

Perceived duration of visual motion increases with speed

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Despite wide recognition that a moving object is perceived to last longer, scientists do not yet agree as to how this illusion occurs. In the present study, we conducted two experiments using two experimental methods, namely duration matching and reproduction, and systematically manipulated the temporal frequency, spatial frequency, and speed of the stimulus, to identify the determinant factor of the illusion. Our results indicated that the speed of the stimulus, rather than temporal frequency or spatial frequency per se, best described the perceived duration of a moving stimulus, with the apparent duration proportionally increasing with log speed ([Experiments 1 and 2](#)). However, in an additional experiment, we found little or no change in onset and offset reaction times for moving stimuli ([Experiment 3](#)). Arguing that speed information is made explicit in higher stages of visual information processing in the brain, we suggest that this illusion is primarily mediated by higher level motion processing stages in the dorsal pathway.

Keywords: motion, speed, temporal frequency, time perception

Citation: Kaneko, S., & Murakami, I. (2009). Perceived duration of visual motion increases with speed. *Journal of Vision*, 9(7):14, 1–12, <http://journalofvision.org/9/7/14/>, doi:10.1167/9.7.14.

Introduction

Although proper perception of time is important in performing almost every daily action, our time perception sometimes seems distorted. For example, we might experience a “shorter” hour when we are absorbed in reading an interesting book or a “longer” second during a frightening event (Stetson, Fiesta, & Eagleman, 2007). Research on chronostasis (Yarrow, Haggard, Heal, Brown, & Rothwell, 2001) and the saccadic compression of time (Morrone, Ross, & Burr, 2005) has clearly demonstrated that our perception of time can be distorted within a much briefer timeframe, as well.

The relationship between the motion of a visual stimulus and its perceived duration represents another situation in which physical time and perceptual time can differ. Several studies have demonstrated that the perceived duration of a moving stimulus is longer than that of a stationary stimulus having the same actual duration (Brown, 1995; Kanai, Paffen, Hogendoorn, & Verstraten, 2006; Lhamon & Goldstone, 1975; Mitrani & Stoyanova, 1982). For example, Mitrani and Stoyanova (1982) reported that a spot of light moving horizontally from left to right was estimated to last longer than a stationary spot of the same physical duration. Similarly, Brown (1995) examined the perceived duration by reproduction and production methods and found that subjects perceived the duration of a spot moving along a randomly curved path to be longer than the duration of a stationary spot staying

at a randomly chosen location on the same path. Although researchers have been aware of these phenomena, which Kanai et al. (2006) termed “time dilation”, for some time, the mechanism underlying them remains uncertain.

Brown (1995) explained the relationship between visual motion and perceived duration in the framework of the “change model” (e.g., Poynter, 1989). This model posits that salient events, such as changes in visual stimuli, index the passage of time so that we know how much time has passed by counting these indices. Stimulus motion is accompanied by continuous changes in spatial location and thus provides important temporal indices. To explore this interpretation, Brown (1995) manipulated stimulus velocity and found that, in agreement with the change model, the duration of a moving stimulus was judged to be longer than that of a stationary one, and faster stimuli were judged to be longer in duration than slower ones (see also Tayama, Nakamura, & Aiba, 1987). Stimulus complexity was also manipulated, but it affected the perceived duration under limited conditions.

In Brown’s (1995) study, the durations tested were relatively long (i.e., 6–18 s). Several researchers have argued that different mechanisms of temporal processing operate depending on the duration of the stimulus (e.g., Iry & Spencer, 2004; Lewis & Miall, 2003; Mauk & Buonomano, 2004), suggesting that a different principle might be involved when stimuli are of a shorter, subsecond duration. However, some prior studies (Kanai et al., 2006; Lhamon & Goldstone, 1975; Mitrani & Stoyanova, 1982) have reported a similar phenomenon with short-duration

stimuli. Because some researchers have suggested that the perception of shorter times is “automatic” (Lewis & Miall, 2003) and involves no cognitive control, we decided to examine this subsecond range of stimulus duration.

The fundamental challenge in understanding this mechanism is the identification of the variable of the moving stimulus that is critical in creating the illusion. In most previous studies on duration dilation caused by motion (Brown, 1995; Lhamon & Goldstone, 1975; Tayama et al., 1987), the distance traveled by the stimulus covaried with speed. We selected the stimulus for the current study, a Gabor patch, with the intent of separating the effects of these two variables.

The use of a Gabor patch had two advantages. First, a moving Gabor patch (a drifting carrier with a stationary envelope) does not change its overall location in the visual field. Though the carrier continuously moves within the static envelope and thus displacement information is physically available, it is difficult to individuate and track a feature of the stimulus because of the crowding effect and thus effects of motion trajectory are minimized. Second, the temporal frequency and spatial frequency of the carrier of a Gabor patch can be manipulated independently, an important consideration in identifying the mechanism of this illusion. If temporal frequency alone or spatial frequency alone determines the magnitude of the illusion, then the illusion probably occurs at an early stage of visual information processing where frequency information is explicitly retained for use. On the other hand, results suggesting that speed determines the magnitude of the illusion would imply that the illusion occurs at a later stage of visual information processing where speed becomes explicit in neural representation.

