, 47]. Postdiction, related to perceptual grouping, would be a reasonable explaination to explain shifts of the second flash at the midpoint of the first and third flash. When three flashes are presented within a certain temporal window, after the third flash physically appears, the interpretation of the group of events (three flashes) could be constructed. This process implies that not only is our brain capable of predicting events, but it can also reconstruct how we interpret the past. What we think of as happening "in real time," might involve be an even more complex process that involves some mental reconstruction which might occur when perceptual expectations are not met [48, 47]. Postdiction has also been used to explain motion-induced phenomena and even the CRE [49, 50].

Bayesian perceptual model

Goldreich [51] utilized a Bayesian model to explain saltation in the CRE and its related illusions. A Bayesian model is based on Bayes' Theorem which provides a mathematical framework for updating probabilities based on new evidence. A study that used the Bayesian model to explain decision-making processes in visual perception found that prior assumptions play a significant role in resolving ambiguity in the perception of 3D shapes [52]. The rapidly presented flashes of the VSI could also fall under the same category as ambiguous stimuli.

When VSI stimuli are presented, our brain will rely on cognitive priors, specifically that of slow-moving objects as a comparison to interpret the stimuli. The Bayesian observer uses the expectation combined with sensation (a flash or a tap) to produce perception through statistical models. [51, 49] Lastly, in line with Gestalt principles, it also assumes that humans tend to find a connection to stimuli presented close to each other in space and time [51]. This could explain why flashes presented at a considerate distance from each other spatially and temporally in the VSI would result in the illusion's nonappearance.

The visual saltation illusion is a fascinating phenomenon that can provide answers in how reality is interpreted. However, there is still much that is unknown as the basic approach to its investigation has not been varied. Research on the VSI will not only enrich the field of understanding saltation phenomena but also provide some insight into similar visual effects.

1.2 Objectives and research plan

Unlike the CRE, research on the VSI has not been as extensively explored. In the study previously mentioned that investigated how patients with schizophrenia perceived visual illusions [3], the VSI was not included in the list of examined illusions. This lack may be due to the basic limitations of vision. When direct attention is focused on the tap locations in the CRE, the hopping sensation can still be felt and reported [53]. However, when the same attention is given to flashes in the VSI, it is unlikely that the illusion will be perceived. The VSI is limited to subjects viewing stimuli at a peripheral location [10, 11, 49].

Past VSI experiments have varied the stimulus properties such as presenting the VSI using 3D objects [54] presenting it in 3D space [44], or changing other feature aspects of the stimuli and background. However, the location of the stimuli presentation in the reduced VSI has not been altered. Typically, studies continue to present the first and second flash in the same location and the third at a distance (L1-L1-L3), utilizing the translation presentation mode.

Thus, this research's goal was to approach this classic illusion from a different angle and fill gaps in VSI research. This was carried out through a series of psychophysical experiments that could serve as a basis for future, slightly more invasive experiments.

The first approach was to change the typical presentation of the VSI by presenting the first flash in one location and the second and the third flash in the same location (L1-L3-L3).

If the results of this experiment are successful, it would be plausible that more novel positions can achieve saltation (L1-L2-L3 in perception).

The second approach was to change the transformation mode of the VSI, which has not been researched before. The purpose of this would be to observe the versatility of the VSI. In this thesis, it would be to test whether size misjudgment would occur in the expansion and contraction presentations mode. Achieving saltation in this novel presentation mode would mean other parts of the brain are susceptible to this phenomenon. This could also imply memory—a principal factor in size illusions—and perception may rely on similar neural mechanisms [55, 56].

Not only are these novel approaches to studying the VSI, but successfully achieving saltation would indicate higher level processing, such as memory and attention, are involved in this illusion. This is linked to another objective, which was to test whether motion-induced position shifts, which involve low level processing, are solely responsible for saltation. As such, this study could show how postdiction and/or other neural mechanisms play a more prominent role in the VSI and accordingly, other saltation illusions. This in turn provides more evidence of shared underlying principles in how our brain perceives and processes information from different sensory inputs; giving comprehensive insight into the saltation phenomenon.

1.3 Thesis structure

The main chapters (Chapters 2-3) were originally written in the style of individual papers but were slightly adjusted for this thesis to address any overlaps, especially in the methods sections. Chapter 2 has been published in the journal i-Perception. The results of Chapter 3 were presented in the Vision Society of Japan Winter Conference (Tokyo, 2024).

Chapter 2 describes the initial study focused on changing the typical position of the second flash in a series of three experiments. The purpose of these novel positions was to determine whether the neural mechanisms used to explain the VSI second flash are still applicable under conditions that seemingly contract the original hypotheses. The outcome of these experiments displayed the strength and variability of the illusion, which paved the approach for preceding experiments. The same apparatuses described in Chapter 2 were utilized in the remaining chapters as well. A short discussion regarding preliminary experiments will mention some interesting discrepancies between a few participants' responses; this is addressed again in the final chapter.

Chapter 3 applied the versatility of the VSI by utilizing in a different presentation mode. Experiment 4 applied similar parameters (stimuli duration and interstimulus intervals) of past VSI studies under the new mode of expansion and contraction. Experiment 5 further investigated whether stimuli duration or ISI has more of an impact on visual saltation by employing a combination where ISI or duration was constant, while the other parameter was manipulated.

A summary of the main chapters is discussed in the final section. Chapter 4 contains further discourse regarding the impact and implication of this study not addressed in the individual chapters. Limitations of the thesis as a whole, potential studies, and a conclusion are also made.

Chapter 2

Novel positions of the second flash in the visual saltation illusion

2.1 Introduction

One goal of this research is to further examine potential causes of the VSI by using novel second flash positions. This chapter tests the low-level motion-signal based explanation of the VSI and demonstrates a new type of VSI that has not been reported to date. Varied positions of the second flash were used as main factors in three experiments. The differences and similarities in responses throughout all three experiments will reveal whether there is shared mechanism in position misperception.

In Experiment 1, the second flash was presented at the same position as the third flash. Asai and Kanayama [53] had tested this backwards presentation (L1-L3-L3) with the CRE and showed that, although less frequently than the typical forward CRE pattern (L1-L1-L3), subjects can perceive taps at three separate locations (L1-L2-L3). Pairing the backwards presentation with a flash that is congruent to the midpoint of the first and third tap can strengthen this perception as well. However, Asai and Kanayama [53] did not require subjects to locate the position of the second tap, nor was any response collected regarding the flash stimuli. Would the same results occur solely using visual stimuli? It can be hypothesized that the perceptual position shift of the second flash would not arise if VSI is caused by motion signals because there are only possible motion signals arising between the first and the second (or the third) flashes and there is no room for a forward position shift of the second flash. To perceive the hopping, that is, to perceive the second flash as to be in midway of the first and the third flash positions, the position of the second flash should shift backward. Thus, the stimulus condition could test the motion-based explanation of VSI.

In Experiment 2, the motion-based hypothesis was further investigated by breaking the spatio-temporal relationship through reversed conditions, where the second flash appeared outside the area between the first and the third flashes. The direction of a hypothesized motion signal between the first and second flashes was opposite to that between the second and third flashes. Furthermore, the positional relationship was not sequential here. The most similar phenomena akin to this second flash presentation would be the flash grab effect, a motion-induced effect that does not rely on motion in one continuous direction. A texture presented repeatedly moving in one direction and then reversed can induce a positional shift of a flash shown at the moment of the motion direction reversal [43]. Although the VSI is not presented on a moving background, the presentation of the second flash out of bounds can be likened to the back-and-forth motion of the flash-grab. Since "motion" of the VSI would reverse at the second flash position, it may account for perceiving the second flash close the flash (either the first or the third) it was presented to, those but may not be sufficient to explain perception at the midpoint.

In Experiment 3, the second flash was presented midway between the first and the third flashes but with a physical shift in a right-angle direction. In the grouping hypothesis, the second flash position should not be limited to being aligned with the first and the third flashes to cause VSI. If the hopping-in-line percept arises even when the position of the second flash shifts from the midway point between the first and the third flashes in any direction, the VSI may not be based on low-level motion signals but caused in a higher-level interpretation process.

2.2 Experiment 1

As aforementioned, the VSI is typically presented with the first two stimuli in the same position. The objective of this experiment is to observe if results can be replicated if the experiment were to be presented backward, or where the last two stimuli are presented in the same position. A preliminary experiment was conducted to observe whether all three stimuli can be perceived even when the last two stimuli were presented in the same position (see Appendix A). Except for two volunteers (PS1 and PS2), all three stimuli were perceived in the correct sequence by the remaining participants. The first and third flashes were perceived approximately at their actual flashed positions, and the second flash was perceived to occur at a point between. Since the perception of the first and third flash locations was established to be consistently identified between participants, the following experiment asked participants to identify the second flash only. The unusual perception of the entire flash sequence of PS1 will be discussed that the end of the chapter.

2.2.1 Methods

Participants

Thirty-nine participants (18 men, 17 women, and four who did not disclose their gender, ranging in age from 18 to 34 years) with normal or corrected normal vision participated in this experiment, eight of whom were familiar or aware of the VSI. Thirty-six of these participants were Kyushu University students. All participants were informed of the possible risks, gave written consent, and were compensated monetarily for their time, except for one faculty member.

Apparatus

The PsychoPy [57] program was used to create the experiment, which was displayed on a 24.5-inch organic light-emitting diode display (SONY PVM- 2541) in a dark room [58]. The screen resolution was horizontally 1920 × vertically 1080 pixels. Participants' eyes were distanced approximately 40 cm from the screen with their heads resting on a chinrest. The display refreshed at 60 Hz.

Stimuli

Flashes were white circles, measuring 100 pixels (4.1 deg) in diameter with a luminance of 99.4 cd/m^2 and presented on a grey background that had a luminance of 19.8 cd/m^2. The first and the third flash positions were presented 15.7 deg apart on the same horizontal line.

Using the length of the first and third flash as a scale, the second flash was presented at the same position as the first flash (0%), at the midpoint (50%) between the first and third flash positions, at the center point between the midpoint and the first flash (25%), at the center point between the midpoint and the third flash (75%), and at the third flash position (100%) (Figure 2.1). Flashes originated from the left or right.

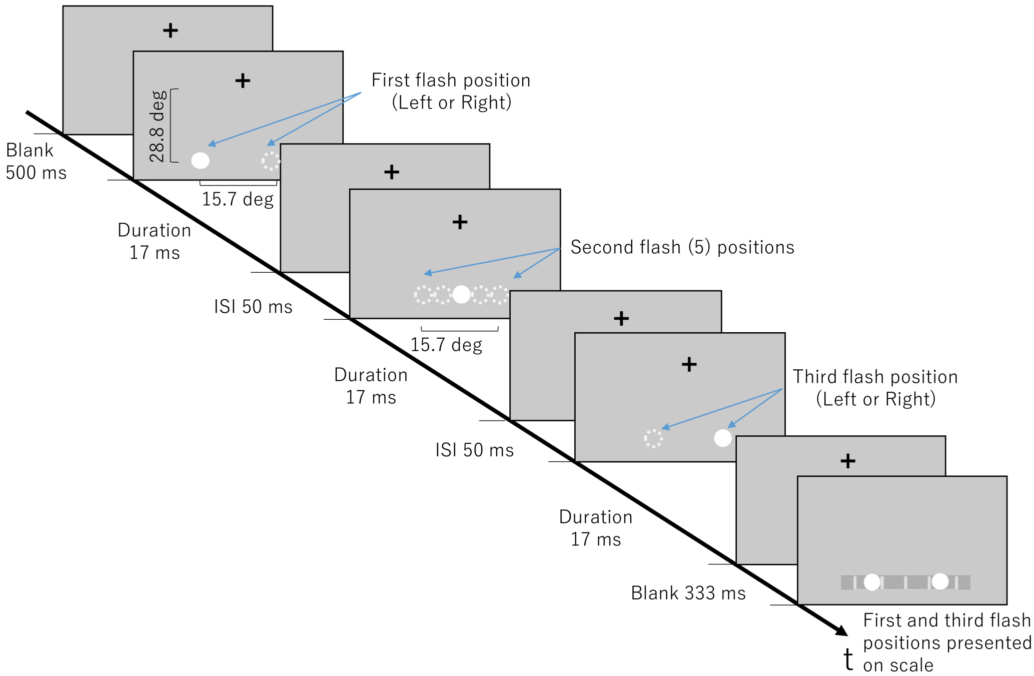

Fig. 2.1 Experiment 1 stimulus parameters for illusion conditions. Experimental display that gives an example of stimuli moving in the left to right direction, indicated by solid white circles. Dashed white circles indicate other possible positions the flash could occur during the indicated time.

Stimuli had an ISI of 50 ms and a SOA (Stimulus Onset Asynchrony) of 67 ms in the illusion condition and an ISI of 950 ms and SOA of 1000 ms in the control condition. To investigate the effect of second flash position in the saltation illusion, a duration and ISI (thus, SOA) that could produce a clear saltation illusion was needed. Through a preliminary experiment, the short ISI and duration as noted above for the illusion condition was selected. Ito et al. [37] also showed short SOAs are favored by the VSI. To demonstrate that the valid position could be perceived when the saltation illusion did not occur, the long ISI and duration as noted above were chosen for the control condition.

Procedure

Participants performed practice trials until they were comfortable with the task before commencing the actual experiment. They were instructed to fixate their eyes on a cross on the screen that was in horizontal alignment with their eyes during the trials. This fixation point was located 28.8 deg above the horizontal midpoint where the flashes would occur. A trial consisted of three flash stimuli. Participants were informed of the first and third flash locations on the monitor and that they will interchange randomly between trials; they were not informed of the exact second flash positions. After one trial, a scale would appear, and participants were instructed to click at a point on the scale where they perceived the second flash relative to the first and third flash.

The scale appeared in the same horizontal location as where the flashes occurred, as a gray bar with five light gray markings at equally spaced positions that did not correspond to any of the second flash positions, except for a mark at the center that represented the midpoint of the first and third flash positions as shown in Figure 1. White circles (same as the flash stimuli) on the actual position of the first and third flashes also appeared on the scale (Figure 2.1). Participants were advised that the white circles indicate the actual positions of the first and the third flash and can assist in identifying where they perceived the second flash. They were also advised the white markings could help to make their selection more precise, but that the markings did not represent locations of flashes. Participants were told to click anywhere on the scale where they perceived the second flash. After a selection was made, the next trial began.

Each participant underwent the 10 conditions (5 s-flash positions × 2 directions) six times in random order under the illusionary condition and the control condition, resulting in two blocks of 60 trials for a total of 120 trials. The administration order of the illusion and control block was randomly assigned for each participant to observe for any order effects.

Data Analysis

R software [59] was used to analyze perceived positions of the second flash relative to the position of the first and third flash. Three participants' responses were not included in the final data analysis after noticing their results had abnormalities in the control conditions. In control conditions, two participants reported the second flash to occur at the opposite location. For instance, if the second flash was presented in the same location as the first flash, the two participants would report the second flash to occur in the same area as the third flash. If the second flash was presented 25% from the third flash, they would report it to occur 25% from the first flash. The third participant reported mostly seeing one flash, rarely two or three, in illusionary conditions and would typically select the position of where they perceived the first flash. Under control conditions, this participant reported seeing mostly two to three flashes, and would typically select the first or their flash positions as where they perceived the second flash. Due to the inability to perceived approximate locations of the second flash in control conditions their data was not included and, the results are that of 36 participants.

The five physical second-flash positions and corresponding perceived second-flash positions were aggregated with horizontal reversals according to the presentation direction (left-to-right or right-to-left). Clicking the center mark of the scale would be equivalent to a proportional value of 50%, while clicking at the exact point of the first flash position and third flash position would be equal to 0% and 100% respectively. These proportional values were used for data analysis. Preliminary tests showed that gender and age did not make a substantial difference in the overall results.

2.2.2 Results and Discussion

Figure 2.2 displays the proportions of perceived second flash positions relative to the first flash location for both illusionary and control conditions across 36 participants. As data analysis revealed the effect of direction was not significant; Figure 2.2 shows the combined responses from the left and right directions. Consistent with previous studies, for illusionary conditions where the second flash was presented in the same position as the first flash position (0% for the horizontal axis), the perceived second flash position was around 30%, that is, the saltation illusion occurred (Figure 2.2). Presentation of the second flash in the same position as the third flash led participants to mislocalize the flash 1.0–0.5 deg (11.8–21.2%) from the center point of the first and third flash, achieving saltation. The perceived second-flash positions did not change greatly despite the actual position changes between the first and third flash positions. For control conditions, the second flash was perceived to occur close or approximately at the actual position it was flashed, indicating that regardless of the second flash position, duration and timing of the stimuli are what influence the perception of hopping across a screen. The results indicate a VSI is perceived with a postdictive position change of the second flash under varied second flash conditions.

