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RESEARCH ARTICLE

Unconscious Elapsed Time Perception Controller Considering Unintentional Change of Illusion: Designing Visual Stimuli Presentation Method to Control Filled-Duration Illusion on Visual Interface and Exploring Unintentional Factors That Reverse Trend of Illusion

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ABSTRACT Delays (wait times) often occur in computer use, and an illusion changing the subjective elapsed time can occur unintentionally due to perceptual stimuli from computer interfaces. Since this can adversely affect users' experience and state of mind, investigating and manipulating such an illusion with computer interfaces has been an important topic for many years. While many studies have focused on visual interfaces, few studies examine these two research directions: 1) the possibility that illusion-manipulation methods verified under specific conditions may cause illusions to have completely different trends due to certain factors and 2) the feasibility of illusion-manipulation methods for changing the subjective elapsed time by using only visual stimuli in a small space at the edge of the field of view/screen. Therefore, this study verified these two directions. We designed two methods for changing the frequency and duration of visual stimuli. We also designed two visualization styles: the blinking visualization style and vibration visualization style. Three evaluations were conducted. First, the results showed the feasibility of illusion-manipulation methods using visual stimuli in a small space at the edge of the field of view/screen. The subjective elapsed time changed with a constant trend from −8.9 to 0.6% in 10 seconds. Second, the results showed that the trend in elapsed time of illusions caused by the same visual stimulus pattern could change when different visualization styles were used. Specifically, when using the method of changing the duration of visual stimuli, the increase or decrease in the subjective elapsed time was reversed depending on whether the blinking or visualization style was used. Third, the results showed that the trend in elapsed time of illusions caused by visual stimuli could change when there is visual information other than illusion-inducing visual stimuli (i.e., when some of the user's attention is diverted to something other than illusion-inducing visual stimuli). Specifically, when using the method of changing the frequency of visual stimuli, the increase or decrease in subjective elapsed time was reversed depending on whether there was visual information other than illusion-inducing visual stimuli (e.g., an advertisement video, a first-person perspective movie of walking outdoors). These results could provide new insights for designers, researchers, and users to explore and consider the illusion of changing the subjective elapsed time with visual interfaces.

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INDEX TERMS Information presentation, visual stimulus, filled-duration illusion, perception of elapsed time, wait time, mind, psychological effect, nudge, design implications.

I. INTRODUCTION

In recent years, people have been using information displays to carry out various activities, such as gathering information at work, watching video content for entertainment, and chatting with others. During these activities, there may be some minor latency (i.e., wait time), such as for processing and responding to computer input, retrieving web pages, installing applications and software, and watching uninteresting video advertisements. In fact, on mobile terminals, which account for more than half of the world's Web traffic [1], page load times are increasing yearly (according to a report from the HTTP Archive's Loading Speed report site). These wait times can increase user dissatisfaction and damage the reputation of a service itself. A 23-year review shows that users are constantly frustrated by slow load times despite continuous improvements in overall Internet speed (The Need For Speed, 23 Years Later. Nielsen Norman Group [2]). For example, previous studies have shown that 10% more customers leave a website for every second increase in load time and that reducing the page load time by 2 seconds increases the number of users who complete a transaction by 15% [3], [4], [5]. Many other researchers have investigated the changes in user behavior [6], [7] and impressions of services [8], [9], [10], [11], [12], [13] due to wait times. Thus, it has long been shown that wait times in using information devices are an important issue.

To confront this issue, many studies in the fields of HCI (Human-Computer Interaction) and wearable/mobile computing have investigated the existence of illusions related to subjective elapsed time and methods for controlling them. Among them, many have focused on visual information interfaces. For example, visual feedback of the current processing state of a computer, such as a progress bar, reduces the subjective elapsed time [14], [15]. In addition, the subjective elapsed time can be manipulated by moving a square visual object across the corners of the screen on a head-mounted display [16]. In addition to vision, a method using tactile stimuli on a smartwatch [17] and a method using auditory stimuli from a speaker device [18] have been studied. People cannot control their subjective experience of elapsed time, and its perception is affected unintentionally by information interfaces. Therefore, it is important to investigate the existence of and methods for controlling the phenomenon in which perceptual stimuli of information devices change how subjective elapsed time is experienced in order to develop methods and interfaces that control users' subjective elapsed time as desired and to prevent unintentional changes in subjective elapsed time that worsen the user experience.

Although many studies have used visual information, few have focused on the following hypotheses. Verification of these possibilities would lead to important findings for designers and users.

- *RQ1. Is it possible for the trend in elapsed time of illusions caused by the same visual stimulus pattern to change when different visualization styles are used?* For example, there is a method that changes the frequency of visual stimuli (e.g., 5 times/10 seconds, 10 times/10 seconds). When using this method, does the trend in elapsed time of an illusion affecting the subjective elapsed time change depending on how the frequency of the visual stimuli is visualized (e.g., the frequency of blinking or the frequency of vibrations)? There are few previous studies on examining illusions with the same stimulus patterns but different visualization styles. This is because there seems to be an implicit assumption that the same stimulus pattern causes phenomena with roughly the same trend in elapsed time (or at least, phenomena with the opposite trend do not occur) regardless of the visualization style. However, if this assumption is incorrect, problems will occur. For example, on the basis of academic findings that have been validated with a certain visualization style X, if companies and users use different visualization styles Y without validating them, problems can occur where users get the opposite effect of what they expect (e.g., the subjective elapsed time increases, while users want it to decrease). Therefore, it is important to test the possibility of whether using different visualization styles changes the way an illusion occurs.
- *RQ2. Is it possible to create an illusion that changes the subjective elapsed time only with visual stimuli in a small space at the edge of the visual field/screen?* Previous methods present visual information in the center of the screen (e.g., progress bars) [14], [15] and visual icons running across the entire edge of the screen [16]. There are few previous methods for presenting visual stimuli that overcome the limitations of there being little room for movement and there being only a small visual field/screen area for icons. Such a method would be helpful for controlling the subjective elapsed time in situations where previous methods are not suitable because it would not harm the field of vision or screen design. Therefore, it is important to verify what kind of stimulus patterns effectively manipulate subjective elapsed time when using visual stimuli to overcome these limitations.
- *RQ3. Is it possible for the trend in elapsed time of illusions caused by the same visual-stimulus pattern to change when there is visual information other than illusion-inducing visual stimuli (i.e., when some of a user's attention is diverted to something other than illusion-inducing visual stimuli)?* Most previous studies have been conducted under conditions with no visual information other than illusion-inducing visual stimuli in the field of view/screen. Since these conditions can be seen in practical situations involving wait time when