In the present study, we measured the perceived durations of moving stimuli using the matching method in [Experiment 1](#) and the reproduction method in [Experiment 2](#). Additionally, in [Experiment 3](#) we recorded reaction times (RTs) for stimulus onset and offset, so that we could explore the relationship between the perception of onset (the event) and the perception of duration (the interval).

Experiment 1: Matching

The main question we posed in the present study was what variable of a moving stimulus determines the illusion of motion-induced duration dilation. The goal was to clarify which of the three factors determines the illusion: spatial frequency, temporal frequency, or speed. In [Experiment 1](#), we measured the perceived durations of moving stimuli using the matching method. Two Gabor patches appeared on a computer display in temporal sequence ([Figure 1](#)). One of the two was stationary, and the other contained a moving carrier within a stationary envelope. By comparing these two, we determined the

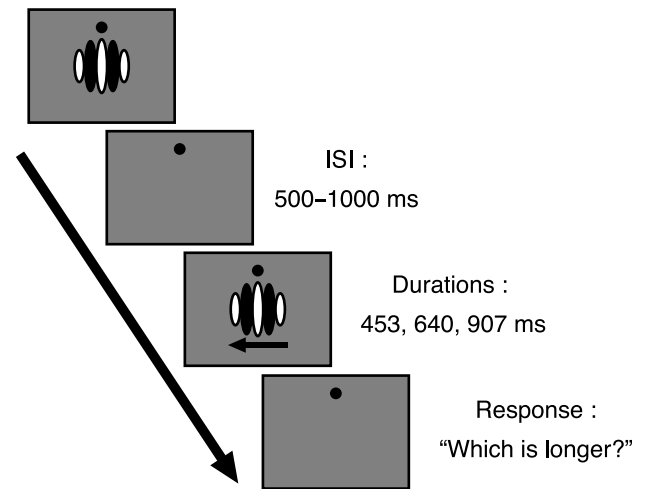


Figure 1. A schematic of a single trial of [Experiment 1](#). Subjects compared the durations of two consecutively presented stimuli and then reported which seemed to last longer.

physical duration of the stationary stimulus that was perceived as subjectively equal to the duration of the moving stimulus. We examined how this perceived duration changed with spatial frequency, temporal frequency, and speed.

Methods

Subjects

Eight naive subjects with normal or corrected-to-normal vision participated.

Apparatus

All stimuli were presented on a CRT monitor (Mitsubishi Diamondtron M2, 22 inch, 40×30 deg) under computer (Apple PowerMac G5) control. The experiment was conducted in a dark room, with a chin rest to restrain the subject’s head. The viewing distance was 57 cm. In order to preclude auditory clues that might assist in time estimation, we used a function synthesizer to generate white noise, presenting the sound via loudspeakers at a constant level throughout each experimental session.

Stimuli

We generated stimuli on MATLAB (The MathWorks) using the software library Psychtoolbox (Brainard, 1997; Pelli, 1997). Vertical Gabor patches served as stationary and moving stimuli. Within a stationary two-dimensional isotropic Gaussian contrast envelope ($SD = 2$ deg; the visible extent was approximately 6 deg in radius), a vertically oriented sinusoidal luminance modulation was drifted rightward or leftward (with the direction chosen at random) at a predetermined temporal frequency (0, 1, 2, 4,

8, and 16 Hz) and spatial frequency (0.5, 1, 2, and 4 c/deg). The peak contrast was nominally 100%, and the mean luminance was 41.6 cd/m². The background was maintained at the mean luminance level. The spatial frequency of the stationary patch was always 1 c/deg. The physical durations of the moving stimuli were 0.45, 0.64, or 0.91 s, with the duration for each trial chosen at random. We will refer to these as the “standard durations” hereafter.

Procedure

Subjects were instructed to fixate at the fixation point 6.6 deg above the center of the Gabor patch. Two Gabor patches, one moving and the other stationary, appeared at the center of the monitor in temporal sequence. During the inter-stimulus interval (ISI) of 0.5–1 s, only the fixation point was present. The presentation sequence was the same during each session; each subject experienced two sessions in which the moving stimulus appeared first and two sessions in which the stationary stimulus appeared first. After the second stimulus disappeared, subjects indicated which of the two stimuli seemed to last longer by pressing one of two buttons. The next trial started automatically 0.8–1 s after this response.

To avoid cognitive anticipation, the duration of the moving stimulus for each trial was chosen at random from the three standard durations. The duration of the stationary stimulus was varied according to the staircase method, with step sizes of 107 or 80 ms. Three independent staircases were randomly interspersed for the three standard durations of the moving stimulus. Each sequence was terminated after eight response reversals. The point of subjective equality (PSE) of the stationary stimulus for each of the three standard durations of the moving stimulus was obtained by averaging the last four reversals of the staircase sequence.

Quantification

We were interested in identifying which variable best explained the illusion. If the absolute magnitude of overestimation was the same regardless of the physical duration of the stimulus, then the difference between the PSE and the physical duration would be the important measure. If, on the other hand, perceived duration increased in proportion to physical duration, then the ratio of the PSE to physical duration would be the important measure.