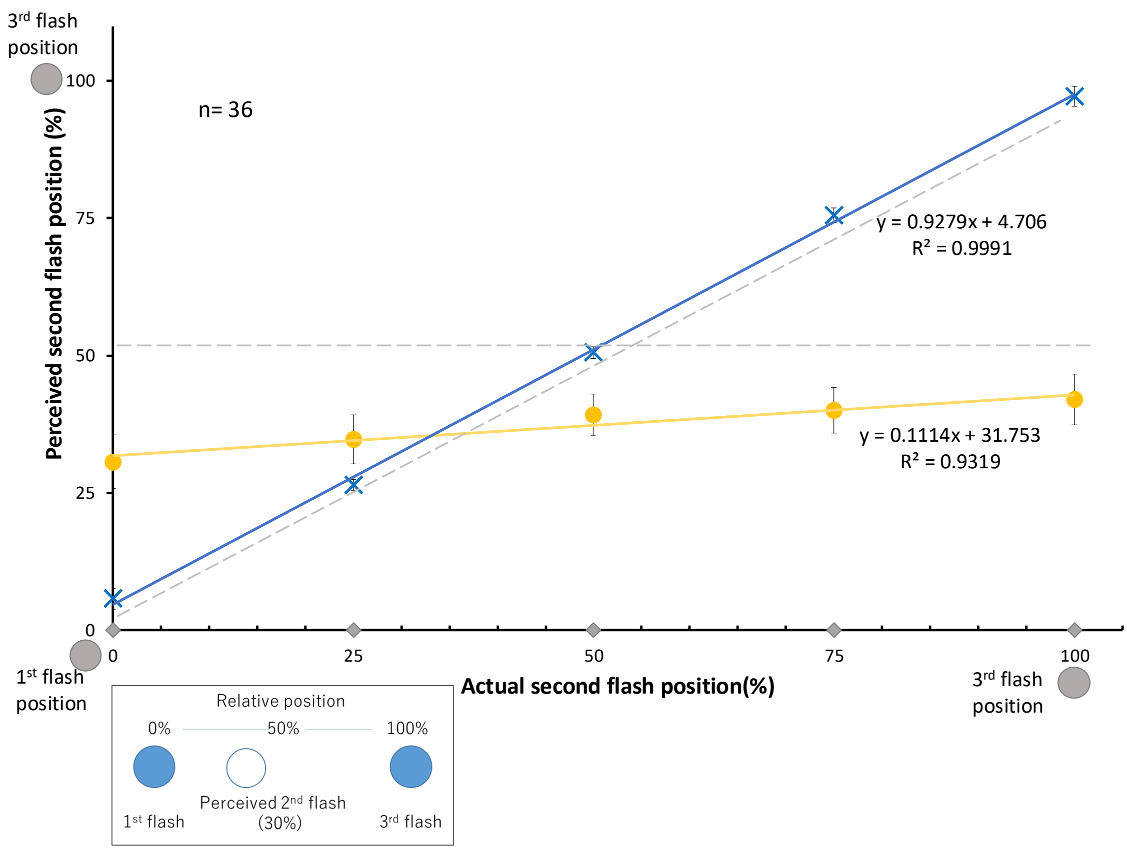

Fig. 2.2 Perceived proportion of second flash positions relative to the first and third flash. Diamonds on the horizontal axis indicate actual second flash positions with 0 representing the second flash in the first flash position and 100 representing the second flash in the third flash position. Yellow circles indicate participant responses in illusion conditions corresponding to the five second flash positions. Blue x's indicate participant responses in control conditions corresponding to the same five positions. The dashed diagonal line indicates values where the second flash would be perceived at its physical position, while the horizontal dashed line indicates saltation perceived at the midpoint. Error bars indicate standard errors of means (SEs). The inset provides an example of what the numerical values of the y-axis indicate in the main graph.

A three-way repeated measures analysis of variance (ANOVA) was conducted to test the main effects of direction, the position of the second flash, and the presentation timing (illusion or control), as well as their interaction effects on the perception of the second flash. As the violation of sphericity was indicated by Mauchly's test, Greenhouse-Geisser's epsilon was used to adjust the degrees of freedom. The effect of the direction of the flashes was not significant ($F(1,35) = 0.5961, p = 0.4453, \eta_p^2 = 0.0167$). The presentation timing factors ($F(1,35) = 16.795, p = 0.0002, \eta_p^2 = 0.3239$) and the effect of positions of the second flash ($F(3.17, 110.79) = 343.5689, p < 0.0001, \eta_p^2 = 0.9705$) were highly significant. The interaction effect between direction and presentation timing was significant ($F(1,35) = 6.1823, p = 0.0178, \eta_p^2 = 0.1501$), suggesting that the perception of the second flash is somewhat influenced by the direction flashes were presented, depending on the presentation speed. The interaction between the second flash position and presentation timing ($F(3.04, 106.5) = 192.5930, p < 0.0001, \eta_p^2 = 0.8462$) was highly significant. This interaction is clearly seen in Figure 2.2, which shows the difference in regression coefficients between the control (0.9279) and illusion (0.1114) conditions.

Shaffer's Modified Sequentially Rejective Bonferroni Procedure (MSRBP) was utilized for pairwise comparisons between perceived flash positions in illusion and control condition responses. This analysis would be beneficial for enabling a more powerful detection of significant differences, especially when making multiple comparisons among the five flash conditions. Under illusion conditions, significant differences in responses were found between the second flash at 0% and at 100% (p < .0001, adjusted p = .0002), 75% (p = .0002, adjusted p = .0013), and 50% (p = .0044, adjusted p = .0264); along with the second flash positioned at 25% and 100% (p = .0047, adjusted p = .0281). These reflect the shallow slope in the graph for the illusion condition (regression coefficient of 0.11). However, even under the 100% (at the third flash position) condition, the averaged perceived second flash position was under 50%, that is, closer to the first flash position than the third flash position. Under control conditions, significant differences were found between each flash position with higher significance levels; indicating that the difference in responses reflects the five different flash positions, together with the regression coefficient of 0.93 and R^2 of almost 1.0.

The common neural mechanisms cited to explain the VSI, such as the Fröhlich effect [38] and flash drag effect [41] are not sufficient to explain saltation when the second flash is presented in the same position as the third flash. If so, then the second flash would have been perceived to occur in the same position as or after the third flash, and the third flash would have also been perceived to have shifted toward the direction of movement. The similar perception of the second flash throughout the different actual flash positions (Figure 2.2) can reflect hypotheses that the brain makes a probabilistic assumption in order to make the most sense of stimuli that is not easily detectable [49, 27]. Perhaps the presentation of the flashes occurred at such high speeds that made it difficult for the brain to correctly process the second flash location. As a result, it is possible that throughout the illusion condition (flashes presented at a faster speed), the brain recounts the second flash to occur in the same spot in each direction respectively because it cannot detect the second flash accurately. In the control condition, when the flash is presented at slower speeds, the second flash can be identified and therefore correctly processed and reported, so there is no need to make a probabilistic assumption. This also indicates duration and ISI are important variables to make the illusion successful since the second flash in the control block was not misperceived.

Perceived second flash positions among participants who were administered the control block first were occasionally more accurate than those who were administered the illusion block first in some second flash positions. However, when analyzing their responses, no significant differences were found. This might be attributed to a possible practice effect resulting from exposure to the actual flash positions in the control conditions, which participants then applied to their responses in the illusion condition. To prevent this, the illusionary block was presented first for Experiments 2 and 3. Successful saltation of the second flash when presented at the same position of the third flash showed that similar parameters can also be applied to Experiment 2.

2.3 Experiment 2

Experiment 2 aims to observe where the second flash is perceived when it is presented out of bounds of the first and the last flash, reversing the usual forward or backward sequence of stimulus presentations. Positions (Figure 2.3) that occurred out of bounds from the first or last flash were chosen. The hypothesis is that second flash positions that occur closer to the first or last flash will be perceived closer to the midpoint of the first and last flash. The farther out of bounds the second flash is presented from either the first or third flash, the more likely a break in the flow of flashes will be perceived, making it less likely for the brain to formulate a consistent pattern.

2.3.1 Method

Participants

A screening test was performed on participants before the actual experiment to ensure their vision was normal and that they could perceive three flashes throughout the trials. Screening tests included presenting trials with two to four flash stimuli, and a potential participant must be able to distinguish between the different number of presented flashes. Twenty-one Kyushu University students and one faculty member (8 male, 13 female, and one person who did not disclose their gender, ranging in age from 20 to 31 years) with normal or corrected-to-normal vision participated in this experiment. Ten were familiar with the VSI, seven of which participated in Experiment 1. Participants were informed of the possible risks, signed a consent form, and were compensated for their time, except for the faculty member.

Apparatus, stimuli, and procedure

The apparatus and procedure were the same as Experiment 1. Stimulus appearance was also the same—only the positions of the second flash, stimulus duration, and ISI changed. The second flash was presented at the center of the first and the third flash or at positions that occurred outside the first or the third flash for a total of seven different flash positions (Figure 2.3). Participants were not advised of actual second flash positions but were told they could click at any point on the scale where they perceived the second flash relative to the first and third flash.

In terms of perceived proportion of the second flash relative to the first and third flash, with the value of 0% being the first flash and the value of 100% being the third flash, the second flash was positioned at values of -16%, -8%, -4%, 50%, 104%, 108%, and 116% relative to the first and third flash. Stimuli flashed from the left or the right, creating a total of 14 conditions. Participants underwent the 14 conditions six times in random order under an illusion block and a control block. The illusionary condition stimuli had an ISI of 33 ms and a SOA of 50 ms; control condition stimuli had an ISI of 33 ms and an SOA of 983 ms. Participants were administered the illusionary block first, then were asked questions to verify the number of flashes they perceived before proceeding to the control block. Participants underwent 84 trials per block for a total of 168 trials.

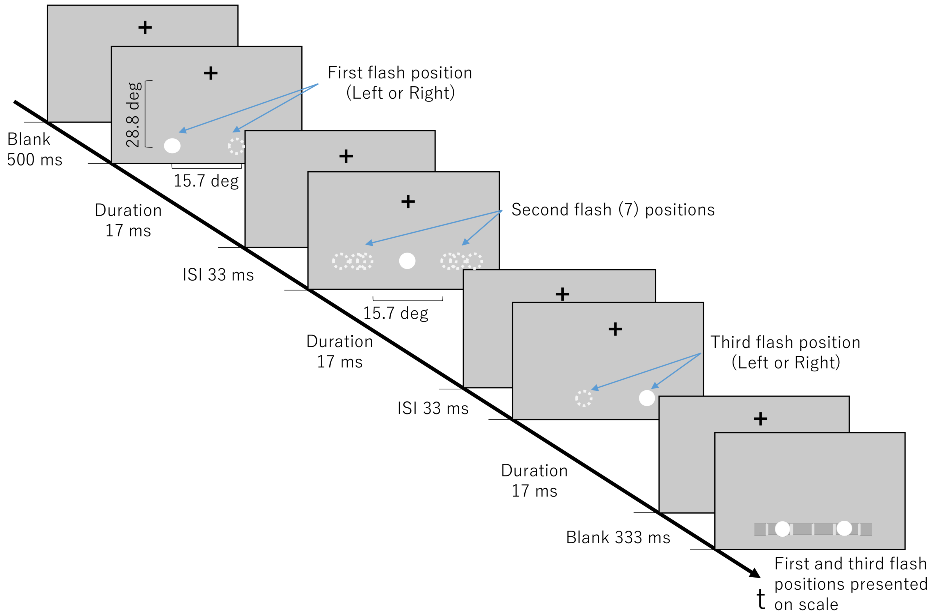

Fig. 2.3 Experiment 2 stimulus parameters for the illusion condition. Experimental display that gives an example of stimuli moving in the left to right direction, indicated by solid white circles. Dashed white circles indicated the other six possible positions the second flash could occur during the indicated time.

2.3.2 Results and Discussion

One participant's results were discarded based on their responses in the control conditions. Like the abnormal responses in Experiment 1, this participant would report perceiving the second flash "opposite" to its actual flashed position. For example, if the flashes were being presented in a right to left direction, and the second flash was presented two deg right of the first flash, they perceived the second flash two deg left of the third flash. The final data analysis includes only the results of 21 participants.

Figure 2.4 shows the results of the perceived proportion of the second flash position relative to the first and the last flash; responses in both direction presentations (right-to-left and left-to-right) are combined. On average, participants' responses under illusion conditions were similar throughout the 14 conditions; reflected by the yellow circles that are almost parallel to the horizontal dashed line shown in Figure 2.4. Under the illusion conditions, the perceived second flash positions were almost constant around 50% against the changes in actual flash positions, demonstrating that the VSI occurred even when the second flash was presented out of spatial order. Blue Xs indicate the perceived proportion of second flash positions under control conditions. Control responses almost linearly reflected the actual flash positions even outside the horizontal range between the first and third flash positions. This means that participants could validly perceive the spatial positions of the flashes when the ISI and/or duration was long.

A three-way repeated measures ANOVA was conducted to observe the same three effects as Experiment 1. As the violation of sphericity was indicated by Mauchly's test, Greenhouse–Geisser's epsilon was used to adjust the degrees of freedom. The main effect of direction ($F(1,20) = 0.3498$, $p = .5609$, $\eta_p^2 = 0.0172$) was not significant; participant responses did not vary between flashes presented in the left or right direction. The effect of stimulus presentation timing ($F(1,20) = 0.9793$, $p = .3342$, $\eta_p^2 = 0.0467$) was not significant. The main effect of the second flash position was highly significant ($F(3.71,74.18) = 991.0215$, $p < .0001$, $\eta_p^2 = 0.9802$). The interaction effect between the flash position and presentation timing was found to be highly significant ($F(3.54,70.77) = 593.0878$, $p < .0001$, $\eta_p^2 = 0.9674$). These statistics confirm that the perceived second flash positions were not much varied by the actual flash positions under the illusion conditions (regression coefficient was 0.0839), while the perceived flash positions strongly reflect the actual stimulus positions under the control condition (regression coefficient was 1.073 and R^2 was 0.99).

Using the same post-hoc analysis as Experiment 1, in control conditions, MSRBP revealed significant differences in responses between all flash positions. The ability to distinguish the correct second flash positions when presented at slower speeds can be responsible for these differences, similar to Experiment 1. In illusion conditions, significant differences were found between the second flash position at -4% and at the midpoint (50%) (p = .0014, adjusted p = .0209), at 104% (p = .0012, adjusted p = .017), 108% (p = .0002, adjusted p = .0031), and 116% (p = .0001, adjusted p = .0031). The second flash position at -16% had significant differences between the flash positions close to the third flash position; 104% (p = .0022, adjusted p = .0327); 108% (p = .0007, adjusted p = .0108). Lastly, a significant difference was present between the second flash positions at -8% and at 108% (p = .0013, adjusted p = .0188). It can be inferred that the second flash positions close to the first flash (-16%, -8%, -4%) may be perceived in a similar manner but differently from the second

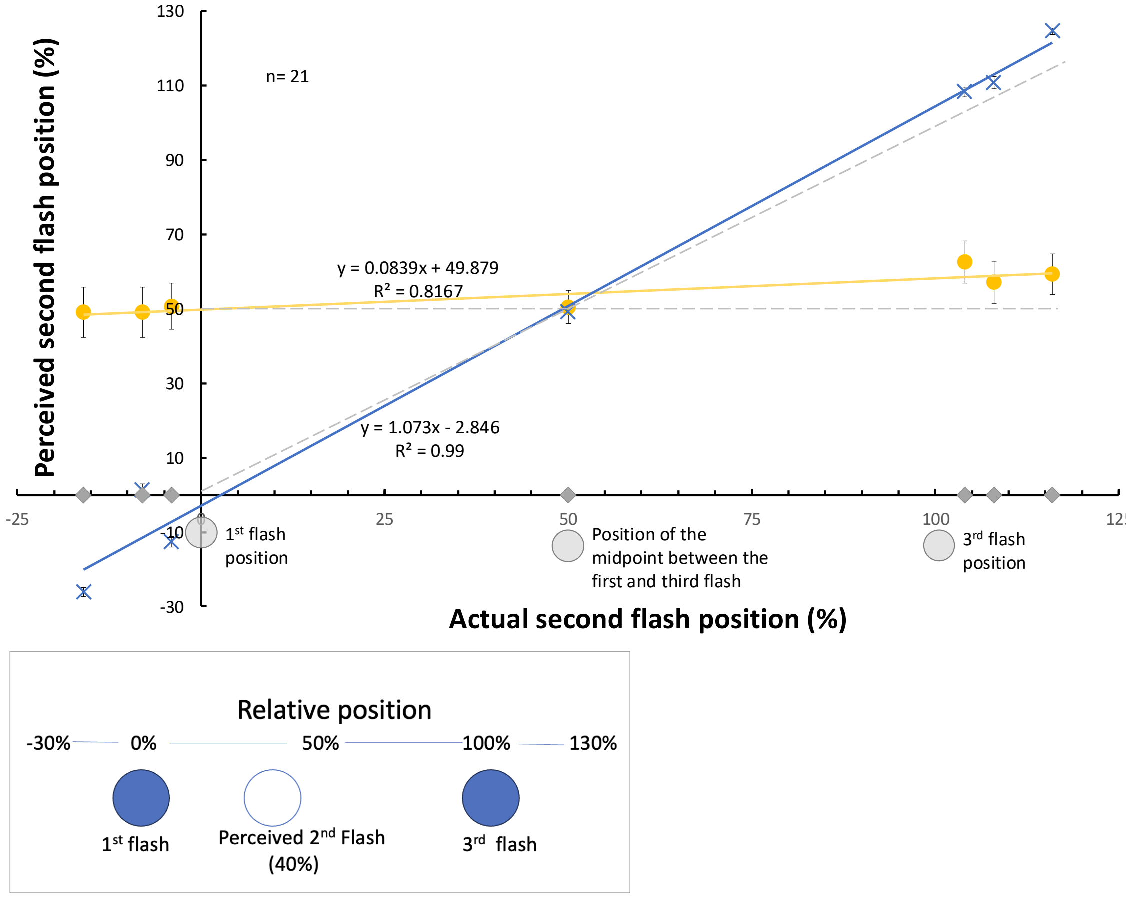

Fig. 2.4 Perceived proportion of second flash positions relative to the first and third flash. Grey diamonds indicate actual flash positions, yellow circles (participant responses in illusion conditions) and blue x's (participant responses in control conditions) correspond to the same positions. The dashed diagonal line indicates values where an illusion is not perceived, while the horizontal dashed line indicates saltation perceived at the midpoint. Error bars indicate standard errors of means (SEs). The inset on the bottom provides an example of the what the numerical values of the *y*-axis indicate in the main graph.

flash positions close to the third flash (104%, 108%, 116%) and vice versa. However, the difference is not large as indicated by the regression coefficient of 0.08.