using information devices, findings obtained under these conditions are valuable. However, some companies' designers and users may interpret these findings as applicable to other conditions in which there is visual information other than illusion-inducing visual stimuli in the field of view/screen. For example, some people will try to use illusion-inducing visual stimuli to shorten the subjective elapsed time when viewing boring images (e.g., video advertisements) or hearing boring speech (e.g., other people's conversations in a video). Nevertheless, there has been little research on the differences between these various conditions. If the trend in elapsed time of an illusion becomes reversed under different conditions, problems can occur where users get the opposite effect of what they expect. Some previous findings indicate that the subjective elapsed time is affected by what some of the user's attention is diverted to [19], [20], [21], [22]. Therefore, testing this hypothesis on visual interface is important.

Therefore, this study aims to verify the above three hypotheses. We designed a method of presenting visual stimuli that overcomes the limitations of there being little room for movement and there being only a small visual field/screen area for icons. The proposed method consists of two methods: one is for changing the frequency of visual stimuli, and the other is for changing the duration of the stimuli. In addition, visual stimuli are expressed in two different visualization styles: blinking or vibrating. The proposed method was implemented. Three types of evaluations were conducted to test the hypotheses.

The three main contributions of this study are as follows. First, we show the feasibility of a method for manipulating the subjective elapsed time using visual stimuli in a small space at the edge of the field of view/screen. Second, we show that the trend in elapsed time of illusions caused by the same visual stimulus pattern could change depending on the visualization style used. Third, we show that the trend in elapsed time of illusions caused by visual stimuli could change depending on the different screen/visual information used other than illusion-inducing visual stimuli. The results could provide new insights for designers, researchers, and users to explore and consider the illusion of changing the subjective elapsed time with visual interfaces.

II. RELATED WORK

A. RESEARCH FOCUSING ON CHANGES IN SUBJECTIVE ELAPSED TIME

The subjective elapsed time in our study means the time width perceived for a certain experience. Psychological findings have reported phenomena in which perceptual stimuli change subjective elapsed time unconsciously. One of the well-known phenomena is the filled-duration illusion (FDI) [23]. This phenomenon changes subjective elapsed time depending on the amount, speed, and frequency of perceptual stimuli. For example, a visual stimulus with a faster speed makes the subjective elapsed time longer than a visual stimulus with a slower speed. Psychological studies reported that this phenomenon occurs with visual stimuli [24], auditory stimuli [23], [25], [26], and tactile stimuli [23]. In addition, the phenomenon of changing subjective elapsed time or time perception has been studied in various contexts. Examples of this context include waiting for an event (e.g., waiting in line at a theme park [27], [28]), driving a car [29], meditation [30], spending time in the natural environment [31], [32], looking at disgusting pictures [33], predicting the time required for future tasks [34], task-switching [35], negative states such as clinical depression [36] and stressed states [37], [38], and so on. It has been an important topic to understand the existence and manipulation of factors influencing subjective elapsed time.

Based on these psychological findings, studies have been conducted to reveal and design factors that affect the subjective elapsed time at information device interfaces. Among them, many studies focused on visual information. For example, presenting visual feedback, such as a progress bar, changes the subjective elapsed time [14], [15]. Other examples include a method that changes the shape of the progress bar and the speed at which the bar moves forward [39], a method that adds animation such as blinking to the progress bar [40], [41], [42], a method that adds interactive elements [43], and a comparison of several methods(bar indicator, pie indicator, and cartoon indicator) [44]. These methods directly present the computer's processing status to the user. Shimizu et al. [16] proposed a method of moving a square visual object across the corners of the screen on a head-mounted display. Some methods use auditory information. For example, the method that varies the frequency and time interval of sounds [18], a method adding sounds to the progress bar [45], and a method using characteristic sounds [46], [47], [48]. Suwanaposee et al. investigated the illusions of subjective elapsed time created by auditory stimuli under conditions in which human attention is devoted to an interactive task,and they provided an example of how a user's attentional state can reverse the filled-duration illusion caused by an auditory stimulus [5]. On the basis of their work, our study focuses on the visual interface. Regarding tactile interfaces, Shirai et al. focused on the existence and manipulation method of illusion where tactile stimuli from wrist-worn devices like smartwatches affect subjective elapsed time [17]. These previous studies in information technology showed that perceptual stimuli from information devices affect subjective elapsed time unintentionally and that subjective elapsed time can be manipulated by devising information device interfaces.

B. TECHNIQUES FOR MANIPULATING ILLUSIONS, PSYCHOLOGICAL EFFECTS, COGNITIVE BIASES

Like our study, many methods support users by investigating and creating unconscious phenomena (e.g., illusions, psychological effects, and cognitive biases) using information devices. The necessity of studies that focus on investigating and controlling such unconscious phenomena caused by the use of information systems have been emphasized [49], [50].

Some studies have focused on illusions of perception. As mentioned above, many methods to manipulate the subjective elapsed time are proposed. There are studies focusing on illusions related to physical and mental load, such as weight and fatigue when holding an object. For example, a sensor value feedback method of presenting modified myoelectric sensor values (i.e., presenting sensor values that are larger or smaller than the actual measured values) [51] and a VR-based visual field modification method that changes the color of an object to be lifted [52].

Some studies have focused on psychological effects related to motivation and behavior. In order to generate a positive peer effect from viewing competitive information of exercise life-log (e.g., rankings with rivals), there is a method that modifies competitive information (e.g., by generating and showing rivals whose effort degree is similar to the user) [53]. There is a method to present modified false other's evaluation log on social networking sites in order to cause a positive behavior change of healthy meal selection [54]. There is a method to improve the motivation by presenting an environment to compete with ghosts having the user's future skills and ghosts having the user's past skills [55].

Some studies focused on cognitive biases related to how people are seen. There are a method to present a pseudo-smile of the self-face to induce positive emotions [56] and a method that improves the quality of collaborative work by modifying the other's facial expressions during video chatting [57]. Some studies reduce mental load and stress in interpersonal situations by a method that modifies the pitch of the voice of the self and others [58] and a method that makes others look far away with VR to reduce the mental stress of interpersonal distance [59].