Typical PSEs for the moving stimulus at 0.5 c/deg and 16 Hz for the three standard durations are shown as the open circles in the log–log plot in Figure 2. The lines connecting them appear to remain at a constant vertical distance above the identity function, reflecting a constant duration ratio.

An analysis of variance (ANOVA) for duration differences revealed a main effect of standard duration, $F(2, 14) = 6.46$, $p < 0.05$, but this effect disappeared

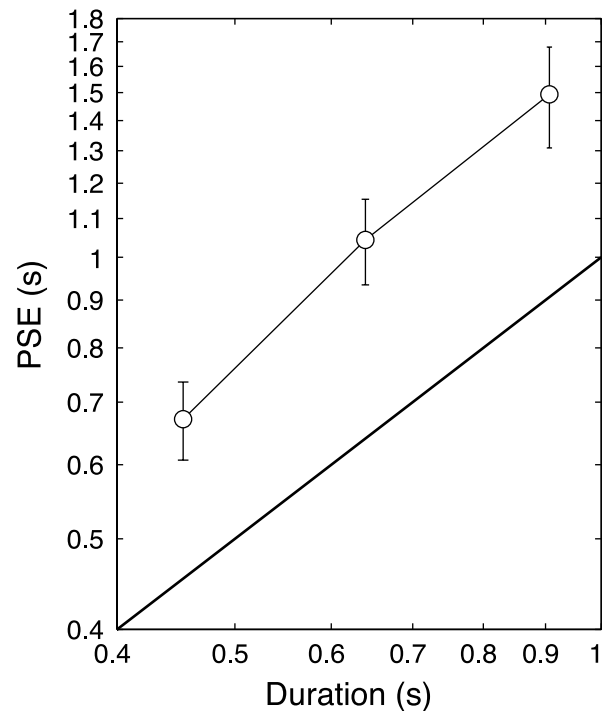


Figure 2. PSEs for the three standard durations in the representative condition, i.e., 0.5 c/deg, 16 Hz. Open circles indicate actual PSEs and the solid line below them indicates veridical duration ($y = x$).

when we performed the same analysis on the duration ratio, $F(2, 14) = 0.603$, $p = 0.56$. Therefore, we chose the ratio of PSE to physical duration as the better index of the illusion. Because the ratio did not systematically vary across standard durations, we calculated the average ratio for each spatiotemporal frequency condition.

The ratio of overestimation (RO), the index of the illusion, was defined for each spatiotemporal frequency condition by the following equation:

$$RO = \sum (PSE_i / DM_i) / 3, \quad (1)$$

where DM_i and PSE_i indicate the physical duration of the i th moving stimulus (of the three standard durations) and its PSE, respectively.

Results and discussion

If duration dilation occurs, ROs should be greater than 1. Moreover, if Brown’s (1995) finding could be extrapolated to a subsecond timeframe, ROs of faster stimuli should be larger than those of slower ones, suggesting two alternative predictions (Figure 3). On the one hand, if the temporal frequency of the stimulus determines the illusion, ROs would be best described as an increasing function of temporal frequency and would show no

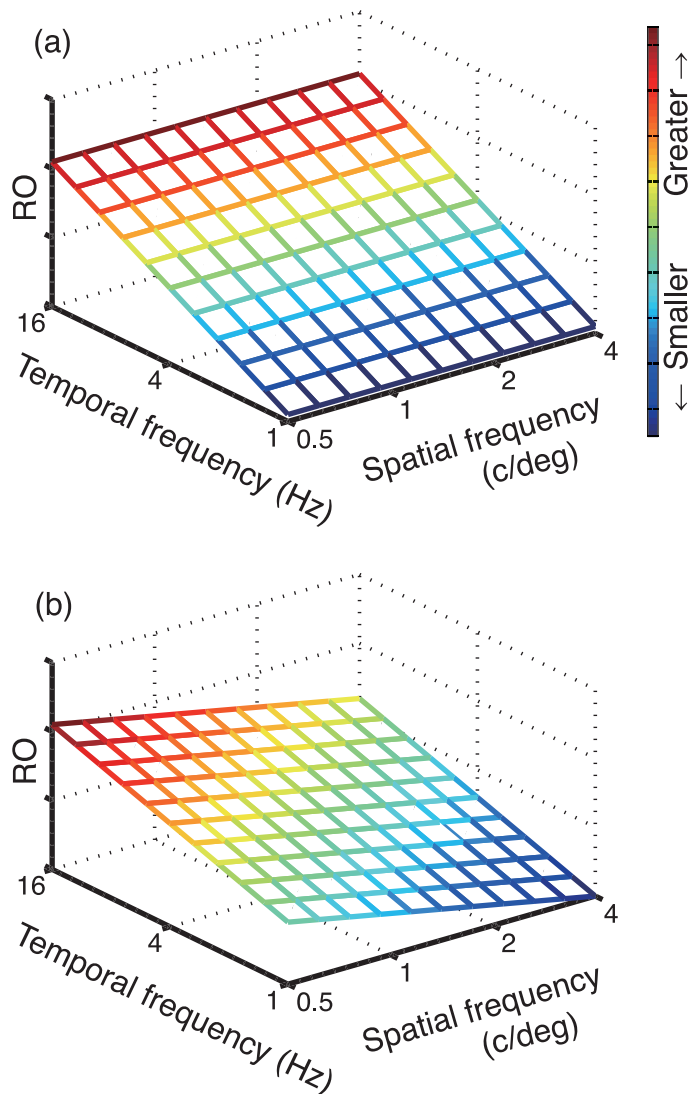


Figure 3. Two predicted best-fit planes. (a) If the temporal frequency of the stimulus alone determined the illusion, ROs would be best described as a function of temporal frequency, regardless of the spatial frequency. (b) Meanwhile, if the speed of the stimulus determined the illusion, ROs would be a function of speed.