Individual results between participants varied but, on average, saltation was achieved when the second flash was presented in a reverse condition. In control conditions, when stimuli were presented at a slower speed, participants were able to report the positions of the second flash almost accurately, indicating the importance of stimulus duration and timing. One would expect these reverse conditions to cause a 'break' in the flow of the stimuli since such positions go against previous priors which dictate a moving object should occur in sequence. Yet, for illusion conditions, participants perceived the second flash to occur somewhere between the first and the last flash position, even when the second flash was presented near the third flash, akin to responses in Experiment 1.

A possible explanation for saltation in the reverse condition could be the brain adapting to the visual crowding of stimuli; perceiving the second flash closer to the midpoint is the average position of where the brain believes it should be [60]. Crowding combined with higher speed presentation of the second flash are not typical stimuli our eyes receive on a day-to-day basis. As there is a lack of "prior" knowledge of such stimuli, the flashes are reconstructed into a pattern that makes sense: the flash is reported at the midpoint because it is consistent with real-world stimuli where fast-moving objects tend to travel in a linear sequence [61]. This can be combined with both post-and predictive effects to determine where the brain believes the second flash position should occur. For example, if the second flash occurred to the right of the first flash, and the third flash appeared to the left of the first flash, the brain would process the second flash to occur as some point left of the first flash, as this is the most logical order that a moving object would follow.

Another explanation for the perception of saltation under illusion conditions is that either the first or third flash—depending on the second flash position—was misperceived as the second flash. This misperception of flash order led to a rearrangement of the perceived sequential order of the flashes. If the second flash was presented in reverse (e.g., -8%) to the first flash, then the actual second flash will be perceived to be the first flash, and the actual first flash (which is closer to the midpoint) will be shifted perceptually near the midpoint. This hypothesis still plays into the idea of a postdictive effect under illusion conditions since a perceived positional shift still occurred through retrospective interpretation of the three-flash event.

It is also interesting to note in preliminary tests that some individuals verbally reported that they saw only two flashes (only responses of participants who perceived all three flashes were used for data analysis) while undertaking illusion conditions where the second flash was presented out of bounds. These individuals usually reported only perceiving one flash approximately at the same position as the first flash and a second (or third) flash approximately at the same position as the third flash. However, when the second flash was presented at the midpoint in illusion conditions, they reported seeing all three flashes. It is possible in out-of-bounds conditions, the brain disregards the second flash because it occurred out of sequence at such a high presentation speed that there was not enough time to process it. It is also possible that the first or third flash was disregarded, and these individuals perceived the first two or the latter two flashes due to high presentation speeds.

2.4 Experiment 3

Experiment 2 revealed that saltation can occur even if flashes are not presented in a spatially sequential order. However, for both Experiments 1 and 2, flashes occurred in linear alignment, a parameter that is constant in saltation illusions. Would saltation be possible if the position of the second flash was presented out of alignment? To test this, in Experiment 3 the second flash was presented at the midpoint between the first and the third flash—which is in alignment with the fixation point—but at different vertical locations. We hypothesized that the second flash would be perceived at a position in horizontal alignment with the first and the third flash positions because simple linear movement would be favored as a postdictively reconstructed path for high-speed object motion.

2.4.1 Methods

Participants

Preliminary tests were conducted to ensure participants can perceive three flashes throughout the conditions. Potential participants were exposed to some conditions where the second flash was completely out of alignment (such as in the upper corner of the screen, or close to the fixation point) to observe if their attention was focused on the task and not automatically clicking a certain point. Only individuals who could perceive three flashes were allowed to take part. A total of 17 participants took part in the experiment (two male, 14 female, and one who did not disclose their gender, ages ranging from 23 to 40); fifteen were Kyushu University students and one was a faculty member. Four individuals participated in both Experiments 1 and 2, while six participated in Experiment 2 only. Participants gave written consent and were compensated for their time, except for the faculty member.

Procedure

The same experimental set up as in Experiments 1 and 2 was utilized. Position of stimuli shifted 2.6 deg vertically closer to the fixation point than previous experiments. The position of the second flash occurred at five possible locations vertically along the midpoint of the first and the last flash. These second flash positions were located 30.15 deg (0%), 28.18 deg (25%), 26.2 deg (50%); 24.22 deg (75%), and 22.22 deg (100%) below the fixation point. Pilot tests revealed that some individuals did not see the second flash at the vertical midline between the first and third flash, but still perceived the second flash to occur in linear (horizontal) alignment with the first and last flash. Others consistently saw the second flash to occur along the vertical midline. Thus, based on practice trials, participants were assigned a vertical scale response screen or, a free-response screen where they were able to click at any location on the screen (Figure 2.5).

The scale's physical appearance was the same as Experiments 1 and 2 but was rotated 90 degrees so that it appeared at the midpoint of the first and third flash positions, on the same vertical line as the fixation point (Figure 2.5). The scale had the same light gray markings that did not correspond to any of the second flash positions, except for a mark at the center that represented the midpoint of the first and third flash positions. Selecting this mark would indicate the participant perceived the second flash to occur in horizontal alignment with the first and third flash. For scale-responders, the scale would appear simultaneously with two white circles that represent the first and third flash positions after three flashes occurred (Figure 5); they were free to click anywhere on the scale. For free-responses, after a trial occurred, only the two white circles would appear on the screen and participants were free to

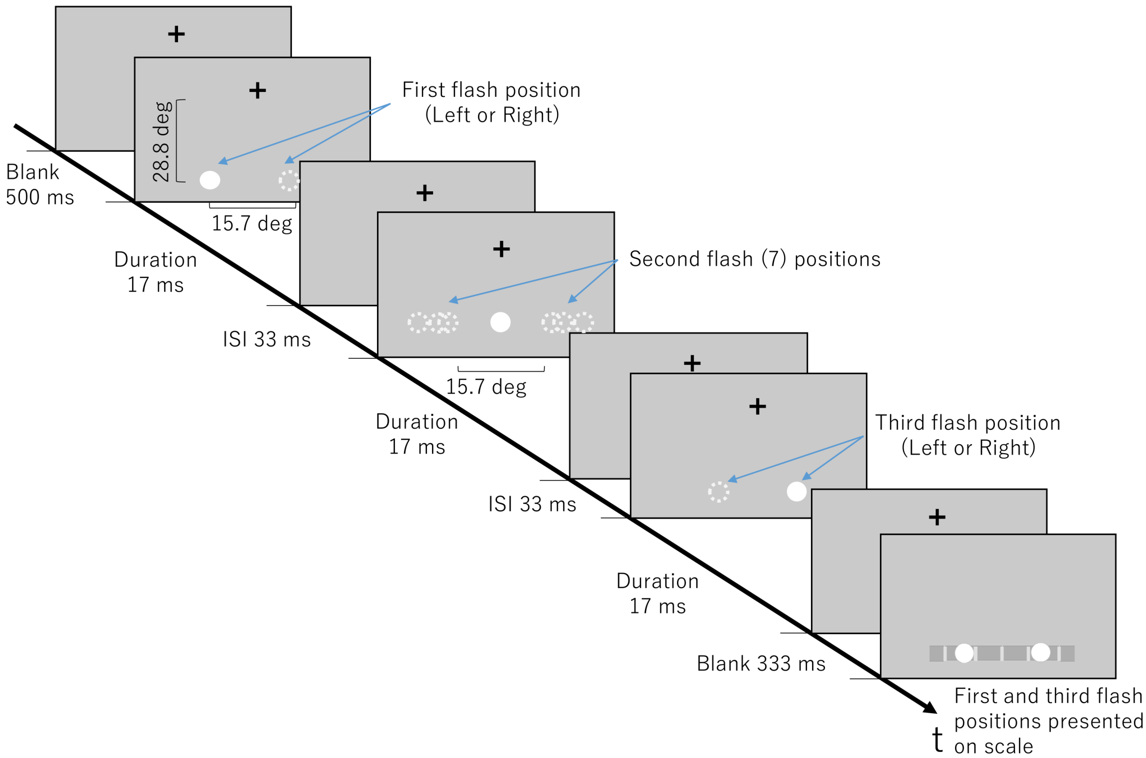

Fig. 2.5 Experiment 3 stimulus parameters for the illusion condition. Caption: Experimental display that gives an example of stimuli moving in the left to right direction, indicated by solid white circles. Dashed white circles indicated the other four possible positions the second flash could occur during the indicated time. The last screen displays the scale-response option; a free-response option looks the same but without the scale.

click at any point on the screen. Participants were instructed to use the white circles to help indicate where they perceived the second flash. Only vertical values of the free-responses were used for data analysis.

There were five second flash positions, presented in the left or right direction, creating a total of 10 conditions. Participants underwent the 10 conditions six times, under a control and an illusion setting, creating a total of 120 trials per participant. The illusion condition presented flashes with an ISI of 50 ms and a SOA of 67 ms, while the control condition had an ISI of 1000 ms and SOA of 1033 ms.

2.4.2 Results and Discussion

One participant's (P17) results were on average the same in control conditions (perceiving the second flash at the vertical midpoint) as well as in illusion conditions (perceiving the second flash around 30.15 deg below the fixation point). Grubb's test for outliers was employed. It was found that P17's responses on 3 out of the 10 conditions under the illusion parameters were outliers. P17 verbally reported seeing the three flashes form an arch in illusion conditions and perceiving the flashes mostly in a straight line in control conditions. Based on the outlier test and the inability to perceive the flashes in their approximate positions in control conditions, P17's responses were not included in the final data report. The following results are those of 16 participants only.

Out of the 16 participants, only three perceived the second flash to occur along the vertical midline between the first and their flash positions and were given the scale response. The rest used the free-response option. For easier data analysis, the y-components of free-responses were converted to scale values. Due to the low number of scale responders, their responses were combined the free-responses and analyzed together. Figure 2.6 displays the results of the participant responses of how they perceived the second flash in the illusionary and control conditions both in the right and the left direction. Throughout all illusion conditions, the 16 participants misperceived the second flash to occur somewhat in alignment with the first and last flash. Second flash positions farther from the fixation point (i.e., below 50% position) were more likely to be reported to occur exactly at the midpoint of the second flash (Figure 2.6).

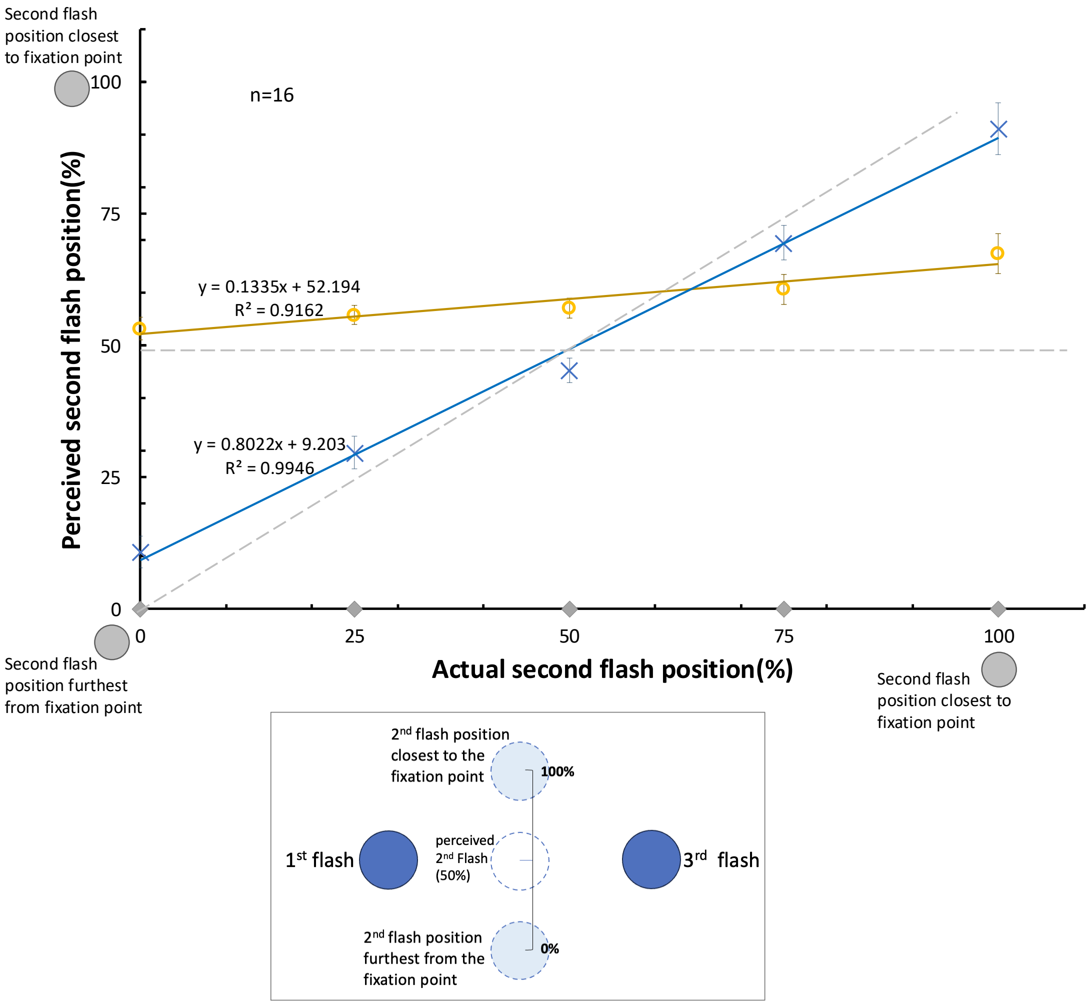

Fig. 2.6 Perceived proportion of second flash positions relative to the first and third flash. Grey diamonds indicate actual flash positions, yellow circles (participant responses in illusion condition) and blue x's (participant responses in the control condition) correspond to the same positions. The value of 0 represents the second flash at the farthest position from the fixation point and 100 represents the second flash position closest to the fixation point. The value of 50 represents the horizontally aligned position with the first and third flashes. The dashed diagonal line indicates values where an illusion is not perceived, while the horizontal dashed line indicates saltation perceived at the midpoint. Inset shows how participant perception is interpreted into a percentage value.

The main effects of direction, the position of the second flash, and the timing (control and illusion) as well as their interaction effects on perception of the second flash were analyzed using a three-way repeated measures ANOVA. As the violation of sphericity was indicated by Mauchly's test, Greenhouse-Geisser's epsilon was used to adjust the degrees of freedom. Just as in Experiments 1 and 2, the direction the flashes were presented was not significant ($F(1,15) = 0.3233$, $p = .5780$, $\eta_p^2 = 0.0211$). The effect of presentation timing ($F(1,15) = 15.055$, $p = .0015$, $\eta_p^2 = 0.5009$) was significant. The main effect of the vertical positions of the second flash ($F(1.48, 22.15) = 110.8029$, $p < .0001$, $\eta_p^2 = 0.8808$) was highly significant. The interaction between the vertical flash position and the control and illusion condition ($F(2.38, 35.68) = 96.0262$, $p < .0001$, $\eta_p^2 = 0.8649$) was also highly significant. The difference in regression coefficients (0.1335 for the illusion condition vs. 0.8022 for the control condition) indicates that the perceived vertical position of the second flash did not vary much when the flashes are presented at high speeds, versus slower speeds, depending on the changes in the actual vertical position of the second flash.