Several studies focused on cognitive biases related to concentration. To improve concentration and productivity at work, a work productivity log feedback method that highlights logs that the user was low productivity [60], a method that modifies the passing time rate of a clock faster than the actual one [61], a method for modulating the audio of lecture videos when the user's attention reduces [62], a method to improve cognitive function for vocabulary memorization learning by dynamically changing the visual interface to create the filled-duration illusion [63], and a method for changing the shape of the timeline showing the time remaining [64].

Several studies focused on the psychological effect related to mental state and exerted performance. Some studies found the existence and manipulation method of a phenomenon in which psychological anxiety and cognitive performance changed to match the feedback content of heart rate sensor information, even though the presented heart rate was false (i.e., different from the actual heart rate) [65], [66], [67].

Some studies have shown that users' self-efficacy and their mental and physical abilities in tense situations are improved by a method that presents a pseudo-success experience in VR space [68] and a method that presents sound stimuli conditioned with the user's success experience based on Pavlov's classical conditioning [69].

Other studies also focused on information presentation elements that cause psychological effects. There is a bus timetable presentation method that modifies bus departure time intervals to induce the user's psychology and behavior to accept arriving early and waiting at the bus stop so as not to miss the bus [70]. There is a method of presenting a lie in the remaining strength gauge to design behavior in the game [71].

These previous studies have shown the importance of examining unconscious phenomena that occur unintentionally with the use of information devices. They also showed that the manipulation method of this phenomenon is effective for unconsciously changing the user's perception, mental and physical states, behaviors, etc. Such phenomena are difficult to prevent because they are assumed to be caused by an automatic mind of the dual-process theory [72], [73] that causes unconscious irrational and subjective responses. Similar to these previous studies, our study investigates the illusion caused by information devices and develops a method to support users by utilizing the illusion.

III. METHOD

In this section, we describe our methods for presenting visual stimuli to test the hypotheses described in Section 1. This study was approved by the research ethics committee of Ritsumeikan University (Permission number: 2021-069), and informed consent was obtained.

A. DESIGN OF VISUAL STIMULI IN SCREEN/FIELD OF VIEW

Our method uses visual stimuli in small spaces at the edge of the screen. The visual stimulus is expressed as a visual icon in the upper right corner of the screen. Figure 1 shows an example. The visual icons occupy about 5% of the entire screen. The aspect ratio of the screen is 9:16, and the icons of the visual stimuli are located in the upper right corner of one block when the screen is divided into four vertical columns and five horizontal columns. It is not uncommon for visual icons (e.g., weather, sensor information, the direction of travel) to exist in this area, so the proposed method can be

FIGURE 1. Location of visual stimuli on screen.

applied to such visual icons. The experimental material was implemented with Processing and Premiere Pro.

The proposed method presents visual stimuli that overcome the limitations of there being little room for movement and there being only a small visual field/screen area for icons. Previous methods include presenting visual information in the center of the screen (e.g., progress bars) [14], [15] and presenting visual icons running across the entire edge of the screen [16]. However, such visual information can obstruct the visual field and interfere with visual screen design, and some visual stimuli (e.g., progress bars) require the user to gaze at them. The proposed method will help in using methods for controlling the subjective elapsed time in situations where previous methods are unsuitable. For example, a previous method may not be comfortable for some situations where users want to control the subjective elapsed time while obtaining necessary visual information.

B. DESIGN OF PATTERNS FOR PRESENTING VISUAL STIMULI

The patterns for presenting the visual stimuli were designed from the following two elements as shown in Fig. 2.

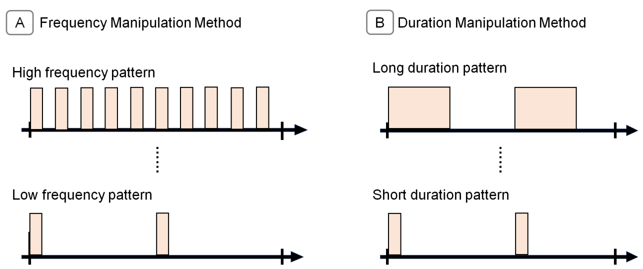

FIGURE 2. Patterns for presenting visual stimuli. (A) Frequency manipulation method, (B) duration manipulation method.

1) FREQUENCY MANIPULATION METHOD

This method manipulates the subjective elapsed time by changing the frequency of visual stimuli, for example, by changing the frequency of stimuli per 10 seconds to 2 or 10 times. We assume that the subjective elapsed time increases as the frequency of visual stimuli increases. This assumption is based on the filled-duration illusion [23], [74]. In addition, there are examples in which the subjective elapsed time was changed by changing the frequency of auditory stimuli [18] and tactile stimuli [17]. Note that the previous study reported an example in which the trend in elapsed time of an illusion was reversed between auditory stimuli and tactile stimuli.

2) DURATION MANIPULATION METHOD

This method manipulates the subjective elapsed time by changing the duration of visual stimuli, for example, changing the duration of the display time of a visual icon to 0.5 or 2 seconds. We assume that the subjective elapsed time increases as the duration of visual stimuli increases. Thus, the subjective elapsed time is assumed to change depending on the amount of stimuli that satisfies a certain time width. This assumption is also based on the filled-duration illusion [23], [74].

C. DESIGN OF STYLES FOR VISUALIZING STIMULI

There are two types of visualization styles for the aforementioned presentation patterns.

1) BLINKING VISUALIZATION STYLE

In this style, the visual stimuli blink (Fig. 3(A)). An example is a visual icon blinking twice when the frequency of the stimuli is two times. One blinking flow consists of lights turning off and on.

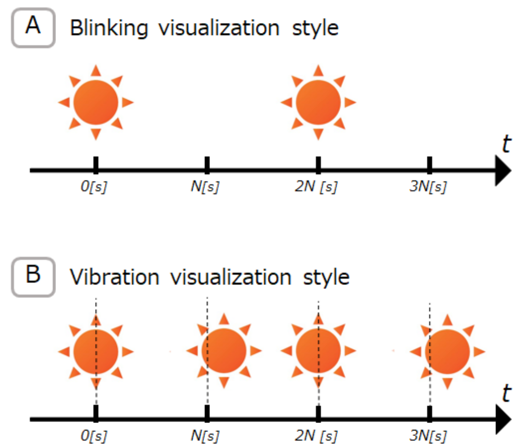

FIGURE 3. Visualization style. (A) Blinking visualization style. Visual icon turns on and off. (B) Vibration visualization style. Visual icon moves rightward and leftward.