differences across spatial frequency conditions (Figure 3a). On the other hand, if the speed of the stimulus determines the illusion, ROs would be influenced by both temporal and spatial frequencies because the speed of a sinusoid is defined as temporal frequency divided by spatial frequency (Figure 3b).

We calculated each RO for each subject and each spatiotemporal frequency condition and then averaged the data across all subjects for each condition. These results, shown in Figure 4, indicate that RO increased as temporal frequency increased and as spatial frequency decreased. Clearly, RO was influenced by both temporal and spatial frequencies.

The main question we asked was whether the magnitude of this illusion is determined by temporal frequency or by

speed. To address this question, we performed a multiple linear regression analysis, with spatial frequency and temporal frequency as the independent variables. The function is written as $RO = \beta_0 + \beta_1 S + \beta_2 T$, where S indicates $\log_2(\text{spatial frequency})$ and T indicates $\log_2(\text{temporal frequency})$. The best-fit function, which defines a slanted plane above the two-dimensional spatiotemporal frequency axes, was plotted as a mesh plot (see Figure 4). The corresponding equation is given as follows:

$$RO = 1.267 - 0.059S + 0.047T. \quad (2)$$

If either the S or the T axis alone were the determinant factor of the illusion, we should obtain a slanted plane passing through the T or S axis, respectively (Figure 3a).

If, on the other hand, stimulus speed governed the illusion, we should obtain a slanted plane with a 45 deg tilt, or equivalently, $RO = k + aV = k - aS + aT$, where V indicates $\log_2(\text{speed})$ and k and a are constants (Figure 3b). The best-fit function supported the second prediction, i.e., that speed governs the illusion. The coefficients of S and T were both significant, $t(153) = -2.99$, $p < 0.05$ for S ; $t(153) = 2.98$, $p < 0.05$ for T . This finding confirms that both frequency components contribute to the magnitude of the illusion. Furthermore, the values of the two coefficients were similar in size but with opposite signs. In fact, the value of each coefficient fell within the confidence limits of the other, reflecting no significant difference between them. Since S and T are logarithmic, $T - S$ provides a logarithmic measure of stimulus speed, or V . Therefore, Equation 2 can be rewritten as

$$RO = 1.267 + 0.047V - 0.012S. \quad (3)$$

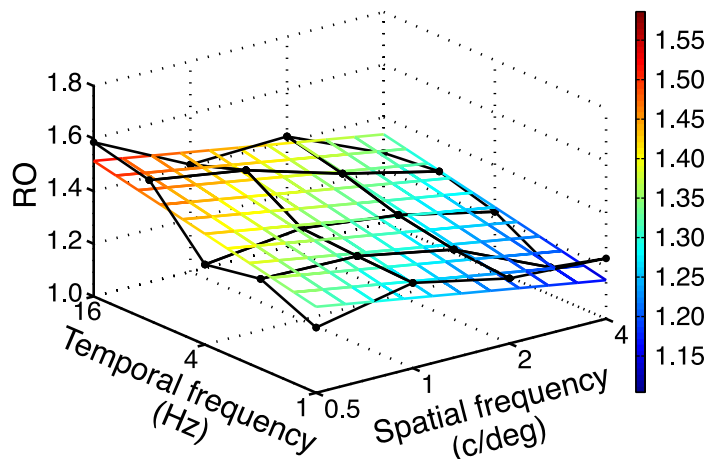


Figure 4. Average ROs in Experiment 1 plotted against logarithmic spatiotemporal frequency axes. An RO greater than 1 means the overestimation of stimulus duration. Circles indicate ROs for each spatiotemporal frequency condition (data for eight subjects, except that one subject did not undertake 16 Hz conditions). The mesh plot indicates the best-fit function.

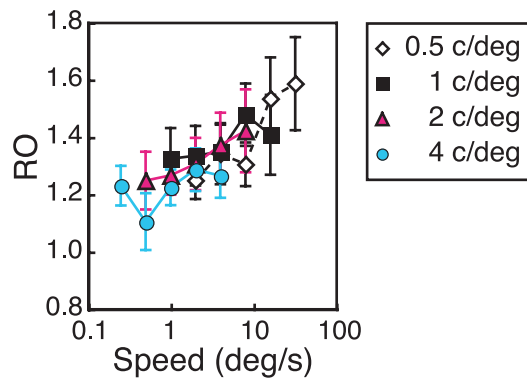


Figure 5. ROs were replotted against speed, with spatial frequency as the parameter. Error bars indicate 1 SE.