Shaffer's MSRBP found significant differences for the second flash perceptions at all positions in control conditions. Under control conditions, participants were able to locate the approximate position of the second flash. Under illusion conditions, MSRBP showed significant differences between the second flash position closest to the fixation point (100%) and each flash position; at 75% ($p = .0013$, adjusted $p = .0122$), 50% ($p = .0012$, adjusted $p = .0122$), 25% and 0% ($p = .0017$, adjusted $p = .0122$). Flash positions closer to the fovea would be less likely to be perceived in linear alignment and therefore more likely to be perceived accurately even when presented at high speeds. A significant difference was found between the flash position at 75% and at 0% ($p = .0066$, adjusted $p = .0396$) as well. Flash positions at and below the horizontal midpoint were perceived in a similar manner.

Under the illusion condition, the farther the second flash was from the fixation point, the more likely the participant would select the second flash to occur close to the vertical midpoint of the first and third flash. This may be attributed to the fact that objects presented farther from the fovea are harder to detect spatially when the presentation is brief. Because there is limited information or spatial ambiguity, stimuli are processed according to the principle of good continuity, resulting in the perception of coherent patterns. While flashes closer to the fixation point are closer to the fovea and therefore should be more likely to be perceived in the correct position, these flash positions were still misperceived to occur farther from their physical position. The speed of stimulus presentation possibly allowed second flash positions to be misjudged to occur close to the midpoint in the illusion conditions, although not as close to the midpoint as second flash positions further from the fixation point. This reflects that top-down processing may be more dominant over bottom-up processing in experimental setups such as the VSI, consistent with previous perceptual studies [62].

This experiment is limited as it only presents the second flash along the vertical midpoint of the first and the third flash. Also, the differences in response options prevent a completely cohesive output, although scale responders were only three. Future experiments can approach the vertical shift in combination with the parameters of Experiments 1 and 2. However, the results of Experiment 3 are very promising for future saltation illusions, indicating that linear presentations of stimuli are not necessary to achieve saltation.

2.5 General Discussion

This chapter explored VSI by varying the position of the second flash in relation to the first and third, introducing it in the same position as the third flash, a reverse position, and outside of linear alignment; demonstrating the brain's remarkable ability to construct meaningful interpretations from visual stimuli. These modifications to the traditional saltation experiment not only challenge previous constraints but also highlight the flexibility of human perceptual systems. These findings align with the CRE conditions outlined by Geldard and Sherrick [10], providing evidence that novel positions of the second stimulus can still elicit perceptual hopping effects if the duration and ISI are optimally set. Our methodology, following Geldard's [28] work, involved using a minimal stimulus configuration of three flashes to dissect the complexities of low-level and high-level processing effects, a significant leap from prior studies where the first and second flashes were collocated and where flash stimuli are presented in alignment.

In comparison with other sensory modalities, a similar pattern of stimulus parameters can be observed from the results of this chapter. The original CRE [10] favored ISIs of 40 to 60 ms, while the CRE administered on the fingertips favored ISIs of 20 ms [63]. CRE projected out of the body was achieved with an ISI range of 50 to 80 ms [20]. This is consistent with the short ISIs used in this study—33 and 50 ms—that favor the VSI under novel conditions. This also aligns with the ideal range of ISIs at 20 to 150 ms for successful saltation in hearing [25–27]. In this chapter, a short duration of 17 ms was found to be the most effective, which is consistent with Bremer et al.'s [25] study, which utilized a 20 ms duration. Shore et al. [27] used an extremely rapid click duration of 1 ms; however, SOAs of 121 and 150 ms were sufficient to produce the illusion, which, although not tested in this chapter, may prove to be a sufficient SOA value for the VSI under these novel conditions. For saltation under temperature and pain perception, an ISI of 1000 ms between the first and second stimuli could produce a saltation effect paired with a preceding ISI of 60 ms. ISIs or durations of 950 to 1000 ms used in this chapter's experiments were the ideal timing for control conditions. Perhaps the rapid presentation of laser beams in Trojan et al.'s experiment would be difficult to distinguish as three separate stimuli, unlike flashes presented on a screen.

The observed effects from these experiments cannot be solely attributed to low-level motion signals such as that of MIPS, particularly when considering the altered positions of the second flash that do not align with expected motion directions. The perception of the second flash at a midpoint opposite the motion direction in Experiments 1 and 2, or beyond the third and/or first flash position in Experiment 2, suggests a reversal in motion perception that challenges the motion-signal hypothesis. If MIPS were the sole cause of the illusion, placing the second flash in the same position as the third flash should have caused it to shift in the direction of motion, displacing it beyond the bounds of the first and third flash locations. Additionally, the position of the third flash might also have been expected to shift, occurring at a point farther from its original location. However, this was not observed in this chapter. When the second flash was presented at the same location as the third in Experiment 1, it was displaced to appear at the midpoint between the first and last stimuli, while the first and last stimuli remained anchored at their true locations.

These phenomena, akin to the flash-grab effect [43], point towards a postdictive mechanism where the brain reconstructs the event's sequence after receiving signals, indicating a level of perceptual processing that goes beyond simple motion tracking. In Experiment 3, flashes are still presented in the left or right direction, with only the vertical position of the second flash changing between trials. Here, motion signals can explain the second flash shifting away from the horizontal midpoint, but not shifting down or up towards the vertical midpoint. A postdictive hypothesis may be plausible in which the three positions of the flashes become a perceptually reconstructed event after the brain receives the three flash signals.

The interplay between attention and VSI is touched on in Experiment 3, where the illusion's intensity diminished for stimuli closer to the fixation point. Experiment 3 shows the possibility of an attentional affect, while also aligning with Geldard's [28] observations that the VSI predominantly occurs in peripheral vision. This pattern is consistent with reports indicating that focused attention weakens similar illusions, such as the flash lag effect [64–66], where the unpredictable positioning of stimuli amplifies the illusion, suggesting a contrast to VSI's behavior where predictability of flash position change might intensify the illusion. Adamian and Cavanagh [67] further elucidated that directed attention, especially when participants concentrate on specific aspects like a flash position, significantly alters the perception of illusions such as the Fröhlich effect. This insight, coupled with evidence that subsequent motion signals can correct misperceptions by revealing an object's true starting position [50], points towards how attention and prediction of motion paths influence VSI. These findings pave the way for future inquiries into the role of attention in VSI, especially how the perception of flash sequences and the consequent illusions are affected by the focal point of attention and the predictability of motion.

Cognitive biases may also explain saltation between the three experiments. Past research on slow priors theorizes that the typical exposure to slow-moving objects does not perceptually prepare our brain to process fast-moving stimuli such as those in visual saltation experiments [61], which leads to the misperception of stimuli. The results of this study show that although there is a similar perception of such fast-moving stimuli peripherally, on average there are some individuals who process such stimuli differently, such as participants who were not able to process all three flashes. By applying the idea of how past experiences shape perception, it may be possible to train the senses to perceive fast-moving stimuli. Normal people who look down from a skyscraper report seeing people walking on the street as ants, while window cleaners who have been exposed to vision from extreme heights, do not report the same description [7]. This can be a clue on how saltation illusions can be "broken" or even strengthened. It would be interesting to test the illusion for a baseball player who is accustomed to viewing a ball in rapid motion.

Optimizing flash duration and ISI is essential for inducing the saltation effect in VSI, highlighting the effectiveness of these parameters and their role as a limitation in our study. The need to adjust these parameters became apparent when the initial settings from Experiment 1 were insufficient to elicit the desired saltation effect in later experiments, necessitating varied timing adjustments to accommodate different second flash position conditions. This underscores the relationship between stimulus positioning and timing requirements to achieve visual saltation, indicating the importance of tailoring these variables specifically for each experimental setup, especially when diverging from traditional stimulus presentations. Our findings further suggest that regardless of the second flash's spatial position, when three flashes are presented in quick succession, the perceived location of the second flash tends to be near the center of the first and third flashes. This indicates that stimuli presented within a short temporal frame are processed collectively as a single event, emphasizing the dual influence of timing on both motion detection and postdictive processing across our experiments. Such integrated perception implies a uniform expectation for the second flash's appearance between the first and third flashes, irrespective of its actual placement. This insight into how temporal adjustments can influence perceived spatial relationships within groups, without altering between-group perceptions, sets groundwork for future research to explore universal temporal parameters that might govern the perception of saltation and other spatiotemporal illusions.

Another observation consistent with the original VSI is that, even with novel second flash positions, the VSI primarily arises in the peripheral retina. While the eccentricity range of 26 to 29 deg used in this chapter mirrors the parameters of the original VSI, Geldard utilized even lower values, such as 20 degrees. Based on preliminary tests, such distances would not induce a saltation effect under these novel second flash positions. This may suggest that more complex presentations of stimuli require peripheral adjustments in stimuli presentation. As the peripheral retina is more attuned to detecting motion and changes in the visual field, this specialization may explain why the VSI is stronger in the periphery, where the visual system prioritizes motion cues to maintain spatial awareness and monitor the environment. This peripheral preference aligns with the brain's tendency to process sensory information based on ecological relevance, favoring motion-sensitive pathways in the periphery to ensure rapid and efficient responses to environmental changes. This is why, under the rapid presentation of stimuli, the VSI arises, while in control conditions, where motion is less likely to be perceived—even in the periphery—saltation does not occur.

Investigating novel second flash positions shows even more possibilities for the VSI. Successful saltation can be carried on in different presentation modes of the illusion, such as 2D or 3D rotation. However, the results of this chapter suggest that for these novel versions, customized parameters would be necessary for successful saltation. Future experiments can also utilize the novel second stimulus positions presented in this study using different sensory modalities; outcomes of such experiments can reveal nuances in the somatosensory cortex.

2.5.1 Discrepancies in participant reports of flash location and number

Among the preliminary experiment participants, two individuals (PS1 and PS2) misperceived the position of all three flashes under illusion conditions. If the first flash was presented from the left relative to the fixation point, they would perceive the flashes to originate from the right (see Appendix A). However, like the other participants, they perceived the second flash to occur at the midpoint across the illusion trials. Participant PS1 later reported having a certain visual condition. In preceding experiments, no other participants displayed this opposite location identification trend.

However, in Experiment 1, a few volunteers consistently reported perceiving only two flashes under some illusionary conditions during the practice trials, with one volunteer even reporting seeing only one flash throughout the trials. These individuals were excluded from participating in the experiment. This ratio increased slightly in Experiment 2 but was not observed among the volunteers of Experiment 3. Based on verbal reports, individuals who perceived two flashes typically described seeing one at the first flash location and another at the third flash location. It remains unclear whether, during visual processing, the brain discarded the second flash entirely, allowing participants to perceive only the first and third flashes, or whether they perceived the second flash but mislocalized it to the position of the last flash.

Very few individuals reported perceiving four flashes under illusion conditions in Experiments 1 and 2 (once or twice during the practice trials). Based on their verbal reports, they perceived the first flash near the actual first flash position and the fourth flash near the third flash position. The second and third flashes were not perceived to occur at the same location but rather at points between the first and fourth flash positions, equidistant from each other. The phantom flash was not reported in conditions where the second flash was presented at the midpoint.

These reports, though few, may indicate the subjective nature of perception and the tendency toward perceptual continuity. While the majority of participants perceived three flashes, these few individuals, when the second flash was presented either near the first or the third flash, perceived an incomplete sequence—albeit one that was consistent between them. The under- and over-reporting of flashes may be loosely explained by the interstimulus interval (ISI) of the flashes [32, 33]. Although no trends were identified in preliminary tests based on age or gender, it is possible that children may interpret the VSI results differently, even under classic conditions. Perception of the first flash at the first location and the last flash at the third location is consistent between two-flash and three-flash reporters. This emphasizes the presence of saltation with a postdictive effect, where an initial flash is reported near the approximate location and a final flash (whether second or third) near the last location. Despite differences in processing, flashes are perceived at the first and final stimuli locations.

PS1 participated in all three experiments of Chapter 2 (their results were excluded from the final data analysis). While data on how PS1 perceived the first and third flashes was not collected, their data on the perception of the second flash aligned with that of the other participants. It is possible that the VSI configuration can bring awareness of underlying visual abnormalities. Despite the visual discrepancies reported by PS1, the emergence of saltation illustrates how the visual system compensates for deficiencies. Since PS1 reported that their visual condition was acquired later in life, it is plausible that cognitive priors were still at work in ensuring cohesive visual experiences.

Chapter 3

Expanding and contracting the visual saltation illusion

3.1 Introduction

For humans, to know the position and the size of an object is a basic function of vision. However, such information is not directly acquired from the retinal image. Even the perceived position of the object is often different from the position indicated in the retinal image. The visual saltation illusion [28] is a typical example of such a position illusion. This research was inspired by this phenomenon and aims to develop it further from the position to size domain.

Past VSI studies have focused on explaining the VSI solely in its translational transformation mode. The property of translation has provided insight into how motion and flashing objects, similar to apparent motion, can cause misperception. However, other invariant properties of our visual flow—such as expansion/contraction, rotation, and even shearing—can offer just as much insight [68] and have yet to be applied to the VSI. Ito, Kubo, and de Jesus [37] showed that the translational VSI could be produced using the Kanizsa triangle and demonstrated the possibility of VSI in rotation or expansion. This study investigated size judgment in the VSI under expansion and contraction as the transformation mode.

Size misjudgment

The appearance of expanding and contracting objects is an everyday occurrence for those with normal vision [69]. When one walks closer to an object or if an object, such as a bus, moves toward the observer, although it appears larger, intrinsically it is known that the object has not physically changed in shape or size. Whitaker et al. [69] found participants misperceive the size of expanding and contracting stimuli in comparison to a reference stimulus, when they were of the same size. In the same study, the same effect was found when the outline of the object remained the same, but the texture within expanded or contracted. The researchers found there is a bias in the direction of size change, similar to motion induced positional shifts.

Movement may not always be a factor when it comes to size misjudgment. Famous static illusions such as the Müller-Lyer [70], Delbouef [71], and Ebbinghaus [72] Illusions are examples of size misjudgments even if the observer's gaze is directly on the object. In these illusions, lines or circles of the same size are misjudged to be larger or smaller in relation to each other when other surrounding shapes are present or attached near the target. Researchers cited size constancy scaling was behind the Müller-Lyer illusion [73–75]. Properties of the inducers, such as image contrast, size, and distance from the target circles can cause overestimation or an underestimation of the target size in the latter two illusions [76, 77]. When other objects are present surrounding or attached to the target, this additional information along with prior cognitive knowledge about size relativity is used to determine the target size, possibly leading to misjudgment.

A postdictive effect on size judgement was also reported. Kawabe [78] showed how the perceived size of an object can also be influenced by succeeding stimuli. Participants only judged the size of the initial stimuli: two target bars. Participants reported the size of one of the target bars in reference to the other; whether one was larger or smaller than the other, or if both bars were equal in size after another set of bars flashed. The results showed that the relative size judgement of the initially presented set of bars reflected the relative size difference of the succeeding set of bars.

The current study applied previous parameters, such as the stimulus eccentricity typical of VSI translation experiments but modified the stimuli to consist of three flashes that appear to expand or contract. While Kawabe [78] used a two-flash sequence, the present study utilized a three-flash sequence, where a participant judged the size of the second stimulus in reference to the first and the last stimuli. The illusion conditions involved keeping the sizes of the first two flashes the same while making the third flash either smaller or larger. Alternatively, the sizes of the last two flashes remained the same while the first flash was either smaller or larger. The participants' perception of the second flash determined whether the illusion was successful. Consequently, the results indicated whether the VSI would be adaptable enough to be tested across other properties of vision.

To investigate the strength and adaptability of the VSI, two experiments were conducted. Experiment 4 presented the VSI in expansion and contraction modes. Experiment 5 examined the parameters of stimulus duration and interstimulus intervals while presenting the VSI in both expansion and contraction modes. Trials where either the stimulus duration or interstimulus interval was kept constant while the other parameter increased were conducted to determine which, if any, had a greater effect. The results of these experiments may reveal shortcomings in the visual process, not only regarding location perception but also in overall feature judgments.

3.2 Experiment 4

3.2.1 General Methods

Participants

Twenty-one individuals (10 females, 8 males, 3 who did not disclose), participated in the two experiments in this study. All reported having normal or corrected-to-normal vision. Nineteen participants were Kyushu University students and one faculty member. Participants underwent practice trials to ensure they could detect three flash stimuli consistently, as well as notice size changes in flashes. It was important that a participant was able to perceive three distinct flashes or flickers and not the visual of a circle smoothly becoming larger or smaller. According to this criterion, one participant's data was discarded. All signed a consent form and were compensated for their time except for the faculty member.

Materials

Just as in Chapter 2, participants viewed the stimuli on a 24.5-inch organic light-emitting diode (OLED) display (SONY PVM- 2541) in a dark room [58] with a screen resolution of 1920 x 1080 pixels. The background was gray with a luminance of 19.8 cd/m^2. A chin rest was used to secure participants' heads and create a distance of 40 cm between the screen and their eyes. The monitor was refreshed at 60 Hz. Psychopy [57] v.2022.2.4 was used to generate the experiment.