2) VIBRATION VISUALIZATION STYLE

In this style, the visual stimuli vibrate (Fig. 3(B)). An example is a visual icon vibrating twice when the frequency of the stimuli is two times. One vibration flow consists of moving rightward from a fixed position and returning to the fixed position by moving leftward. Visual icons will move 24 pixels rightward and leftward on a screen area of 1255 pixels in width and 706 pixels in height. One round trip (i.e., moving right and left once) takes 500 ms. In other words, moving 24 pixels to the right takes 250 ms, and moving 24 pixels to the left takes 250 ms.

3) (OTHERS) SPECIFIC EXAMPLES

Fig. 4 shows a pulse diagram for stimuli and the stimulus for each visualization style corresponding to the pulse diagram. The waveform in the pulse diagram indicates the case with stimulation or without stimulation. For example, the pulse diagram in Fig. 4 (A) shows the following. In the blinking visualization style, the icon turns on for 500 ms and then turns off for 4500 ms. In the vibration visualization style, the icon moves right and left once for 500 ms and then stops

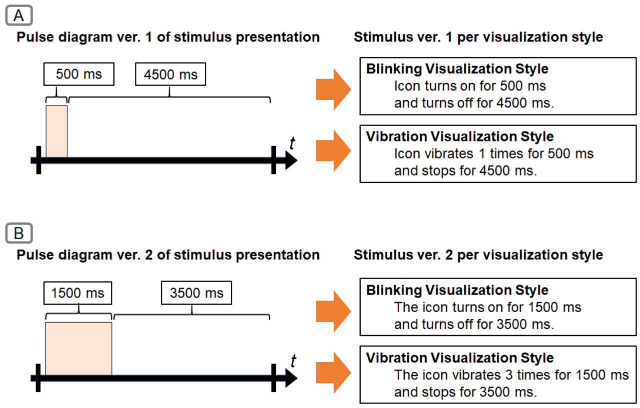

FIGURE 4. Stimulus per visualization style corresponding to pulse diagram of stimulus presentation.

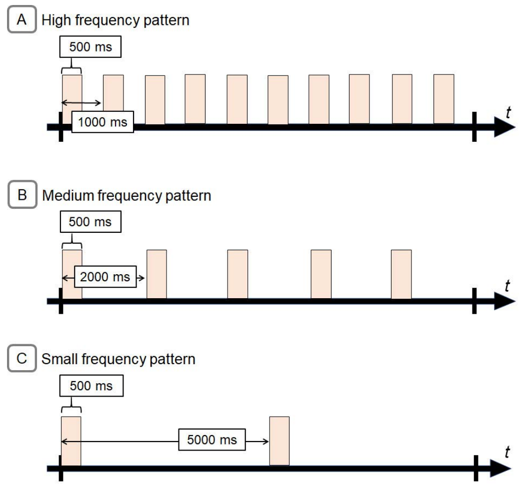

FIGURE 5. Pulse diagram of stimulus pattern with frequency manipulation method.

for 4500 ms. The pulse diagram in Fig. 4 (B) shows the following. In the blinking visualization style, the icon turns on for 1500 ms and then turns off for 3500 ms. In the vibration visualization style, the icon moves right and left three times for 1500 ms (i.e., moves right and left once every 500 ms) and then stops for 3500 ms.

IV. EVALUATION 1

Evaluation 1 investigated effective visual-stimulus presentation patterns for manipulating subjective elapsed time intentionally. We also investigated whether different visualization styles can change the trend in elapsed time of an illusion. These were tests for RQ1 and RQ2 described in Section 1.

A. EXPERIMENT A: EVALUATION OF FREQUENCY MANIPULATION METHOD

This experiment evaluated whether the subjective elapsed time is changed with a constant trend by changing the frequency of the visual stimuli. Twenty-seven subjects participated. Their status was as follows. They were university students, aged 20-25, and Asian. They were recruited within the university. They understood and practiced the experimental task in advance using an explanatory video.

1) STIMULUS PATTERNS

Three stimulus patterns were prepared as shown in Fig. 5. The first was a low frequency pattern (2 times/10 seconds), the second was a medium one (5 times/10 seconds), and the third was a high one (10 times/10 seconds). The time intervals of the stimuli were equally spaced. These were verified for each of the two visualization styles.

We used stimuli with 10 s for the following reasons. The first was that 10 s was used in previous studies [17], [18]. By experimenting with the same time range, we could compare this current study with the previous ones. The second was that finding stimulus patterns that make the subjective elapsed time feel shorter than the actual passage of 10 s of time has been recognized as useful [18] based on the fact that wait times over 10 s change the user experience in several ways (e.g., in terms of task concentration [75], satisfaction with the experience [9], the withdrawal rate of Internet video viewers [76]).

2) EXPERIMENTAL PROCEDURE

The experimental task was to experience two different stimulus patterns and select which one was longer. This task is called paired comparison and was adopted on the basis of previous studies [17], [18], [23], [74], [77], [78].

The procedure was as follows. One trial was done to compare the subjective elapsed time of two stimuli. One trial consisted of three parts: 10 s to perceive the first stimulus pattern, 5 s to rest, and 10 s to perceive the second stimulus pattern. Since these three parts were contained in one video, the subject continued to watch the same video. Then, subjects stated which stimulus was longer or whether both were the same. This trial was conducted for a total of three pairs, in which two patterns were paired from three types of stimulus patterns. This task was conducted separately for each visualization style. Therefore, subjects performed a total of six trials (i.e., three trials for the blinking visualization style and three trials for the vibration visualization style). The order of the three pairs, the order of two types of stimulus patterns, and the order of two types of visualization styles were randomized. The subjects used a laptop with a 14-inch screen (Lenovo ThinkPad, CPU: Intel Core i7-5600, 2.60 GHz, RAM: 8.00 GB), and the experimental video was displayed in full screen.

We calculated the score for each stimulus pattern as follows. A point of 1 was given to a stimulus pattern that felt longer, −1 point was given to a stimulus pattern that felt shorter, and zero points were given to a stimulus pattern that felt the same. The average score for each stimulus pattern was calculated for each individual. The statistical analysis was a within-subjects design ANOVA for two factors and a multiple comparison test using the Bonferroni method.