This indicates that stimulus speed was the major determinant of RO; as speed increased, RO increased proportionally with log speed. The influence of S was unclear and did not reach statistical significance.

In the above, we performed the linear regression using the linear plane model, but we also tested whether functions with nonlinearity could yield better fits to our data. We tested the quadratic function, $RO = \beta_0 + \beta_1 S + \beta_2 T + \beta_3 S^2 + \beta_4 T^2 + \beta_5 ST$, and compared the goodness of fit in terms of Bayesian Information Criterion (BIC)¹. The best-fit parameters were (1.283, -0.006 , 0.028, -0.020 , 0.007, -0.017), and $BIC = 71.19$, whereas $BIC = 58.64$ in the linear fit. We next tested a linear plane model with a floor nonlinearity, $RO = \max(\beta_0 + \beta_1 S + \beta_2 T, \beta_6)$, but the best-fit parameters (1.258, -0.062 , 0.051, 1.185) resulted in a poor fit, namely $BIC = 63.01$. Therefore, we concluded that the linear plane model without nonlinearity was the most reasonable one.

Having demonstrated the dependency of RO on speed, we replotted RO data against stimulus speed; Figure 5 shows the results of these calculations. Again the RO data were well described as an increasing linear function of log speed with spatial frequency having little influence. We also tested a model with a quadratic term, $RO = \beta_7 V^2 + \beta_8 V + \beta_9$. The best-fit parameters were (0.006, 0.033, 1.247), but only β_8 and β_9 were significantly different from 0 ($p < 0.05$), which confirmed the claim that the RO increased proportionally with log speed.

One might argue that the data points at high temporal frequencies might construct a steeper slope than the slope at low temporal frequencies and that, if high temporal frequency conditions were excluded, the best-fit function for the remaining data points might become flat. Did high frequency conditions distort the overall data shape? To address this question, we performed the simple linear regression analysis on the data shown in Figure 5 excluding 8 and 16 Hz conditions. The result showed that the slope of the best-fit line became less steep, 0.032, but it was still significantly greater than 0 ($p < 0.05$).

We must note here that in some parts of the data it was not clear whether only stimulus speed governed RO. Let

us focus upon the 1 Hz conditions in Figure 4. Within these conditions, there seemed to be only small differences of RO values among the four spatial frequencies. When one-way ANOVA was performed within these conditions, we could not find a statistically significant effect of spatial frequency ($F(3,21) = 0.43$, $p > 0.05$). The reason for this is not clear, but we think that there might be two possible reasons. One possibility is that the speed dependence of the illusion that we propose here exists only in the frequency area higher than 1 Hz. Since the aforementioned linear regression analysis on the data excluding 8 and 16 Hz showed a shallower slope, we cannot reject this possibility. The other possible reason is the noisy nature of the data. We noticed that even at 1 Hz, some tendency of speed dependence was seen for the data at 1, 2, and 4 c/deg, but the point at 0.5 c/deg was located irregularly against the speed dependence scenario. At this low spatial frequency, subjects might be able to track the displacement of one of luminance stripes in the Gabor patch to judge duration based on displacement information. In any event, currently we cannot resolve whether the conclusion of speed dependence is applicable to all data points with a conditional statement about random noise, or whether the conclusion is applicable to a subset of parameter space without 1 Hz conditions. We do not emphasize that duration dilation should strictly obey a linear function of log speed at every spatiotemporal frequency point; a rising function with some nonlinearity and floor/ceiling effects would be more realistic. However, since the present study lacks strong evidence for these claims, it is concluded that linear speed dependence is the best summary of the present data.

These results are consistent with previous studies demonstrating that the duration of a moving stimulus is perceived to be longer than that of a stationary stimulus (Brown, 1995; Lhamon & Goldstone, 1975; Mitrani & Stoyanova, 1982). Our results demonstrating the importance of stimulus speed are also consistent with previous studies that focused on longer time intervals (Brown, 1995; Tayama et al., 1987).

In addition, we demonstrated that a Gabor patch, with a moving carrier within a stationary contrast envelope that never changes its overall position in the visual field, also creates motion-induced duration dilation. This new finding implies that a motion trajectory is not required for the illusion to occur.

Experiment 2: Reproduction

There is a general agreement that object speed is calculated at relatively higher stages of the visual information processing system, using outputs from earlier stages that process frequency information (e.g., Adelson & Bergen, 1985). Thus, the results of Experiment 1 imply

that this illusion occurs at relatively high levels of visual information processing.

However, Kanai et al. (2006) claimed that the magnitude of duration dilation caused by motion is determined by the temporal frequency of the moving stimulus rather than by its speed. There are important differences between the study by Kanai et al. and the current study that might account for this discrepancy in conclusions. First, the two studies employed different methodologies. In [Experiment 1](#), we used the matching method, in which we matched the physical duration of the stationary stimulus with the apparent duration of the moving stimulus. In contrast, Kanai et al. (2006) used the reproduction method, in which the subject manually reproduced the apparent duration of the moving stimulus by pressing a button. To examine whether this methodological difference might account for the discrepancy, we conducted another experiment, [Experiment 2](#), which repeated [Experiment 1](#) substituting the reproduction method.