Stimuli

Stimuli were white circles that were perceived as flashes or flickers in the lower periphery. Three sized stimuli were utilized measuring: 8.9, 6.3, and 3.7 deg in diameter. They are referred to as large, medium, and small, respectively throughout the text. The sizes of the large and small flashes were selected to ensure they were easily distinguishable in size relative to each other even when viewed peripherally. The large flash was chosen such that its edge remained at an appropriate distance from the fixation point. Once the large and small flashes were determined, the medium flash size was set to the median value. All stimuli had a luminance of 99.4 cd/m^2 and were presented at the same location, 25.9 deg below the fixation point (Figure 3.1).

A trial for expansion consisted of three flash stimuli where the first flash was small and the third flash was large. The size of the second flash interchanged between small, medium, or large between trials, creating three conditions: small, small, large; small, medium, large; and small, large, large.

A trial for contraction consisted of three flash stimuli where the first flash was large, and the third flash was small. Just as in expansion trials, three conditions were created by interchanging the size of the second flash: large, small, small; large, medium, small; and large, large, small.

Stimuli were presented under an illusion and a control condition. Under illusion conditions, stimuli had a duration of 33 ms and an interstimulus interval (ISI) of 50 ms. Preliminary experiments were conducted to determine the fastest presentation of the flashes at which, on average, no illusion would be perceived. Thus, for control conditions stimulus duration was 983 ms with the same ISI of 50 ms.

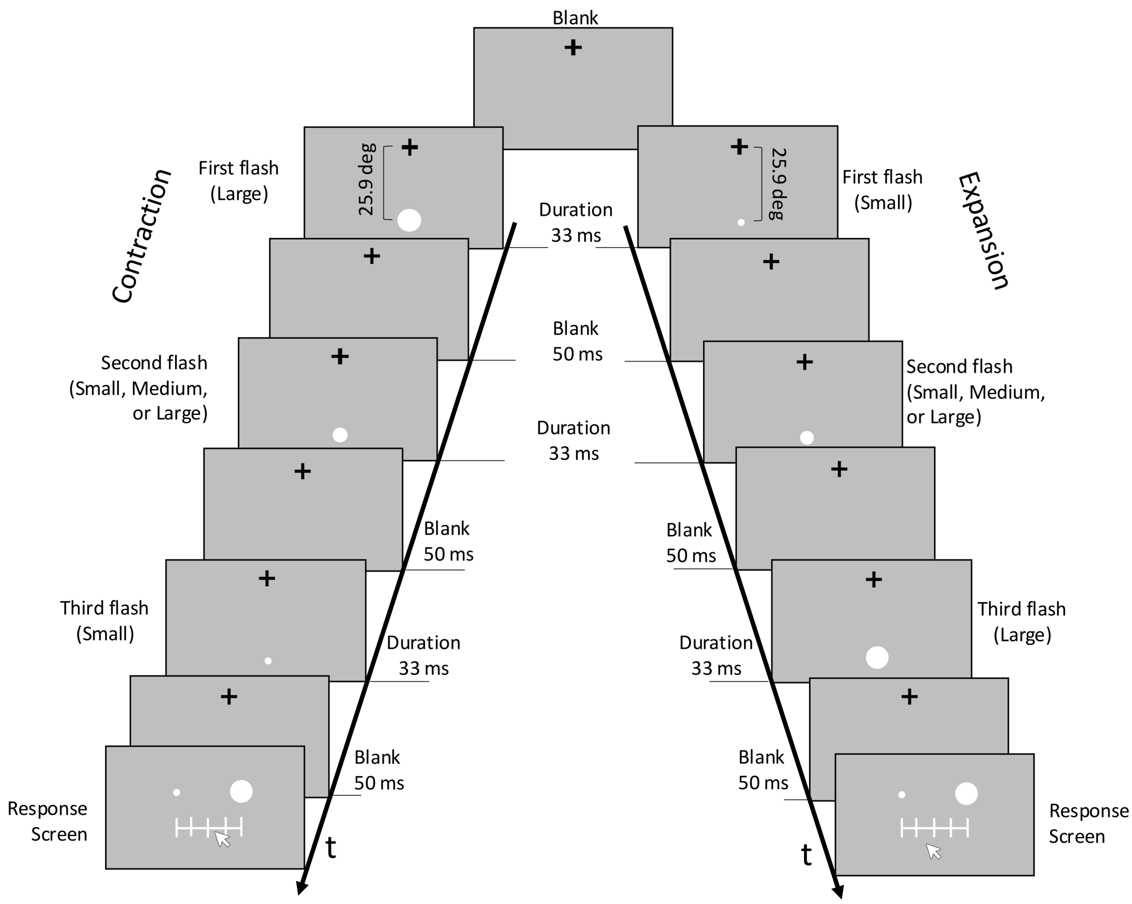

Fig. 3.1 Schematic diagram of Experiment 4. Examples of a contraction trial and an expansion trial.

Procedure

In Experiment 4, participants underwent a series of trials involving three expansion conditions and three contraction conditions, each repeated six times, resulting in 18 trials per set. For each transformation mode, participants completed three sets of these trials. Participants, except for the faculty member, were naïve to the flash conditions and were not informed that flashes would expand or contract. Within each trial set, participants were asked to randomly determine the size of the first, second, or third flash. For example, in the first set of 18 trials, a participant might determine the size of the third flash, then the first flash in the second set, and finally the second flash in the final set.

Experiment 4 included a control block (three trial sets) and an illusion block (three trial sets) for each transformation mode. In total, participants completed four blocks of trials, amounting to 216 trials. The four experiment blocks were administered randomly. After completing all trial blocks, participants were debriefed. No motion aftereffects from stimuli presentation were reported by any of the participants.

Participants focused their gaze on a fixation cross for 300 ms, then a trial of three flashes occurred in their lower peripheral while participants were still gazing at the fixation cross. After a trial was completed, a scale would appear with a small-sized circle at one end and the large-sized circle at the other end. The scale appeared as a gray line with five gray markings that divided the scale into four equal sections. (see Fig. 3.1) The sizes of these circles corresponded to the actual small and large flashes. Participants were asked to click on a point on the scale that reflected the perceived size of the assigned flash the size relative to the small and large circles. After the participant clicked on the scale, the next trial would begin. After completing a set, they were given a short break before commencing the next set.

Data analysis

All analyses were performed using R Statistical Software [59]. Participants' scale responses were converted to a proportional value, where the value of a 100% equates to the large flash size, a value of 60% is equivalent to the medium flash size, and a value of 20% is equivalent to the small flash size in diameter (Fig. 3.2). The proportional values of the perceived first flash and third flashes were analyzed between expansion and contraction conditions, flash sequence (second flash size), and presentation condition (illusion and control).

The relative value of the perceived second flash size was individually calculated and averaged, defining the perceived size of the large flash as 100% and that of the small flash as 0%. This is summarized in Figure 3.2.

By utilizing the z-score method, two data points from two participants were identified as outliers and rejected under a significance level of 0.01. Their responses were removed and thus the results are of 18 participants only.

3.2.2 Results

Proportional values of the first and third flashes

Two-way repeated-measures analyses of variance (ANOVA) were conducted to see the effect of the presentation condition (illusion or control) and flash sequence (second flash size) on the perceived size of the first or third flash was large in expansion and contraction conditions. Mauchly's test revealed the violation of sphericity, so Greenhouse-Geisser's epsilon was applied to correct the degrees of freedom.

For the judged size of the first flash (small) in the expansion condition, the main effects of the presentation condition ($F(1,17) = 8.6548, p = 0.0091, \eta_p^2 = 0.3374$) and the flash sequence ($F(1.80,30.54) = 3.8341, p = 0.0367, \eta_p^2 = 0.1840$) were significant on its perception. Multiple comparisons (MSRBP) indicated there was only a significant difference between the sequences when the second flashes were small (Small-Small-Large) and large (Small-Large-Large) ($p < .05$). Thus, in expansion conditions, the first flash (small) was judged to be relatively larger in illusion conditions than in control conditions. Furthermore, for both illusion and control conditions, the first flash (small) was judged to be larger when the second flash was large in size compared to other expansion sequences.

For the judged size of the third flash (large) in the expansion condition, the main effect of the presentation condition was not significant ($F(1,17) = 0.1811, p = 0.6758, \eta_p^2 = 0.0105$) on how it was perceived. However, the effect of the flash sequence was significant ($F(1.43,24.24) = 8.0596, p = 0.0046, \eta_p^2 = 0.3216$). Multiple comparisons indicated significant differences between the sequences when the second flashes were small (Small-Small-Large) and medium (Small-Medium-Large) ($p < .05$), as well as when the second flashes were small and large (Small-Large-Large) ($p < .05$, adj. $p = 0.0167$). As the size

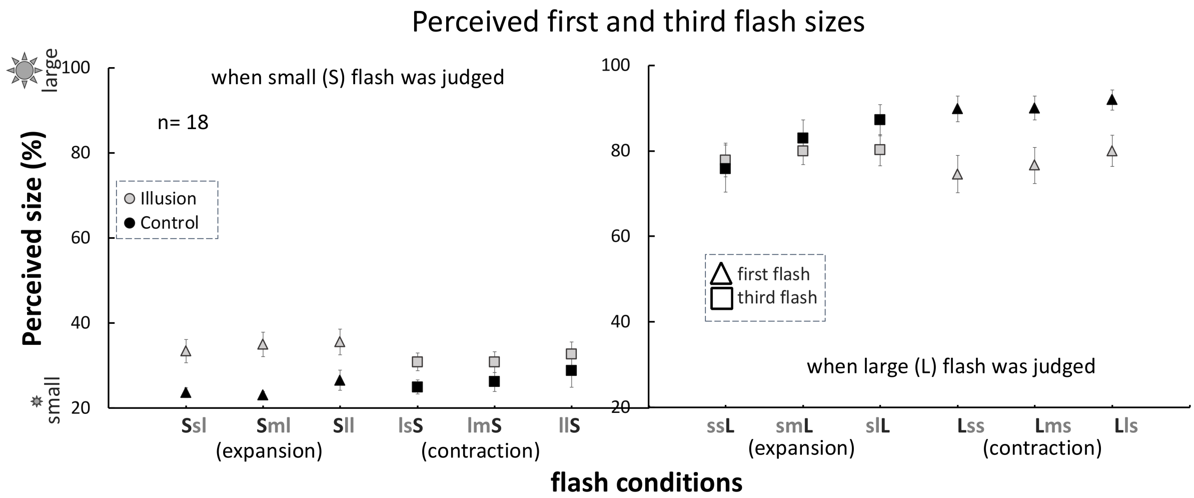

Fig. 3.2 Participants' proportional values of the first and third flashes. The *y*-axis indicates the participants' perceived size of flashes as percentage values. The *x*-axis indicates the trial condition. The letters indicate the size of the flash: s for small, m for medium, l for large. Uppercase letters indicate the specific flash size that was judged by participants. Triangles represent the perceived first flash and squares represent the perceived third flash. Error bars represent standard error of the mean.

of the second flash increased, so did the overall size of the third flash. The interaction between presentation condition and sequence was not significant ($F(1.31, 22.23) = 3.9077, p = 0.0509, \eta_p^2 = 0.1869$). Thus, in the expansion conditions, the third flash (large) was judged relatively larger when the second flash was medium or large in size.

For the judged size of the first flash (large) in the contraction condition, the main effect of the presentation condition was highly significant ($F(1, 17) = 24.6977, p = 0.0001, \eta_p^2 = 0.5923$) on its size judgement. In control conditions, the judged sizes were approximately 90% while those in the illusion conditions were 80% or lower. The effect of the flash sequence was also found to be significant ($F(1.94, 33.02) = 6.4755, p = 0.0045, \eta_p^2 = 0.2758$). Multiple comparisons showed significant differences between the sequences when the second flashes were small (Large-Small-Small) and large (Large-Large-Small) ($p < .05$), and between the sequences when the second flashes were medium (Large-Medium-Small) and large ($p < .05$). The interaction between presentation condition and sequence was not significant ($F(1.81, 30.85) = 1.2090, p = 0.3088, \eta_p^2 = 0.0664$). Thus, in contraction conditions, the first flash (large) was judged relatively smaller in illusion conditions, as well when the subsequent flash was small or medium in size.

For the judged size of the third flash (small) in the contraction condition, neither the effects of the presentation conditions ($F(1,17) = 2.5030, p = 0.1321, \eta_p^2 = 0.1283$) nor flash sequences ($F(1.51, 25.67) = 1.9862, p = 0.1657, \eta_p^2 = 0.1046$) were significant. The interaction of the two factors was not significant ($F(1.35, 22.89) = 0.2331, p = 0.7049, \eta_p^2 = 0.0135$). Perception of the third small flash (small) in contraction conditions was not impacted by the prior flashes. Participants tended to judge the size of this flash similarly across illusion and control conditions.

In short, the main finding is that, under the illusion condition, the first flash in the expansion condition tended to be judged as larger while the first large flash in the contraction condition tended to be judged as smaller.

Relative value of the second flash

The judged second flash size was analyzed with an individually calculated relative value between the judged first and third flash sizes (Figure 3.3). A three-way repeated-measures ANOVA was conducted to test the main effects of the actual size (small, medium, or large) of the second flash presented, the transformation mode (expansion or contraction), and presentation condition (illusion or control), as well as their interaction effects. As the assumption of sphericity was violated, Greenhouse-Geisser's epsilon was applied to correct the degrees of freedom following Mauchly's test results.

The main effect of the second flash size was found to be highly significant ($F(1.78, 30.18) = 38.8964, p < 0.0001, \eta_p^2 = 0.6959$) while the main effects of the transformation mode ($F(1,17) < 0.0001, p = 0.9953, \eta_p^2 < 0.0001$) and the presentation condition were not significant ($F(1,17) = 0.9862, p = 0.3346, \eta_p^2 = 0.0548$). The interaction between the presentation condition and the second flash size was also found to be highly significant ($F(1.54, 26.11) = 18.0665, p < 0.0001, \eta_p^2 = 0.5152$).

When the size of the second flash was small, the simple main effect of the presentation condition was highly significant ($F(1,17) = 29.8267, p < 0.0001, \eta_p^2 = 0.6370$). It was also very significant when the size of the second flash was large ($F(1,17) = 9.5616, p = 0.0066, \eta_p^2 = 0.3600$). However, when the second flash was medium in size, no significant effect was found ($F(1,17) = 0.8712, p = 0.3537$). This indicated that under illusion conditions, participants tended to misjudge the actual size of the second flash when it was small

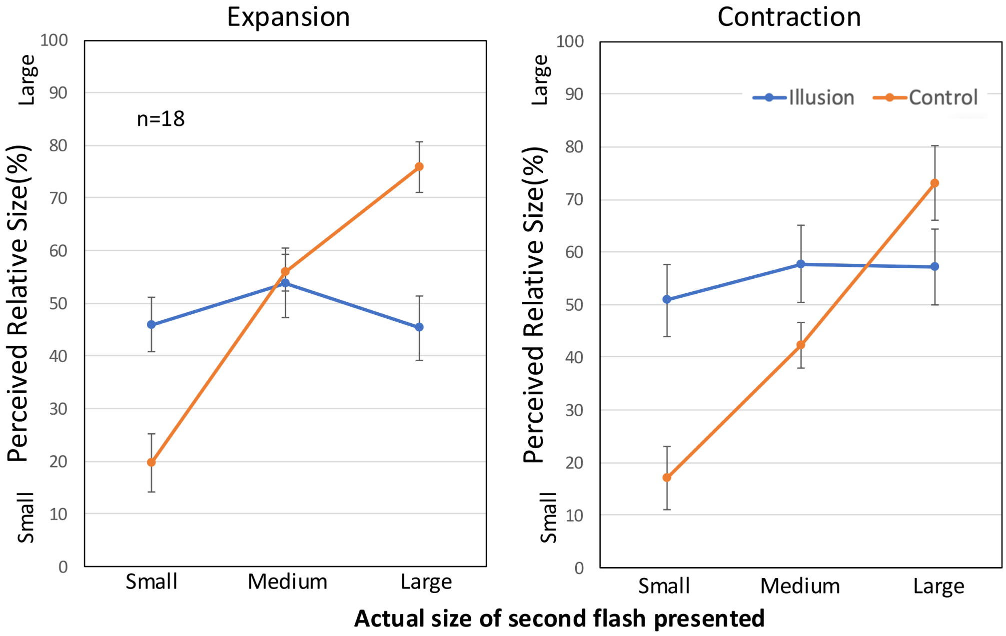

Fig. 3.3 Perceived second flash size in relative values from Experiment 4. Each point indicates the perceived second flash size as relative values between the perceived sizes of the small and large flashes. Error bars represent standard error of the mean.

or large and were less likely to misperceive its actual size when it was medium. Figure 3.3 displays the tendency to judge the second flash as larger when it was small in size, and smaller when it was large in illusion conditions.