B. RESULTS AND DISCUSSION

The average scores of all subjects for each stimulus pattern are shown in Fig. 6. The error bars are the standard error. The higher the score, the longer the subjective elapsed time was perceived to be. There were a main effect and a significant difference between the conditions of the frequency of the visual stimuli ($F(2, 58) = 78.95$, $p < 0.01$). Multiple comparison tests showed the following results. There was a significant difference between the stimulus patterns of the low and high frequency patterns ($p < 0.05$). There was a significant difference between the stimulus patterns of the low and medium frequency patterns ($p < 0.05$). There was a significant difference between the stimulus patterns of the medium and high frequency patterns ($p < 0.05$). The subjective elapsed time increased as the frequency of stimuli increased regardless of visualization style.

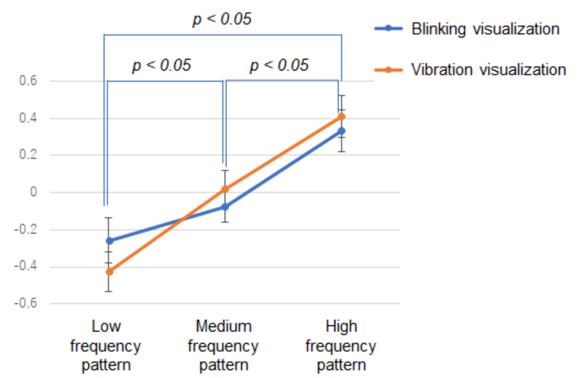

FIGURE 6. Results of frequency manipulation method of Evaluation 1. Average scores for each stimulus pattern.

The results showed that the subjective elapsed time changed with a constant trend in accordance with the change in the frequency of visual stimuli. This phenomenon was consistent with our hypothesis based on the filled-duration illusion. The subjective elapsed time became longer/shorter clearly as the frequency of visual stimuli increased/decreased. This result shows that the subjective elapsed time can be manipulated with a consistent trend by using the frequency manipulation method. In addition, the illusion occurred with a constant trend regardless of the visualization style. This indicates that an illusion caused by the change in frequency of visual stimuli is not changed by the difference in visualization style.

C. EXPERIMENT B: EVALUATION OF DURATION MANIPULATION METHOD

This experiment evaluated whether the subjective elapsed time changes with a constant trend when the duration of the visual stimuli was changed. The experimental task and procedure were the same as in Evaluation 1. Twenty-seven subjects participated. Their status was the same as in Experiment A.

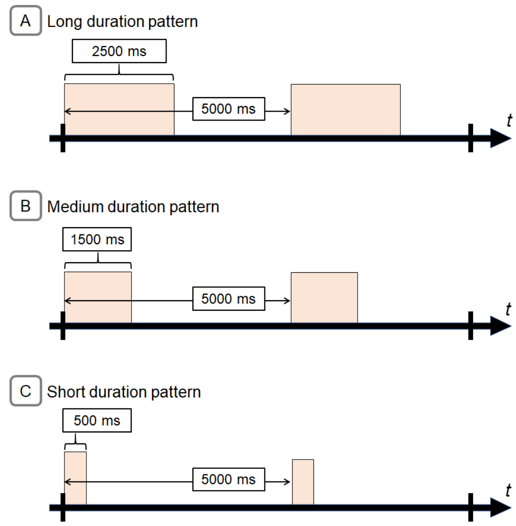

FIGURE 7. Pulse diagram of stimulus pattern with duration manipulation method.

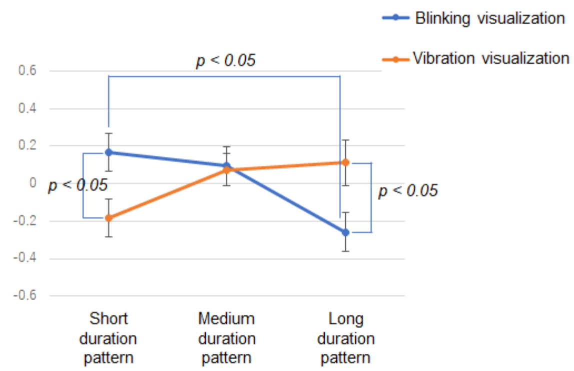

FIGURE 8. Results of duration manipulation method of Evaluation 1. Average scores for each stimulus pattern.

1) STIMULI PATTERN

Three stimulus patterns were prepared as shown in Fig. 7. The first pattern was a short duration pattern (0.5-s duration), the second was a medium one (1.5-s duration), and the third was a long one (2.5-s duration). The time intervals of the stimuli were equally spaced. These were verified for each of the two visualization styles.

D. RESULTS AND DISCUSSION

The average scores of all subjects for each stimulus pattern are shown in Fig. 8. The error bars are the standard error. There was an interaction ($F(2, 52) = 1.76$, $p < 0.05$). There was a significant difference between the visualization style conditions for the short duration patterns ($p < 0.05$), and the blinking visualization style had a longer subjective elapsed time than the vibration visualization style. Contrary to this, there was a significant difference between the visualization style conditions for the long duration patterns ($p < 0.05$), and the vibration visualization style had a longer subjective elapsed time than the blinking visualization style. In addition, for the blinking visualization style, there was a significant difference between the duration of stimuli ($F(2, 52) = 3.27$, $p < 0.05$), and the short duration pattern had a longer subjective elapsed time than the long duration pattern ($p < 0.05$).

The results showed that the subjective elapsed time changed with a constant trend in accordance with the change in the duration of visual stimuli. However, the visualization style changed the trend in elapsed time of the illusion. When the duration of the stimuli was increased, the subjective elapsed time of the blinking visualization style became shorter, and that of the vibration visualization style became longer. This result shows examples in which the trend in elapsed time of illusions can change depending on the visualization style, even if the same stimulus pattern is used.

E. GENERAL DISCUSSION

First, we confirmed the feasibility of a method that manipulates the subjective elapsed time with a constant trend using only visual stimuli that overcome some limitations. For example, the subjective elapsed time can be increased/decreased by manipulating the frequency of visual stimuli in a small space in the upper right corner of a screen. This result supports RQ2.