Methods

Subjects

Six naive subjects participated, five of whom had also participated in [Experiment 1](#).

Apparatus and stimuli

We used apparatus and stimuli identical to those in [Experiment 1](#) except for the standard durations. In addition to those used in [Experiment 1](#), the duration of 0.32 s was added to the standard durations to make them more comparable to those used by Kanai et al. (2006).

Procedure

Stimuli appeared at the center of the monitor. After observing each stimulus, subjects reproduced the duration of the stimulus by pressing a button for the same interval as they perceived the stimulus to have lasted. We provided no visual or auditory feedback during or after reproduction. The fixation point appeared during every session. Each subject completed 15 sessions for each condition.

Quantification

The index of duration dilation, RO, was calculated as in [Experiment 1](#). In [Experiment 2](#), however, we used the reproduction time for the stationary 1 c/deg Gabor patch as the denominator. In other words, this version of RO represented the ratio of the apparent duration of the moving stimulus to the apparent duration of the stationary stimulus that actually had the same physical duration.

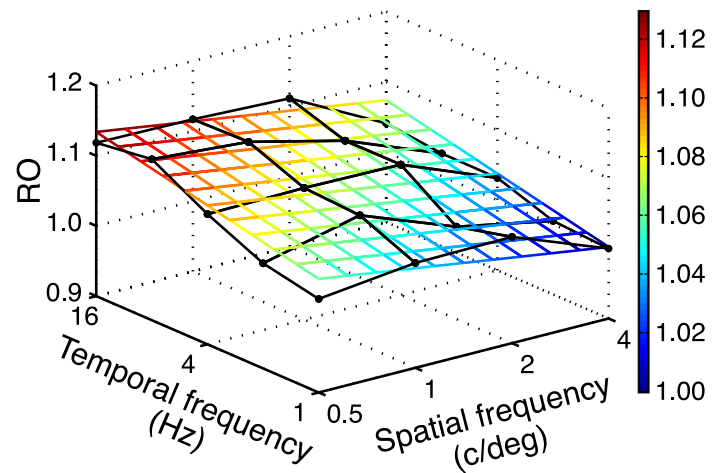


Figure 6. Average ROs in [Experiment 2](#) (cf. [Figure 4](#)).

Thus, in [Experiment 2](#), RO was defined for each spatiotemporal frequency condition by the following equation:

$$RO = \sum (RepT_{Mi} / RepT_{Si}) / 4, \quad (4)$$

where $RepT_{Mi}$ indicates the reproduction time for the moving stimulus having the i th duration (of the four standard durations), and $RepT_{Si}$ indicates the reproduction time for the stationary stimulus having the same duration.

Results and discussion

[Figure 6](#) shows the RO data averaged over subjects. Again, both spatial and temporal frequencies affected RO. RO increased as temporal frequency increased and as spatial frequency decreased.

As in [Experiment 1](#), we again performed a multiple linear regression analysis and obtained the following best-fit function:

$$RO = 1.042 - 0.020S + 0.018T. \quad (5)$$

Both coefficients were statistically significant, $t(117) = -3.05$, $p < 0.05$ for S ; $t(117) = 3.35$, $p < 0.05$ for T ; and there was no significant difference between their absolute values. Thus, as in [Experiment 1](#), this equation can be rewritten as

$$RO = 1.042 + 0.018V - 0.002S, \quad (6)$$

in which the last term is not statistically significant. [Equation 6](#) shows that the RO data obtained in

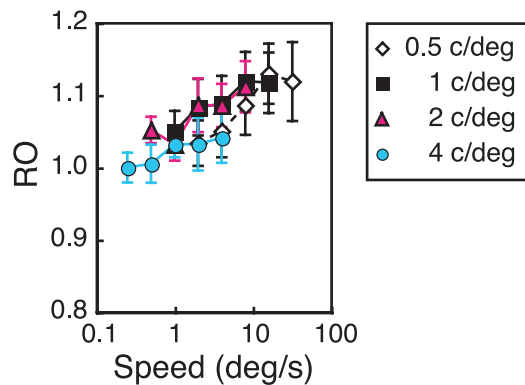


Figure 7. ROs were replotted against speed, with spatial frequency as the parameter. Error bars indicate 1 SE.

Experiment 2 depended on stimulus speed. This result indicates that the magnitude of the duration dilation is determined by stimulus speed regardless of the technique used to measure it.

As in **Experiment 1**, we tested the quadratic function, $RO = \beta_0 + \beta_1 S + \beta_2 T + \beta_3 S^2 + \beta_4 T^2 + \beta_5 ST$, and a linear plane model with a floor, $RO = \max(\beta_0 + \beta_1 S + \beta_2 T, \beta_6)$. Then again we compared the goodness of fit in terms of BIC. The best-fit parameters of each model and BIC were (1.050, 0.003, 0.025, -0.015, -0.004, -0.001), BIC = -236.20 and (1.042, -0.020, 0.018, 0.995), BIC = -240.69, whereas BIC = -245.48 in the original linear model. Therefore, we concluded that the linear plane model without nonlinearity was the most reasonable.