The simple main effect of the second flash size when flashes were presented under illusion conditions was not significant ($F(1.67, 26.46) = 0.7730, p = 0.4498, \eta_p^2 = 0.0435$). Under control conditions, the simple main effect of the second flash size was highly significant ($F(1.31, 22.26) = 54.2516, p < 0.0001, \eta_p^2 = 0.7614$). Multiple comparisons showed that the differences between all pairs of small, medium, and large in second flash size conditions were significant ($p < .05$) under the control conditions. These statistical results (and Fig. 3.3) show that, for the second flash, participants did not perceive a difference between small, large, and medium, and tended to misjudge the second flash to be medium in size in illusion conditions. While in control conditions, the participants' responses tended to mirror the sizes of the actual flashes.

3.2.3 Discussion

By asking participants to judge the size of each flash in a trial for both transformation modes, it was determined they could indeed distinguish if flashes were expanding or contracting. The results show that, on average, participants perceived the correct size order of flashes, but that their actual size judgment is subjective (see Fig. 3.2). The perception of the third flash in both contraction (small) and expansion trials (large) was not influenced by the presentation condition. However, for expansion conditions, the third flash (large) appeared to be influenced by the two preceding flashes. The perception of the first flash in both the contraction (large) and expansion (small) trials was affected by the presentation conditions and by the two flashes that followed. Participants may be more accurate in reporting the size of the third flash, regardless of transformation conditions, due to recency effects. On the other hand, the first flash may be more temporally distant in the memory, causing the brain to rely on surrounding stimuli to assist in size judgement. These results are consistent with Kawabe's [78] study where initial visual information can be overwritten by information presented later. It is important to note that the size distortion of the first and third flashes from their actual size is not as pronounced as the second flash in this study, as will be discussed later.

Based on Figure 3.2, under illusion conditions in contraction trials, participants would perceive the first flash (large) as smaller than they would in control conditions. Likewise, when the first flash was small in expansion trials, participants would perceive it to be larger in illusion conditions than in control conditions. Under the rapid presentation of illusion conditions, it is possible that participants perceive the entire sequence of three flashes to be more condensed in size. This is interesting, because unlike in the VSI with translation, the first and third stimuli in expansion and contraction are slightly misperceived. This shows that stimuli duration and ISI have an influence on the overall perception of the illusion.

Temporal and spatial judgments such as those in the tau and kappa effects [24, 29] may come into play when the VSI is expanding or contracting. Since the sequence of three flashes can be likened to an object moving further away (contraction) or closer (expansion) to the observer, this can influence the overall expectation of size. In line with the tau effect, under illusion conditions, a flash may appear to "travel" a shorter distance compared to a flash in control conditions. For example, in expansion trials, the first flash (small) may be perceived as larger under illusion conditions than in control conditions because of the expectation that it “arrived” faster to the observer, as though it were closer. While this study did not measure the perception of time, it is possible that participants perceived flashes as temporally closer together under illusion conditions, similar to the temporal misperception observed in the kappa effect. This would influence how the flashes were perceived both as an entire sequence and individually under illusion versus control conditions, as the temporal spacing between flashes differed. Analogously, it is easier to count and judge the size of marbles laid out in even rows with adequate spacing than to count those crammed into a jar.

Previous explanations of the typical VSI (translation mode) may also explain the size misjudgment. Motion-induced position shifts can cause the second stimuli to shift from the position of the first flash, motion in the case of expansion or contraction can be likened to movement away or towards the viewer. It is possible that the motion forwards (expansion) or backwards (contraction) can cause the size misjudgment of the second flash, causing the second flash to expand or shrink to a size that matches the direction of movement. This might not be enough to explain saltation conditions where the last two flashes were the same in size, such as in a contraction condition, where the last two sizes were small. If motion induces a size shift, then the second flash (small) would have to be judged even smaller than it is.

The outcome of these experiments also aligns with Gestalt principles, wherein perceiving the second flash to be medium size would be the most reasonable judgment after an observer perceives the first and third flash despite their size. If for example, three flashes of the same size presented with same duration and ISI, it is unlikely that the observer would misjudge the size of the second flash to be different from either the first or the third flash. Successful saltation from these experiments is also indicative of a postdictive effect, where information of the entire flash sequence must be received before making a size judgment on the first and second stimuli. This could suggest that the process of size judgement and location identification as neural processes are linked in a way that allows for a similar saltation effect to take place between the two.

Size judgment can be considered an important factor in how individuals perceive and construct their reality. Just as larger events tend to have a greater impact on memory, humans may be more affected by and likely to remember larger objects, while smaller ones may be overlooked. Overall, Experiment 4 showed that saltation is successful when using expansion and contraction as the transformation mode.

3.3 Experiment 5

Since saltation was successful in Experiment 4, the next step would be to discover the ideal parameters to produce the most effective VSI. Previous research emphasizes the importance of ISI [25, 54] for achieving saltation. Would the VSI in expansion and contraction follow the same trend? Alternatively, Goldreich and Tong [49] predicted that the CRE's success might lie in the intensity of the tactile stimulus. For the VSI, stimulus duration could be a component defining the stimulus intensity. As such, six different durations were tested with a constant ISI of 50 ms, and six different ISIs were tested with a constant flash duration of 33 ms, creating a total of 12 different trial blocks. Participants were administered these trial blocks in a random order.

3.3.1 Methods

The same participants from Experiments 4 partook in Experiment 5. The same experimental stimuli and apparatus were utilized, only the procedure was altered. Participants were asked to determine the size of the second flash relative to how they perceived the first and the third flashes throughout all trials. The same scale from Experiment 4 was utilized, and participants were instructed to use the two circles to represent either the first and the third flash, then click at a point on the scale that represented the size of how they perceived the second flash relative to the first and third flashes.

There were a total of 12 different trial blocks. In six blocks, the stimuli duration was altered (17 ms, 33 ms, 67 ms, 133 ms, 267 ms, 533 ms) but the ISI was constant (50 ms). In the remaining six blocks, the ISI was altered (17 ms, 33 ms, 67 ms, 133 ms, 267 ms, 533 ms) and the duration was constant (33 ms). The constant duration (33 ms) and constant ISI (50 ms) were chosen to create a variety of Stimulus Onset Asynchrony (SOA) times between the trial sets (50, 67, 83, 100, 117, 167, 183, 300, 317, 567, and 583 ms). Also, a stimulus duration below 33 ms when paired with the altered ISIs times created conditions that made it difficult for individuals to perceive each flash distinctly in preliminary trials.

Table 3.1 Trial block conditions with varying durations and ISIs.

Condition	Duration (ms)	ISI (ms)
Variable Duration	17, 33, 67, 133, 267, 533	50
Variable ISI	33	17, 33, 67, 133, 267, 533

Instead of separating expansion and contraction conditions, the six conditions were combined within a trial block. Each condition was repeated six times. In one block, a participant would undergo 36 trials, creating a total of 432 trials for Experiment 5. Participants underwent the trial blocks in a random order.

Data Analysis

Data discarded from the participants in Experiment 4 were also not included. Only the results of 18 participants were analyzed for Experiment 5. Scale values of Experiment 5 were converted to perceived relative values (%) of the second flash relative to the actual size of the large and small flash sizes present on the scale. In Experiment 5, the value of 0% is equivalent to the small sized flash, while the value of 100% is equivalent to the large sized flash.

3.3.2 Results and Discussion

Upon looking at the results initially, there was no immediate difference between constant ISI or duration conditions. At short time intervals for both ISI and duration, the second flash, regardless of actual size, was perceived to be medium in size, and responses slowly became more accurate as time increased. For ease of understanding the responses, the data was analyzed by combining the ISI and Duration time blocks (12 total) to SOA timings (11 total): 50, 67, 83, 100, 117, 167, 183, 300, 317, 567, and 583 ms. The responses from the two conditions: (constant) duration of 17 ms with an ISI 50 ms; and duration of 33 ms and (constant) ISI 33 of ms, were averaged since both conditions created an equivalent SOA of 67 ms.

A three-way repeated-measures ANOVA was conducted on the factors of SOA, transformation mode (expansion and contraction), and the size of the second flash presented. The degrees of freedom were adjusted by Greenhouse-Geisser's Epsilon. It was found

Table 3.2 SOA timings and their corresponding conditions.

SOA (ms)	Conditions Averaged
50	Duration 33 ms, ISI 17 ms
67	Duration 17 ms, ISI 50 ms; Duration 33 ms, ISI 33 ms
83	Duration 33 ms, ISI 50 ms
100	Duration 33 ms, ISI 67 ms
117	Duration 67 ms, ISI 50 ms
167	Duration 33 ms, ISI 133 ms
183	Duration 133 ms, ISI 50 ms
300	Duration 33 ms, ISI 267 ms
317	Duration 267 ms, ISI 50 ms
567	Duration 33 ms, ISI 533 ms
583	Duration 533 ms, ISI 50 ms

that the transformation modes ($F(1,17) = 1.1044, p = 0.3080, \eta_p^2 = 0.0610$) and SOA ($F(5.51, 93.74) = 0.4979, p = 0.7941, \eta_p^2 = 0.0285$) as main factors did not have a significant effect. The main effect of the size of the second flash was highly significant ($F(1.27, 21.51) = 206.9285, p < 0.0001, \eta_p^2 = 0.9241$), indicating its critical role in how participants judged the size of the second flash, particularly in the large SOA conditions.

The interaction between size and SOA ($F(6.07, 103.22) = 57.67, p < 0.0001, \eta_p^2 = 0.7723$) was also highly significant. The effect of the size of the second flash presented on size judgement may vary with the SOA, as Figure 4 shows. The interaction between the transformation modes and SOA was also found to be significant ($F(5.32, 90.44) = 3.4684, p = 0.0055, \eta_p^2 = 0.1695$), implying the impact of SOA may differ depending on whether the VSI is expanding or contracting, though the effect size was small. However, the three-way interaction between the factors was not significant ($F(6.09, 103.51) = 1.0092, p = 0.4241, \eta_p^2 = 0.0560$). This suggests the effects of size and transformation mode interact with SOA independently.

The simple main effect of the transformation mode at SOAs of 50 ms($F(1,17) = 10.4310, p = 0.0049, \eta_p^2 = 0.3803$) and 67 ms ($F(1,17) = 8.4327, p = 0.0099, \eta_p^2 = 0.3316$) were significant. Differences between the responses in transformation mode at SOAs of 300 ms($F(1,17) = 5.7368, p = 0.0284, \eta_p^2 = 0.2523$) and 567 ms ($F(1,17) = 8.1038, p = 0.0112, \eta_p^2 = 0.3228$) were also significant. But the simple main effect of SOA on expansion conditions ($p = 0.1664$) and contraction conditions ($p = 0.2138$) was not significant, along with the remaining seven SOAs. Under certain SOAs, there were differences in the perception of the second flash between the transformation modes.

The simple main effect of SOA when the size of the second flash was medium was not significant ($F(5.10, 86.62) = 0.6166, p = 0.6905, \eta_p^2 = 0.0350$). When the second flash was small ($F(5.69, 96.81) = 42.7749, p < 0.0001, \eta_p^2 = 0.7156$) and large ($F(4.67, 79.40) = 25.6977, p < 0.0001, \eta_p^2 = 0.6019$), the simple main effect of SOA was highly significant. This indicates that, regardless of the transformation mode or the SOA, participants do not misjudge the size of the second flash when it is medium. However, when it was small or large, size judgment was impacted by SOA.

The simple main effect of second flash size at SOAs of 50 ms ($F(1.35, 22.93) = 2.1863, p = 0.1477, \eta_p^2 = 0.1140$) and 67 ms ($F(1.43, 24.30) = 0.3809, p = 0.6176, \eta_p^2 = 0.0219$) were not significant. Regardless of the size of the second flash presented, at SOAs of 50 and 67 ms, participant responses were similar, which, based on Figure 3.4, perceived the second flash to be closer to medium in size. At an SOA of 100 ms, there was a small (but not significant) effect of the second flash size ($F(1.44, 24.46) = 3.1680, p = 0.0740, \eta_p^2 = 0.1571$). The simple main effects of second flash size were significant under the remaining eight SOA conditions ($p < 0.01$).

Similar to Experiment 4, no significant differences were found between expansion and contraction conditions. However, the effect of interaction between the transformation modes and SOA was significant as noted above. Based on Figure 3.4, at smaller SOAs, the overall size judgment of the second flash across all three sizes appears to be smaller in contraction conditions than that of expansion conditions. This is consistent with the results of Whitaker et al. [69], where participants tended to overestimate the size of a stimulus to a reference stimulus during expansion, and underestimate its size during contraction, when in fact the reference stimulus and the manipulated stimulus were the same size. However, unlike Whitaker et al. (1999), the present study did not ask participants to judge stimulus size when motion ends, but rather a flash stimulus that occurred in between during the entire trial sequence. The perceived second flash size might be biased by the transformation mode indicated as a whole.

Saltation under expansion or contraction favors SOAs of 50 and 67 ms, but even SOAs of 317 ms are sufficient to induce a saltation effect, albeit at a lower percentage. SOAs

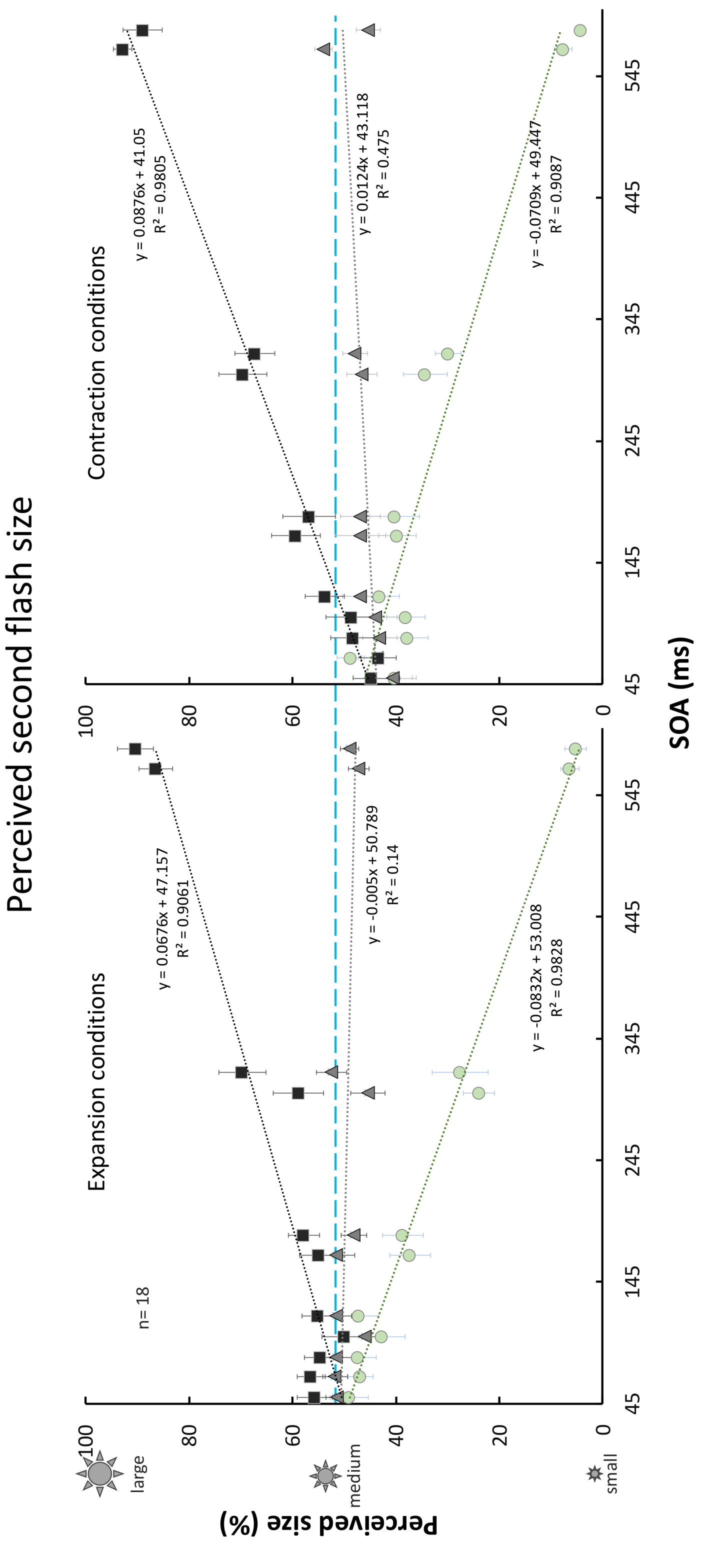

Fig. 3.4 Perceived second flash size in Experiment 5. Circles indicate responses when the second flash was small; triangles indicate responses when the second flash was medium in size; and squares indicate responses when the second flash was large in size. The blue dashed line at 50% on the *y*-axis indicates a response where a participant perceives the second flash to be medium in size relative to the first and third flash. Error bars indicate standard error of the mean.

of 567 ms and 583 ms were no longer ideal conditions for saltation because the perceived second flash size was approaching 100% or 0% for large or small size stimulus, respectively. Specifically for Experiment 5, it would mean a duration of 267 ms paired with an ISI of 50 ms, would be sufficient to produce the illusion. Alternatively, a duration of 33 ms paired with an ISI of 283 ms (a condition not tested in this study) may be sufficient. This reflects the original parameters of Geldard's (1976) experiment, where an ISI of 300 ms was able to produce some hopping effects, but an ISI of 100 ms was the most ideal. SOAs significantly over 317 ms for expansion and contraction may be too large to produce saltation.