Second, the result indicated that it is possible for the trend in elapsed time of illusions to be changed by changing the visualization style even if the same stimulus pattern is used. The trend in elapsed time of illusions with the duration manipulation method was reversed when the visualization style was changed, although the trend in elapsed time with the frequency manipulation method was consistent regardless of the visualization style. This result supports RQ1. Therefore, even if visual stimuli are designed on the basis of the same principle and the same presentation pattern, it is necessary to re-verify how the illusion occurs when the visualization style changes. Moreover, the trend of the illusion caused by the change in the frequency of the visual stimuli was the same as those of a previous study using tactile stimuli with a wrist-worn device [17] and opposite those of a previous study using auditory stimuli from a speaker device [18]. This result indicates the necessity of investigating how an illusion occurs for each perceptual channel, even if the stimuli presentation patterns are the same.

V. EVALUATION 2

In this experiment, we evaluated how much the visual stimuli of our method can change the subjective elapsed time with respect to the actual passage of time (10 s). Twenty-seven subjects participated. Their status was the same as in Evaluation 1.

1) STIMULUS PATTERNS

Four stimulus patterns were prepared: a low frequency pattern (blinking visualization style), a high frequency pattern (blinking visualization style), a low frequency pattern (vibration visualization style), and a high frequency pattern (vibration visualization style). These were prepared to verify the minimum and maximum rate of change in the subjective elapsed time that was caused by the frequency manipulation method utilized in Evaluation 1. Only the minimum necessary stimuli were selected to reduce participant fatigue from the successive trials.

2) EXPERIMENTAL PROCEDURE

The task was for participants to state how many seconds they felt the visual stimuli to be after experiencing the stimuli for 10 s. This task is called verbal estimation in previous studies [17], [18], [26], [79]. The experimental procedure was as follows. One trial of the task involved stating the subjective elapsed time of one stimulus pattern. One trial consisted of three parts: 10 s without a stimulus, 5 s of rest, and 10 s with a stimulus. The part of 10 s without a stimulus involved videos with a white background, and the subject was told that this first video was 10 seconds long to make them understand the criterion of 10 s. These three parts were included in one video. After watching the video, subjects stated how many seconds they felt the 10 s of the stimulus to be. This task was performed for the four different stimulus patterns. The order of stimulation was randomized. Like Evaluation 1, the subjects used a laptop with a 14-inch screen, and the video was displayed in full screen. Since the subjects in Evaluation 1 and Evaluation 2 were the same, they watched the same video twice. However, no significant change in illusions caused by watching the same stimulus video multiple times could ever occur. All subjects were under the same conditions, and there was one day between Evaluations 1 and 2. Therefore, Evaluation 2 had no factors that changed and interfered with the results due to using the same video.

A. RESULTS AND DISCUSSION

The statistical analysis was a within-subjects design ANOVA with two factors. Figure 9 shows each stimulus pattern's average seconds of subjective elapsed time. The error bars are the standard error. There was a main effect and a significant difference between the visualization style conditions ($F(3, 52) = 8.3$, $p < 0.01$). The stimulus with the

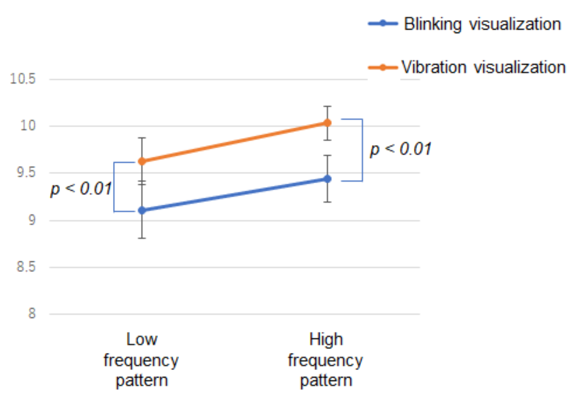

FIGURE 9. Results of Evaluation 2. Average values of seconds of subjective elapsed time for each stimulus pattern.

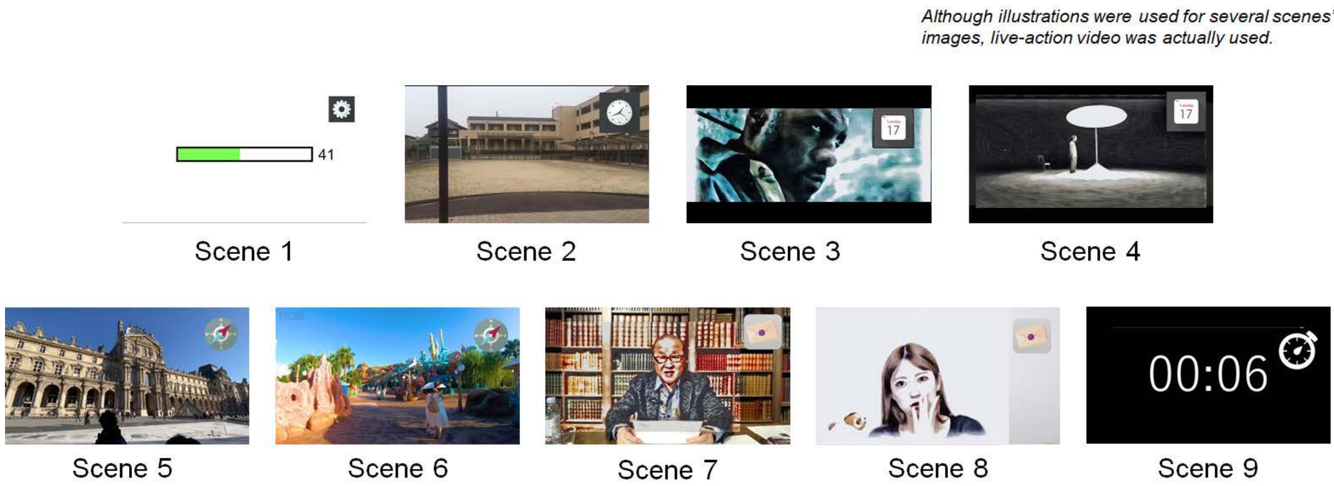

FIGURE 10. Type of scenes in Evaluation 3.

shortest subjective elapsed time was approximately 9.1 s when using the low frequency pattern (blinking visualization style), which was 8.9% shorter than the actual elapsed time. The stimulus with the longest subjective elapsed time was approximately 10.4 s when using the high frequency pattern (vibration visualization style), which was 0.4% longer than the actual elapsed time. The overall trend was that the subjective elapsed time increased as the frequency of stimuli increased regardless of visualization style. The blinking visualization style tended to have a shorter subjective elapsed time than the vibration visualization style.