To compare these results with results from **Experiment 1**, we replotted the data against speed, as shown in **Figure 7**. These data clearly demonstrate that RO was an increasing function of speed.

In the replication of Kanai et al.'s (2006) experiment, we included very short durations in standard duration conditions. However, we were worried that it might be too difficult for the subjects to reproduce such short durations correctly. To exclude the possibility that this caused the floor effect and contaminated the resulting profile, we reanalyzed the RO data excluding short duration conditions, namely 0.32 and 0.45 s conditions and confirmed that the same pattern of results was obtained; the best-fit plane was $RO = 1.024 - 0.017S + 0.020T$ (both coefficients were significant, $p < 0.05$).

Five of the subjects in this experiment had also participated in **Experiment 1**. Thus, for those subjects we were able to compare the data from the two experiments. These calculations revealed a significant correlation between the two experiments, $r = 0.55$, $t(18) = 2.82$, $p < 0.05$, indicating consistency across the two experiments in what was measured.

From the results of **Experiment 2**, we concluded that the difference between the research reported by Kanai et al. (2006) and our **Experiment 1** was not due to a difference

in experimental procedure. As will be shown in the **Discussion** section, the apparent discrepancy between the two studies can be easily reconciled in terms of stimulus difference.

Experiment 3: Reaction time

We can pose another question about why motion appears to expand in time: when viewing a moving stimulus, does one perceive stimulus onset with a shorter delay and/or motion offset with a longer delay than when viewing a stationary stimulus? Regarding the timing of stimulus onset, simple reaction time (RT) in response to the onset of faster motion is shorter than RT to the onset of slower motion (Tynan & Sekuler, 1982). Regarding stimulus offset, RT to motion offset also depends on stimulus velocity (Hohnsbein & Mateeff, 1992). This raises the question of whether the distortions in perceived duration might result from subjects misperceiving the stimulus onset and/or offset. To examine this possibility, we measured RTs to stimulus onset and offset.

Methods

Subjects

Three subjects (2 naive subjects and one of the authors) participated in this experiment. All had normal or corrected-to-normal vision.

Apparatus

The same CRT monitor and computer were used in this experiment. RT was defined as the time difference between the onset or offset of the visual stimulus and the button press by the subject. The stimulus change was optically monitored by a photodiode located in the lower left corner of the monitor, and the button press triggered a voltage change in a custom circuit. Both signals were digitized at 1500 Hz with an analog-to-digital converter (National Instruments PCI-6221 with LabVIEW Signal-Express) and saved in a Windows PC (Epson Endeavor Pro2500) for offline analysis.

Stimuli

As in the previous experiments, we used a Gabor patch with a stationary envelope and a moving or stationary carrier. We varied the duration of stimulus presentation randomly within a range of 0.45–1.36 s.

In this experiment, we used three types of stimuli: a stationary Gabor patch (1 c/deg, 0 Hz) and two moving Gabor patches (one at 1 c/deg, 16 Hz; the other at 0.5 c/deg,

16 Hz). We selected these conditions because they had produced sufficient duration dilation in previous experiments.

Procedure

Stimuli appeared at the center of the monitor one after another with a random ISI (0.6–1.0 s). Under the onset condition, subjects pressed the button as quickly as possible when the stimulus appeared. Under the offset condition, subjects pressed the button when the stimulus disappeared. The onset condition and the offset condition occurred in separate sessions. One session consisted of 110 stimuli. All Gabor patches within one session had the same temporal and spatial frequencies. Following a few practice sessions, each subject completed five sessions for each condition. One session took approximately 5 min.

We discarded the data from the first ten practice trials in each session. In keeping with previous research (Tynan & Sekuler, 1982), we also discarded RTs shorter than 100 ms or longer than 500 ms; 1.45% of all data were discarded by these criteria.

Results and discussion

Figure 8 shows the RT averaged across the three subjects for each stimulus. Under the onset condition, the ANOVA revealed a significant difference in RT among stimulus speed conditions, $F(2,4) = 11.89, p < 0.05$. Post hoc analysis showed a significant difference between slower (1 c/deg, 16 Hz condition) and faster (0.5 c/deg, 16 Hz condition) motions ($p < 0.05$). RT to the onset of the 0.5 c/deg moving stimulus tended to be shorter than RTs to other stimuli. This may be due to spatial frequency, for it is known that subjects react more quickly to the onset of stimuli having lower spatial frequencies (Breitmeyer, 1975; Gish, Shulman, Sheehy, & Leibowitz, 1986; Lupp, Hauske, & Wolf, 1975).

The ANOVA revealed no significant differences for offset RT, $F(2,4) = 4.63, p > 0.05$. Although the RT to the offset of the moving stimulus appeared to be longer than that to the offset of the stationary stimulus, the difference was very small.