These results also align with the original CRE, where an ISI of 200 ms was the threshold for sufficient saltation[10]. This, paired with a tap duration of 2 ms to create an SOA of 202 ms, shows that the perceptual manner of interpreting saltation stimuli is shared. For saltation in thermoceptive and nociceptive pathways, although the ideal average SOA of 500 ms [22] is higher than the present results, the current results still fall within a similar range. For auditory saltation, an SOA of 95 ms was sufficient to produce the illusion for Bremer et al. [25], while an SOA of 151 ms was the maximum condition to produce saltation for Shore et al. [27]. The temporal processing of sound localization appears to be more accurate over SOAs of 150 ms, while accuracy for visual perception can occur over values of 300 ms, especially in the expansion and contraction transformation mode.

3.4 General Discussion

This chapter investigated the visual saltation illusion using the novel transformation modes of expansion and contraction. This provided more insight into the VSI where this transformation mode has not been investigated. No systematic differences were found between expansion and contraction results. This could mean that the brain processes images that shrink and expand generally in the same way when they are presented rapidly. Neither stimulus duration nor ISI as a sole factor impacted the illusion, but rather SOAs between 50 and 317 ms were sufficient to induce the illusion, with values of 50-117 ms being the ideal. This is consistent with Geldard's [28] results in the first VSI experiment that favored ISIs of 100 ms. Ito et al. [37] also reported similar results, that is, the VSI in a horizontal direction was rated highest at the SOA of 67ms and lowest at the SOA of 333ms within their tested range.

These findings have contributed to basic visual perception research, such as expansion and contraction illusions, wherein an observer's size misjudgment is not limited to events at the beginning of a motion sequence, as Kawabe [78] covered, nor to events at the end, as Whitaker [69] discusses. Rather, size misjudgment can expand to events that occur in the middle, without affecting the perception of the initial and final stimuli. Misjudgment of the second flash to be medium-sized when presented as the same size as the first flash (small-small-large sequence in expansion conditions, and large-large-small sequence in contraction conditions) aligns with the motion-induced position shifts theory. Just as in VSI with translation, when the first two flashes are small and the third is large, the perceived motion (toward the observer) can "push" the size of the second flash to be closer in size to that of the third flash, making it appear larger. When the first two flashes are large, and the third is small, the pull of motion (away from the observer) can "pull" the size of the second flash to be smaller in the same manner.

However, MIPS do not explain the misperception of the second flash as medium under conditions where the second flash was presented as the same size as the third flash. Other explanations used for VSI in translation can then be applied to saltation with size misjudgment. The application of Gestalt principles is fitting, as participants tended to perceive the second flash as intermediate in size under illusion conditions, despite it being smaller or larger in size. This aligns with the Gestalt principle of closure, where the brain integrates incomplete or mismatched information to form a cohesive perception. Similarly, continuity may play role, as the brain organizes the sequence of flashes into a smooth progression, leading to the perception of an intermediate size. [79] This is indicative of a postdictive effect, where the perception of three flashes influences the judgment of individual elements.

The size of the second flash demonstrated a significant effect on the overall perception of the illusion across the experiments. However, the lack of differences of the perception of the second flash between expansion and contraction illusions concurs with Eagleman and Sejnowski's [50] finding that motion biases can explain size misjudgment, rather than asynchronous feature binding. When considering flash size as a feature of VSI stimuli, size misperception occurs if motion is perceived, which typically happens at shorter SOAs, ISIs, and durations. Notably, this size misjudgment occurs subsequent to motion perception, explaining why participants report flash sizes more accurately at slower presentation speeds where motion is not observed.

The results are also conclusive with Kawabe's [78] finding that postdictive size modulation can play a key role in size misjudgment. Although Kawabe cited that succeeding stimuli influence the perception of the initial stimuli, the results at present show stimuli surrounding the target in time can also play a role. This supports the tendency that humans' perceptions reflect their expectations of reality [50, 49, 47]. The second flash is perceived to be medium in size relative to the first and last flash, because that is how it would typically occur in real-life. Thus, Kawabe's suggestion of object updating is also applicable to the success of the VSI in expansion and contraction. Object updating is the process in which the brain maintains a consistent perception of objects in a changing environment [80]. Misjudging the second flash to always be medium in size across conditions reflects the need for perceptual continuity.

Successful saltation in this chapter demonstrates the robustness of the VSI and why it still has potential in future research. The VSI may be grounded in fundamental processes of visual perception and spatiotemporal integration. The observed interaction between SOA and perception of the second flash provides insight into temporal size dynamics of size perceptions. At short SOAs when the stimuli can be indecipherable, it makes the most sense to default perceiving the second flash as medium in size. But as SOA increases, more veridical size judgments become possible, suggesting a trade-off between processing speed and perceptual accuracy.

Although this study provided valuable insights into the VSI under a novel transformation mode, some limitations could be addressed in future research. This study only used a constant retinal eccentricity to achieve saltation throughout the two experiments. Future studies could manipulate this variable, which yield interesting results as it does for other size illusions [77]. Other flash shapes could be tested to see if stimulus properties have an effect on this novel VSI presentation. Additionally, only 12 sets of ISIs and duration timings were tested. Varied stimulus timings could be tested to affirm the effects of ISI and duration on the VSI. Also, if manipulating flash intensity can affect the strength of the FLE [81] then adjusting the stimuli luminance under the same parameters might produce different observations. Future VSI research could even combine translation with expanding and contracting stimuli. A recent study on the VSI using a Kaniza-type triangle [37] suggests that the full potential of the VSI has not yet been fully explored.

Another limitation is the real-life application of such stimuli. Although our vision is wired to observe objects getting smaller or larger, a person would rarely encounter images flashed in that same manner as this experiment naturally. Therefore, these findings can most assuredly be applied to media works and animation, which manipulate objects' sizes on a regular basis. Animators may not have to create entirely new frames but reuse the same frames between the initial and last frame to achieve the same result. The results can also be applied to virtual or augmented reality, which relies on sensory feedback to replicate natural experiences. This has been supported by a study using the CRE to invoke emotional responses, they found that less visual feedback may be needed to obtain the same result ([36].

This chapter extends the understanding of the visual saltation illusion by demonstrating its effectiveness in expansion and contraction conditions. The persistence of the saltation effect across different transformation modes suggests it may be an adaptive mechanism rather than a flaw in visual processing, enabling fluid perceptual experiences. The results also show promise for VSI experiments in utilizing other transformation modes such as rotation. The investigation of the ideal parameters showed short SOAs favor this type of presentation, but the threshold may vary depending on the temporal factors involved, that being location, size judgment, or orientation. Other sensory modalities, such as that of the CRE, can also apply expansion/contraction conditions to observe the effects.

3.4.1 Discrepancies in participant reports of flash size and number

Unlike in Chapter 2, where some volunteers did not meet the criteria to participate in the experiments, in Chapter 3, all volunteers reported the correct size order of flashes during practice trials and were allowed to participate. Only one participant could not perceive three flashes under the most rapid condition in Experiment 5; their data was normal for Experiment 4. Two participants' results were disregarded after data analysis revealed that their perception of the flashes differed in the control conditions of Experiment 4. Examples include reporting the second flash to be larger than the third flash (large) in expansion trials or larger than the first flash (large) in contraction trials; however, they perceived all three flashes in Experiment 5.

When PS1 underwent the experiments of Chapter 3 (data not included in final analysis), PS1 did not report any size misperceptions of the first and third flashes. PS1 did experience saltation of the second flash in a manner similar to the other participants. This may suggest that although visual tasks may involve separate processes, the saltation effect persists across different processing streams.

Another factor that could account for the low discrepancies in this Chapter, compared to Chapter 2 would be the location of the stimuli presented. Misreports typically occurred in Experiments 1 and 2, when the second flash in illusion conditions was presented close to the first or third flash position, but not at the midpoint between the two. This points to the role that attention plays in interpreting VSI stimuli. For Experiments 1 and 2, volunteers who only reported seeing two flashes maybe have found it harder to detect the second flash when it was presented further from the fovea (first and third flash locations) than when it was presented at the midpoint. Their brains were still able to process the approximate locations of the first flash and a second flash (whether it was the second or third flash) at the location of the third flash. Whereas in Experiments 4 and 5, all the stimuli were presented closer to the fovea, in the same location, possibly minimizing attentional demands and allowing for the correct number of flashes to be reported.

3.4.2 Shared processing over visual tasks

The similar perception of the second flash across the three novel positions, along with the tendency to perceive the second flash as medium in size in two transformation modes, suggests a shared neural process underlying the VSI. One plausible explanation for the consistent perception of the second flash at the center or as medium in size is that these second flash positions create postdictive effects. Both chapters emphasized the importance of anchoring the first and third stimuli. This is demonstrated in Chapter 2 by the outlier responses, where participants still perceived flashes at the locations of the first and third stimuli, respectively. In Chapter 3, this is evidenced by the consistent size order of all three flashes in both the illusion and control conditions, as well as across the two transformation modes. These findings suggest that when the brain engages in such perceptual tasks, the surrounding information and prior knowledge are used in similar ways to produce a final interpretation.

It is important to question why the brain interprets the second flash in a way that makes the most sense. Cognitive priors—formed by the way humans have experienced similar stimuli—play a significant role in interpreting ambiguous presentations. Prior knowledge is built over years of experiencing visual events. The brain learns from these experiences and applies this knowledge to interpret later stimuli. Fast-moving stimuli are typically processed similarly: if the starting point (first flash) and the endpoint (third flash) are known, the brain deduces that the object likely occurred along the linear path connecting them.

A more superficial reason for this shared median perception of the second stimulus in these experiments could be the similar parameters of the stimuli's positions and presentation speeds. An appropriate peripheral distance between stimuli and the fixation point and an ideal presentation speed are crucial factors for inducing saltation.

Chapter 4

Summary, implications, and conclusion

Illusions can focus on a property of the senses and provide clues to how information is processed by receptors, then the brain. The amount of the discrepancy between perception and reality can not only show the strength of the illusion, but the extent of its effect on the brain. Why humans and even other creatures are prone to illusions remains a topic of debate. While initially it may seem illusions indicate shortcomings of the perceptual system, a different perspective implies there is some sort of benefit as to why information is misinterpreted. Illusions give a deeper insight into how our minds take in the disorder of the world and turn it into organized information.

This thesis examined the visual saltation illusion to deepen the understanding of sensory and cognitive processes related to vision and, ultimately, reality formation. Vision is one of the most relied-upon senses for individuals with normal sensory functions. As Geldard [11] puts it, vision is the modality on which humans are "most dependent to inform us of the locations of objects in space." It is fitting then to investigate an illusion where its measurement relies on observers identifying the locations of presented stimuli.

The VSI has been investigated since its older relative, the cutaneous rabbit effect (CRE) was discovered, yet its foundational parameters have not varied over the years. Researchers have presented the VSI in depth, across the blind spot, and utilized color to see if features can also be mislocalized. Such experiments have undoubtedly contributed to the illusion, yet they have consistently used the same positional format for the flashes. The VSI, has also remained as an illusion of mislocalization, and other transformation modes have not been attempted. This dissertation addressed these gaps not only in VSI research but also for saltation phenomena.

The objective of this thesis was to develop the understanding of the VSI by presenting the illusion in novel ways. By observing the effect of presenting the second flash in novel positions, it can be observed if the VSI relies solely on low-level motion processing. Successful saltation in such conditions would imply that higher-level visual processing is at work when interpreting VSI stimuli. Presenting the VSI in a novel transformation mode would further showcase the strength and adaptability of the saltation phenomenon. The study also aimed to uncover the neural mechanisms behind the successful saltation of these new VSI formats and discuss the implications of these results.

4.1 Summary

Chapter 2 described the initial experiments that challenged the original parameters and hypotheses behind the VSI. These experiments helped define the flow and possibilities that could be studied for the preceding experiments. By focusing on the position of the second flash in the three-flash sequence of the reduced VSI, this chapter uncovered the extent of the effect of saltation and other influencing factors. Three psychophysical experiments were conducted, each presenting the second flash in a novel position.

Experiment 1 presented the VSI under a "backwards" arrangement, by moving the second flash to be in the same position as the third flash. A preliminary experiment was conducted to observe if under the novel presentation condition of the second flash, the perception of the first and third flash would be affected. Consistent with previous studies, only mislocalized the second flash to typically occur at the midpoint of the first and third flash. Under illusion conditions, the backwards presentation of the second flash was successful. These results challenged the original hypothesis that motion-induced position shifts are the sole cause of the VSI.

Experiment 2 presented the second flash of the VSI positionally out of bounds. This was a novel approach to the VSI, as target stimuli of saltation experiments fall at a point at or in between the first and the third stimuli. As Experiment 1 determined that a backwards presentation of the second flash can induce the saltation illusion, Experiment 2 also utilized a backwards format by presenting the second flash out of bounds not only relative to the first flash but relative to the third flash as well. Just as in Experiment 1, the second flash was perceived on average to occur at a point in between the first and the third flash.

Experiment 3 took a different approach by presenting the second flash of the VSI out of linear alignment. This approach further challenged previous VSI experiment parameters that consistently present VSI stimuli in a linear format, even when presenting it in three-dimensional space [54]. Five second flash positions were tested along the horizontal midpoint between the first and third flashes, aligned with the fixation point. One flash location was precisely at both the horizontal and vertical midpoint of the first and third flashes, while other flash locations were positioned above and below this point. Under illusion conditions, participants tended to perceive the second flash as occurring approximately in alignment with the first and third flashes. Flashes positioned further from the fixation point more likely to be misperceived as aligned at the midpoint between the first and third flashes. The results of Experiment 3 were not only consistent with the hypotheses of the previous two experiments, but it also touched on the role attention plays in the VSI.

Since the results of Chapter 2 were promising regarding the adaptability of the VSI, Chapter 3 aimed to explore this further by presenting the VSI in a novel transformation mode using two additional psychophysical experiments. Expansion and contraction modes were selected to determine whether optical flow in size judgment is also influenced by the saltation effect.

Experiment 4 adapted the translational transformation mode of the VSI into expansion and contraction, incorporating elements from Experiment 1. This was achieved by presenting the first two flashes at the same size, followed by a third flash that was either smaller (contraction) or larger (expansion). In the "backwards" arrangement, the first flash was presented in one size, while the second and third flashes were either larger (expansion) or smaller (contraction) but of equal size. Participants reported the perceived sizes of all three flashes in a three-flash sequence to determine whether the first and third flashes were misperceived. Differences in how the first flashes were perceived were found. The first flash was perceived to be smaller in illusion conditions than in control conditions in contraction modes. In expansion modes, the first flash was perceived to be slightly larger in illusion conditions than in control conditions.

The most significant finding was in the perception of the second flash. In both expansion and contraction modes, participants tended to misperceive the second flash as medium in size relative to the first and third flashes, even when it was the same size as either the first or the last flash. The overall size order of the three-flash sequence was correctly reported across all conditions for all participants. Saltation was achieved in these new transformation modes.

Experiment 5 further investigated the new transformation modes by examining how the parameters of ISI and flash duration affect the overall illusion. In this experiment, six trial sets were conducted with a constant duration of 33 ms while the ISI increased, and six trial sets were conducted with a constant ISI of 50 ms while increasing duration for expansion and contraction trials. The results showed no significant differences between trials with a constant duration and those with a constant ISI. Instead, the overall success of the saltation effect appeared to depend on the SOA. The ideal SOA range for inducing the effect was found to be between 50 and 117 ms, while SOAs over 317 ms were less likely to produce the illusion.

4.2 Implications

The objectives of this research were met through the completion of these experiments. Chapter 2 successfully achieved saltation—specifically, the perception of the second flash at the midpoint between the first and third flash locations across all three novel flash conditions. Chapter 3 also achieved saltation in a new presentation mode. These results are significant as they demonstrate that:

- Additional neural mechanisms, beyond motion-induced position shifts, contribute to saltation in the VSI.
- The VSI phenomenon extends to other optic tasks, specifically that of size misjudgment.
- The saltation effect arises not only at short ISIs but also at short durations, suggesting that synchronies might be the key to achieving saltation.

4.2.1 Beyond motion induced position shifts

The results of Experiment 1 challenged the very foundation of the VSI and other saltation experiments with the “backwards” presentation of the second stimuli. The successful saltation results contradicted the common hypothesis that MIPS are responsible for the illusion. Experiment 2 further challenged the MIPS by presenting second flashes out of bounds near the first flash location (akin to the typical forward shift of previous VSI experiments) and near the third flash location (akin to the backwards shift of Experiment 1); the second flash was on average, perceived to occur at the midpoint of the first and third flash.