The rate of change in subjective elapsed time ranged from about −8.9% to +0.4% with respect to 10 s. These results indicate that the implemented visual stimuli can make the subjective elapsed time shorter than the actual one.

VI. EVALUATION 3

This experiment investigated the possibility that the trend in elapsed time of illusions caused by visual stimuli can change when there is visual information other than illusion-inducing visual stimuli (i.e., when some of the user's attention is diverted to something other than illusion-inducing visual stimuli). This was a test of RQ3 described in Section 1. Twenty-three subjects participated. Their status was the same as in Evaluation 1. We used the frequency manipulation method. The stimulus patterns were the low and high frequency ones.

1) TYPE OF IMAGE ON SCREEN

Nine scenes of different video content were prepared as shown in Fig. 10. Some visual icons were also prepared for the visual stimuli. For example, a compass icon was used for an outdoor walking scene, and an e-mail symbol was used for a lecture scene. (1) Scene 1 was a movie with a progress bar in the center of the screen. The visual icon was a gear symbol. The length of the video was 10 seconds. (2) Scene 2 was a first-person perspective movie in which the person sat outdoors with almost no viewpoint movement. The visual icon was an analog clock. The length of the video was 10 seconds. (3,4) Scene 3 was an advertisement video for an action movie, and Scene 4 was an advertisement video for a Japanese pharmaceutical company. Scene 3 changed drastically and quickly, and Scene 4 changed slightly and slowly. The visual icon was a daily calendar. The length of the video was 15 seconds. (5,6) Scene 5 was a first-person perspective movie in which the person is looking around surrounding buildings at an outdoor plaza, and Scene 6 was a first-person perspective movie in which the person is walking in an outdoor theme park. The visual icon was a compass. The length of the video was 15 seconds. (7,8) Scene 7 was a lecture video in which a teacher is giving a lecture to the viewer, and Scene 8 was a video in which a Japanese entertainer is talking to the viewer. These scenes were similar to situations involving listening to others via information devices. The visual icons were icons that imitated e-mails. The length of the videos was 30 seconds. (9) Scene 9 was a video showing a countdown number counting down in order to investigate the influence of viewing an exact amount of elapsed time. The visual icons were icons that imitated a stopwatch. The length of the video was 10 seconds.

2) EXPERIMENTAL PROCEDURE

The experimental task was to experience videos in which two different stimulus patterns were applied in the same scene and to select which one was longer. This was a comparison task similar to Evaluation 1. The procedure was as follows. One trial consisted of three parts: 10 s to perceive the first stimulus pattern, 5 s to rest, and 10 s to perceive the second stimulus pattern. The same scene was used for this first and second stimulus pattern. Since these three parts were contained in one video, the subjects continued to watch the same video. Then, they stated which one was longer or whether both were the same. The stimulus patterns were the low and high frequency patterns, and the order of these two patterns was randomized for each subject. The order of the nine scenes was also randomized for each subject. The same as Evaluation 1, the subjects used a laptop with a 14-inch screen, and the video was displayed in full screen.

A. RESULTS AND DISCUSSION

Using the same method as in Evaluation 1, the average score for each stimulus pattern was calculated for each individual. The statistical analysis was a within-subjects design ANOVA and a multiple comparison test using the Bonferroni method. The average scores of all subjects for each stimulus pattern are shown in Fig. 11. The error bars are the standard error. The average scores for each scene are shown in Fig. 12. There were significant differences between the conditions for the frequency of the stimuli ($F(2, 44) = 31.39$, $p < 0.01$). The subjective elapsed time of the low frequency pattern became longer than that of the high frequency pattern regardless of the scene. Thus, the subjective elapsed time decreased as the frequency of the stimuli increased. This trend is opposite the general trend of the filled-duration illusion.

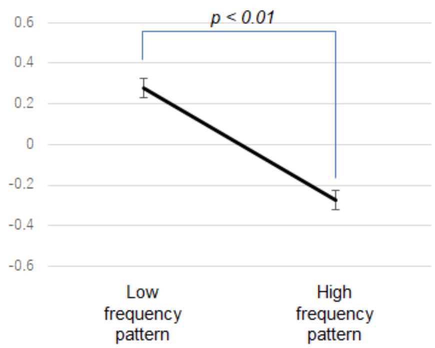

FIGURE 11. Results of Evaluation 3. Average scores of all scenes for each stimulus pattern.

The results show an example in which the trend in elapsed time of illusions caused by visual stimuli changes when there is visual information in the visual field/screen other than illusion-inducing visual stimuli. The trend in elapsed time of the illusions was reversed between Evaluations 1 and 3. The reason is assumed to be that some of the people's attention was directed to visual information other than the illusion-inducing visual stimuli. The amount of attention to illusion-inducing visual stimuli was large in Evaluation 1, while a certain amount of attention was allocated to information other than the illusion-inducing visual stimuli in Evaluation 3. This difference seemed to cause the difference in the trend in elapsed time of the illusions. In fact, some previous findings indicate that the subjective elapsed time is affected by what some of the user's attention is diverted to [19], [20], [21], [22]. These results indicate that designers and users need to assume that it is impossible to know whether the validation results from the conventional conditions of previous studies

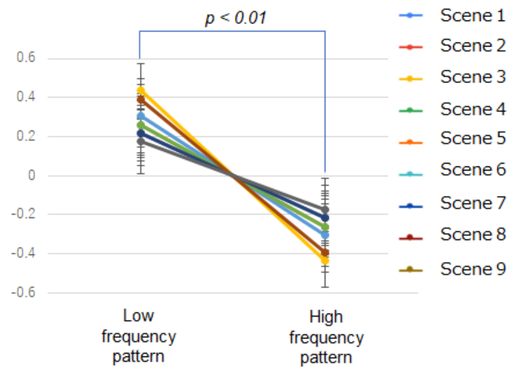

FIGURE 12. Results of Evaluation 3. Average scores for each scene.

(i.e., conditions where only illusion-inducing visual stimuli were in the visual field/screen) can apply to other conditions.

VII. GENERAL DISCUSSION

The results of this study could be useful in the design and use of information devices and applications that consider illusions that change the subjective elapsed time by using visual stimuli.