These results brought further implications. Perhaps MIPS were not the only mechanism responsible for the saltation of target flashes in the original VSI and even the CRE. The theory of MIPS also suggests that cognitive processing of the VSI occurs at lower levels of visual processing. Since the results did not align with the theory of MIPS, it is reasonable to conclude that processing the VSI—and possibly other saltation effects—relies on higher-level visual processing intertwined with low-level motion signals.

From these studies, we can conclude that even more varied second flash positions could replicate this mislocalization at the midpoint, provided the fundamental structure of the VSI experiments is maintained—specifically, short SOAs and stimuli presented within a reasonable eccentricity. This aligns with Geldard’s [11] original assertion that saltation is a *Ding an sich*, a thing in itself.

4.2.2 Beyond location mislocalization

The VSI’s potential as an independent phenomenon is demonstrated by its ability to manifest across different transformation modes, as described in Chapter 3. The tendency to perceive the secondary stimulus at a medium level for both expansion and contraction conditions supports this assertion. Experiment 4 showed that, just as in the translational mode of the VSI, the first and third stimuli do not undergo significant misperception, only the second stimulus. Location identification and size judgment as visual tasks may undergo similar processing in the visual pathway.

Ultimately, this thesis highlighted the strength and adaptability of the VSI. Just as discovering the saltation effect arises across other sensory modalities, achieving saltation in expansion and contraction indicates that saltation in vision can be explored through various avenues and is no longer limited to the translational mode. The success of Experiment 4 is a breakthrough not only for the VSI but also for all saltation experiments, as will be discussed in the future studies section of this chapter.

4.2.3 Beyond the reliance on ISIs

Geldard [11] originally suggested that stimulus duration in saltation experiments was "not crucial", and as a result, its effects have not been studied as extensively as ISIs. Chapter 2 first showed the impact of duration on the VSI by keeping it constant (17 ms) throughout the three experiments, while the ISI of the stimuli was altered to produce the best outcome for illusion conditions. Although preliminary experiments showed that increasing the duration to 33 ms or 50 ms can still induce the illusion, lower values induced more successful saltation outcomes on average.

Experiment 5 showed that there were no critical differences between trials where the ISI was constant and where the duration was constant. As the SOA increased, so did the participants' accuracy. Similar to the VSI with translation, the VSI under expansion and contraction favored SOAs at around 100 ms. This suggested that SOA would be a good parameter to investigate for saltation experiments.

4.2.4 Other implications

Chapters 2 and 3 mentioned the discrepancy between what a few perceived that rendered them unable to participate in certain experiments. In Chapter 2, While some participants reported seeing only two flashes, a few reported seeing four flashes at times, suggesting that additional factors may contribute to the perception of "phantom flashes."

Discrepancies in reporting the correct number of flashes, as well as instances of perceiving initial and final stimuli in opposite positions, provide insight into subjective realities. While this thesis has argued that the saltation mechanism is one that benefits individuals to perceive their reality in cohesive way, it can explain why eyewitness accounts are not always reliable. Differing reports on the same event reflect what individuals truly believe they saw, shaped by how their brain processed the event and created their reality.

The final implication reflects how saltation has been studied across different modalities. The success of saltation in location identification and size judgment suggests that visual tasks can also be processed in a similar manner under VSI conditions. This might also apply to tasks within a sensory modality.

4.3 Limitations

One limitation of this thesis is the lack of naturally occurring stimuli such as that of the VSI. It is uncommon to encounter objects that flash at the same size or location at one point and travel to another; the case of lightning striking the same spot twice might be the closest occurrence. This would make it difficult to pinpoint an exact evolutionary basis for the VSI phenomenon. However such patterns can be found in man-made stimuli; certain sirens or warning lights can make use of this presentation to capture passerby' attention. Therefore this research would be most useful to apply it to area where such deception is necessary, such as animation.

Another limitation of the studies is that rapid presentation of flashes reduces the number of participants who can perceive all three flashes, thereby limiting the inclusivity of the experiment. Further data analysis were not conducted on these who could only perceive one or two flashes, which may be important to understanding the saltation effect. However, as noted previously, the percentage of unable to perceive the correct number of flashes is low compared to those who reported seeing all three. This also highlights a limitation in visual capabilities, as the somatosensory system can successfully experience saltation with durations as low as 5 ms and ISIs as low as 20 ms [63].

Lastly, across the chapters, a consistent set of parameters for the illusion and control conditions, including stimulus eccentricity, was not maintained. Ideally, keeping the same interstimulus intervals (ISIs) and durations across both conditions would have allowed for clearer observation of these parameters' true effects, particularly in Chapter 2. This would also help ensure that no extraneous factors influenced the emergence of the illusion. However, since the goal of the experiments was to determine the most ideal conditions for producing saltation, adjustments to ISIs, durations, and eccentricity were necessary.

4.4 Future studies

As mentioned in the previous chapters, the next step for experiments would be to test the VSI in additional transformation modes. This could include 2D and 3D rotation, which has not yet been investigated. The potential for success in these experiments appears highly likely based on the results of this thesis. Another experiment could involve combining the second flash positions across Chapter 2. For example, presenting the second flash with a backward shift and out of linear alignment, or presenting it out of bounds and out of linear alignment. Similarly, the transformation modes of translation and expansion/contraction can be combined. Two flashes can be presented in one location, with the third at a second location, but larger or smaller in size. Participants would then be asked to report both the perceived location and size of the second flash.

Experiment 3 highlighted the importance of attention in achieving saltation. Attention has been studied in most motion-based phenomena, such as the Fröhlich effect and flash lag effect, which have been used to explain the VSI [82, 83, 67, 84]. Attentional effects have also been prominent in the cutaneous rabbit effect (CRE) [53, 13, 20, 63] but are less studied in the VSI. Future VSI experiments can apply the current parameters of this thesis but implement different eccentricities, as Geldard did in his original works. This would provide a deeper understanding of the limits of vision.

Furthermore, induced attention, such as providing prompts about where the VSI stimuli will occur, can be used to determine if this strengthens the VSI. Does attention enhance spatial awareness, thereby increasing perceptual accuracy, or does it amplify the saltation effect? Presenting the VSI in parallel would be another interesting approach to examine the effect of attention on the VSI. The results of such experiments would also provide more insight into higher-level processing factors, such as the role of memory in processing the VSI.

Returning to the roots of VSI experiments by altering the features of the flash stimuli by using real-life images would also be excellent for real-life application. Flashing images of a person crossing the street, a car moving, or a ball bouncing on background images of real-life scenes would be a valuable approach. Comparing real-life image VSI flashes across different contexts, such as a gray control background or a moving background, would also be interesting. The results of such experiments can be connected to the reliability of eyewitness testimonies. By understanding the limitations and capabilities of our visual perception, efforts can be made to improve it.

Another flash feature that could be manipulated is contrast. This would further support the claim that cognitive priors play a role in the overall perception of VSI stimuli. To test this, an experiment could be designed in which the visibility of the flashes is altered by varying their contrast against the background, and vice versa. The results of such experiments could help determine whether the brain tends to integrate the VSI sequence through top-down processing when stimulus visibility is reduced.

As this research suggests that mechanisms other than MIPS are responsible for the illusion, these results can be applied to updating the Bayesian perceptual model for saltation phenomena. This thesis provides additional data to develop models for perceptual decision-making by combining prior beliefs, such as those discussed by Goldreich [51] and Tong [49], to update posterior beliefs. This can then be used to create simulations, whose outcomes can be observed to see if they align with the experimental results. If they match, it would enhance predictive models for VSI and other saltation phenomena.

It would also be important to gather data for all initial and final stimuli when conducting experiments on the VSI using novel approaches. This would provide insight into what elements of a VSI sequence are affected when the visual task or stimulus feature is changed, and what this suggests in the overall processing of the illusion.

4.5 Conclusion

It would be quick to assume the real-life application of such experiments would be difficult to carry out. However, one can also argue that perhaps fast-moving objects, similar to the stimuli presented in this thesis are an everyday occurrence but are too quick for our senses to process and hence appear to be nonexistent. This may explain why movement outside our direct visual field is often recounted through different means, such as the direction a car came from, where a ball landed on the court, or the color of a runner's shirt. While these arguments suggest potential challenges, they also highlight the broader relevance of understanding how we perceive movement in our environment. The value of this research will stand the test of time, evolving alongside technological advancements.

This dissertation has deepened the basic understanding of the visual saltation illusion through achieving successful saltation in novel presentation forms. These approaches conducted on the classic VSI shows how fundamental it is to revisit the basic construction of illusions to see if altering one feature would still reproduce the same effect. This study paves the way for the basic approach not for saltation experiments, but other perceptual studies.

Moreover, this thesis underscores the significance of perceptual continuity, as the misjudgment of flash location and sizes reflects the brain's inclination to maintain consistent perceptions in a changing environment. This points to a broader principle of human perception, where expectations shape how we interpret sensory information. The results not only enhance our understanding of visual phenomena but also suggest potential applications in fields like animation and virtual reality, where manipulating size and motion can create more immersive experiences. Overall, this investigation highlights the intersection of perception, cognition, and experience, illustrating how our brains construct reality in ways that are both adaptive and complex.

Appendix A

Preliminary Experiment

This preliminary experiment was conducted as a pilot study to determine whether the overall perception of the VSI stimuli would change under a novel presentation. The apparatus and stimuli used in the experiment were the same as those in Experiment 1; only the procedure was altered.

Participants

Seven students from Kyushu University participated in this experiment. All volunteers were observed to have normal vision initially. However, after the experiment was completed and two main outliers were identified, follow-up assessments of their visual capacity were conducted. PS1 reported a specific visual condition caused by an underlying issue, which may have influenced their results. PS2 reported that had normal vision and did not observe any abnormalities in their day-to-day visual experiences.

Procedure

The same five second flash positions from Experiment 1 were used. These five conditions were repeated six times in the left-to-right direction to create a set of 60 trials. Each participant completed three illusion trial sets and three control trial sets, during which they reported the position of the first, second, or third flash within each trial set. The illusion trial sets were administered first in a random order, followed by the control trial sets, also presented in a random order. This resulted in a total of 360 trials for the preliminary experiment.

Results

The graphs provide an example of how PS1 and PS2 responded, illustrating their perception of flash positions with averaged directional data. Figure 4.1 shows that the average responses of participants for the first flash (gray triangles) correspond to the actual position, as do their responses for the third flash (gray squares). However, the responses of PS1 and PS2 differ significantly. They perceived the first flash (red triangles) at the position of the third flash and the third flash (red squares) at the position of the first flash. All participants, including PS1 and PS2, perceived the second flash to be at the midpoint under illusion conditions.

In control conditions (Figure 4.2), the perception of the first and third flashes did not change significantly among the participants with normal vision. However, PS1 and PS2 perceived these flashes closer to their physical positions unlike their responses in control conditions. Despite this, in some trials, they still perceived the flashes at the opposite positions, as they did in the illusion conditions, which altered their overall averages. The positions of the second flash were mostly accurate for participants with normal vision (red circles). PS1 and PS2 also were slightly accurate, but their responses were sometimes opposite of the actual position on the scale, which also affected their overall average (gray circles).

Statistical analysis was not conducted on the participants' data. However, aside from the outlying results of PS1 and PS2, it was observed that participants could approximately identify the positions of the first and third flashes. Consequently, it was decided that, for the formal experiment, it would be unnecessary for participants to report the locations of the first and third flashes.

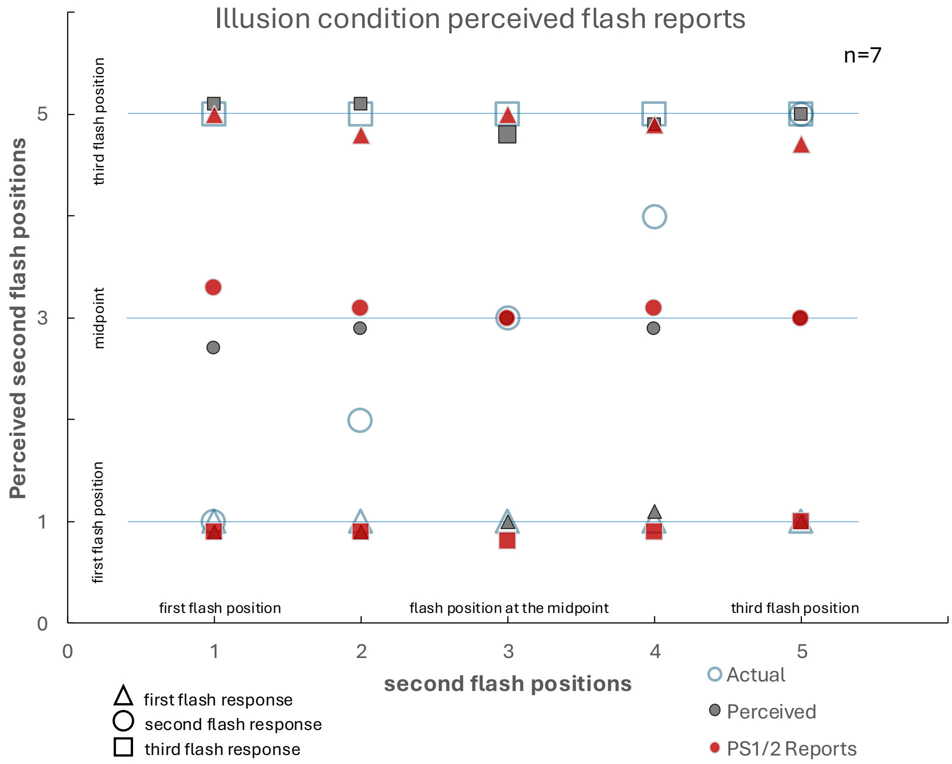

Fig. 4.1 Perceived flash positions in preliminary experiments illusion condition. Triangles indicate first flash responses. Circles indicate second flash responses. Squares indicate third flash responses. Outlined shapes indicate the actual flash position presented, gray indicates the average response of five subjects, and red indicates the average of PS1 and PS2. The value of 1 on both axes corresponds to the first flash position, the value of 3 corresponds to the midpoint position, and the value of 5 corresponds to the the third flash position.

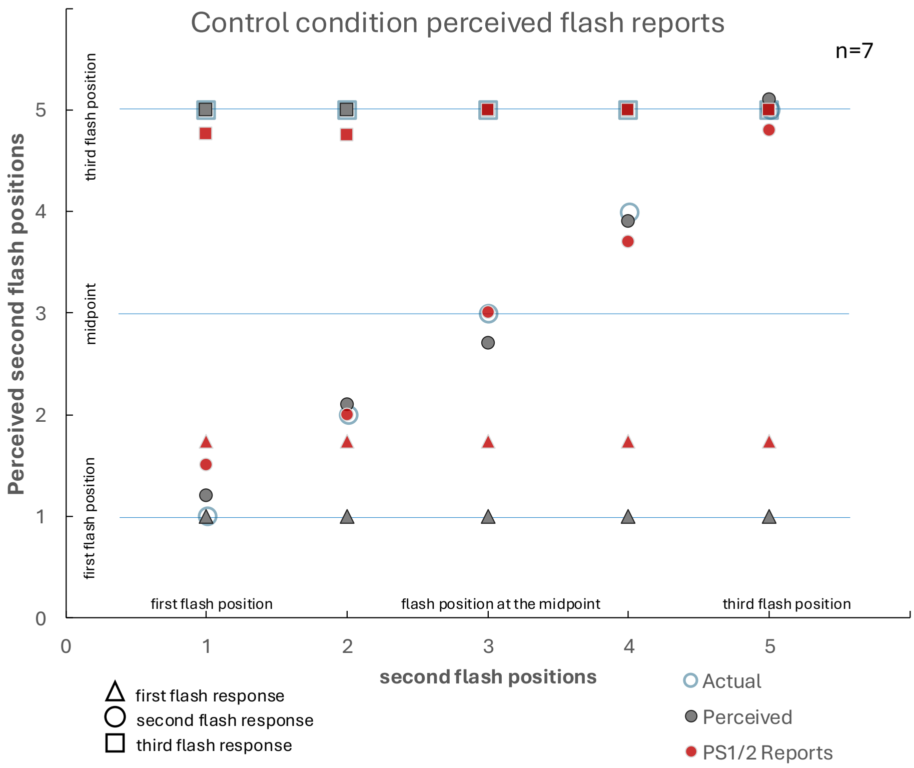

Fig. 4.2 Perceived flash positions in preliminary experiments illusion condition. Triangles indicate first flash responses. Circles indicate second flash responses. Squares indicate third flash responses. Outlined shapes indicate the actual flash position presented, gray indicates the average response of five subjects, and red indicates the average of PS1 and PS2. The value of 1 on both axes corresponds to the first flash position, the value of 3 corresponds to the midpoint position, and the value of 5 corresponds to the the third flash position.

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