A. IMPLICATIONS TO CONSIDER AND EXPLORE CONDITIONS THAT CHANGE TREND IN ELAPSED TIME OF ILLUSIONS

The experimental results indicated that the trend in elapsed time of an illusion involving subjective elapsed time that is caused by visual stimuli could change depending on several conditions. First, the results showed that the trend in elapsed time of illusions caused by the same visual stimulus pattern can change when the visualization style is different. This can be assumed from Evaluation 1, where the trend in elapsed time of illusions caused by manipulating the duration of visual stimuli changed depending on the visualization style. This result supports RQ1. Next, the results showed that the trend in elapsed time of illusions caused by the same visual stimulus pattern can change when there is information other than illusion-inducing visual stimuli in the visual field/screen. This can be assumed from Evaluation 3, where the trend in elapsed time of illusions was changed between Evaluations 1 and 3 by manipulating the frequency of the visual stimuli. This result supports RQ3.

It is an important finding that the trend in elapsed time of illusions was reversed for different visualization style conditions and for different types of screen/visual information. The results suggested that HCI studies examining the change in subjective elapsed time with visual stimuli would need to explore and consider this important finding. If this possibility is not explored and considered, the designer and the user may erroneously cause an illusion with a trend opposite expectations. Information interfaces designed without this understanding may unintentionally distort the subjective elapsed time so that the user experience unintentionally becomes worse. Although additional research is needed to understand these conditions fully, the results presented in this paper are considered valuable for this research topic.

B. FEASIBILITY OF PROPOSED METHOD

The results showed the feasibility of a method for manipulating the subjective elapsed time using only visual stimuli to overcome the limitations of there being little room for movement and there being only a small visual field/screen area for icons. The results supported RQ2. For example, it was confirmed that the subjective elapsed time became longer/shorter when increasing/decreasing the frequency of visual stimuli per time width. The subjective elapsed time of 10 s was shortened by 8.9% with the visual stimuli implemented in this paper, which seemed to be the same extent as in previous studies. For example, auditory stimuli shortened the subjective elapsed time by approximately 7.6% [18], while a visual progress bar shortened the subjective elapsed time by approximately 11% [40], [41], and tactile stimuli shortened it by approximately 3% [17]. Although additional research is needed to evaluate the effectiveness of the shortening rate, this rate is not considered trivial for a 10-second wait time/delay, given the previous examples described in Section 1, where a difference of a few seconds in wait time affects the user experience.

The proposed method can be easily applied to the information interface of mobile devices, stationary laptops, and AR (Augmented Reality) glasses, as long as the visual stimuli can be displayed in a small area at the edge of the screen. AR glasses are a display worn in front of the eyes to present information. Since the proposed method occupies a small area of the field of view or screen design, it is expected to be helpful in situations where previous methods using the center area or entire edge of a screen are not suitable.

C. LIMITATIONS AND FUTURE WORK

(1) Since the subjects were mainly young Asians, we plan to conduct future experiments with subjects of diverse attributes. Although we did not use a crowd works service such as Amazon Mechanical Turk in order to supervise the experiment of subjects, the use of crowd works seems useful when conducting experiments with large numbers of subjects. (2) We fixed the duration to about 10 seconds as in previous studies. This reason is described in Evaluation 1, and the results of previous studies in this time widths have been recognized as useful. On the other hand, the generalization of these results to more extended time widths, such as several minutes or tens of minutes, needs to be validated in future studies. (3) It has not yet been verified whether different information devices cause different illusions. Since this experiment was conducted on a laptop screen, we plan to verify whether differences in illusion can be caused by different information devices, such as laptops and AR glasses. (4) In the present experiment, the number of consecutive trials by the subjects was reduced to the extent possible. In experiments in which subjects make a series of consecutive trials, they may be affected by fatigue or excessive familiarity with the trials, which may lead to a decrease in sensitivity [80]. The importance of reducing the number of consecutive trials of the subjective elapsed time evaluation has been argued in previous studies [5]. The maximum number of consecutive trials in this experiment was nine trials for Evaluation 3, which is significantly less than the number of consecutive trials in previous studies (36 trials for [18] and 45 trials for [40]). Although the adverse effects in this point were reduced as much as possible, consideration of this point is also future work. (5) In the future, we plan to explore the factors and conditions that change the trend of the illusion. We also plan to examine ways to increase the effectiveness of the subjective elapsed time manipulation. An example would be the simultaneous use of multiple perceptual channels (e.g., visual, auditory, tactile). (6) Our study's visual stimulus and icons were representative examples to test the three research questions described in Section 1. Although the results cannot be generalizable across all visual icons, similar illusions are assumed to occur in situations where similar visual icons are used. For example, a visual icon with an appearance other than the orange sun symbol (e.g., yellow flower, blue rectangle) will not cause different illusions from our study. However, it is necessary for designers to verify the illusion of newly created stimuli or interfaces because unintended factors may change its illusion, like Evaluation 1 and Evaluation 3 in our study. (7) We also plan to consider the application of the findings of this study and the proposed method to situations in which changing the subjective elapsed time is effective. For example, among the input interface for visually impaired users [81], [82], [83], vibration feedback methods for touch interfaces have been studied, and prolonged response time is discussed [84]. Upon this, the input interface may become comfortable by reducing the subjective elapsed time with tactile vibration patterns from appropriate devices (e.g., touch interface devices, wearable devices). Other applications include reducing the subjective elapsed time during unpleasant experiences (e.g., injection, physical training, cognitive work) and extending the subjective elapsed time during pleasant entertainment experiences.

VIII. CONCLUSION

This study explored a method for manipulating the illusion changing the subjective elapsed time by using visual stimuli in an information interface. It also explored the conditions that would change the trend in elapsed time of such an illusion. We designed a method that uses only visual stimuli in a small space at the edge of the screen. Two visual-stimulus presentation methods (frequency manipulation method and duration manipulation method) and two visualization styles (blinking visualization and vibration visualization) were designed and implemented. Three evaluations were conducted. The results showed two points: (1) the possibility that an illusion manipulation method verified under specific conditions may lead to completely different trends in elapsed time of illusions due to some factors, and (2) the feasibility of illusion manipulation methods for changing the subjective elapsed time by using only visual stimuli in a small space at the edge of the field of view/screen. These results could provide new insights for designers, researchers, and users to explore and consider the illusion of changing the subjective elapsed time with visual interfaces.

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