These results indicated that there was a negligible difference in detection latency between the stationary stimulus and moving stimulus. The difference, if there was any, might have resulted in some apparent expansion of the duration of the moving stimulus. However, considering that the magnitude of the difference in RTs between

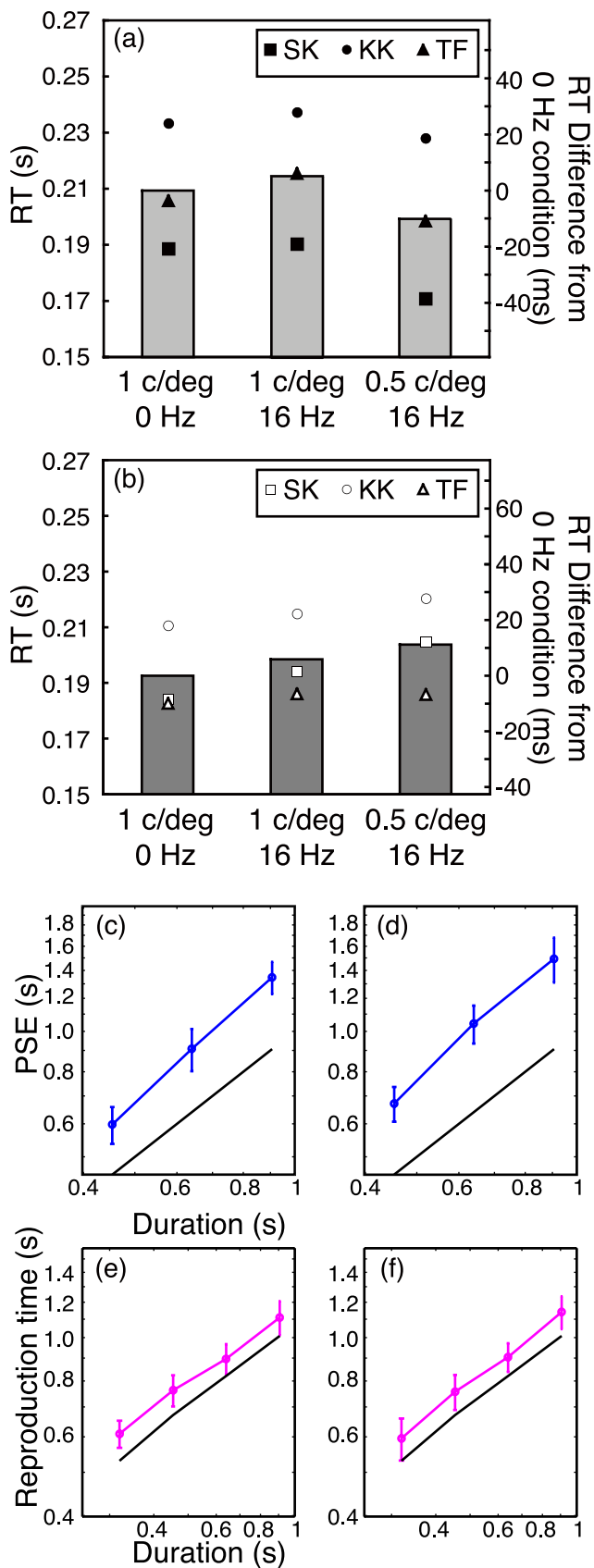


Figure 8. Reaction time (RT) to stimulus (a) onset and (b) offset. The bars show the means of all subjects' RTs. The square, circle, and triangle indicate the mean RTs for the three subjects. (c, d) The PSEs under the slower (1 c/deg, 16 Hz) condition and faster (0.5 c/deg, 16 Hz) condition in Experiment 1; the solid line represents $y = x$. (e, f) The reproduction time under the slower and faster conditions in Experiment 2; the solid line represents the reproduction time under the stationary (1 c/deg, 0 Hz) condition.

the fastest moving stimulus (0.5 c/deg, 16 Hz) and the stationary stimulus (1 c/deg, 0 Hz) was only about 15 ms, it is not reasonable to conclude that this difference in delay length was the only cause of the duration expansion that we identified in previous results.

At first glance, this outcome seems confusing. Subjects perceived the duration to be erroneously long even when they perceived the instant of the stimulus onset and offset accurately. However, other studies have found similar results. For instance, Johnston, Arnold, and Nishida (2006) found that the perceived duration of a moving Gabor patch shrank after adaptation to higher temporal frequency, despite the fact that they found no change in perceived timing of stimulus onset or offset. In addition, Pariyadath and Eagleman (2007) found that when duration dilation occurred, the rate of visual flickers or the frequency of the accompanying sound was perceived correctly. This implies that perceived “time” is not a unitary entity. Their findings and those of the present study imply that the perception of an *event* and the perception of *duration* are not always integrated experiences. Correct perception of stimulus change and distorted perception of stimulus duration can occur simultaneously.

Discussion

In this study, we measured the perceived durations of moving and stationary stimuli using two different experimental procedures. In [Experiment 1](#), we adopted the matching method and observed the apparent expansion of the duration of motion, with perceived duration dependent on speed of motion. In [Experiment 2](#), we adopted the reproduction method and found the same relationship, with the illusion dependent on stimulus speed. From the results of these two experiments, we concluded that duration dilation depends on stimulus speed and argued that the mechanism underlying the illusion occurs at some later stage of visual information processing. In [Experiment 3](#), we recorded the RTs to stimulus onset and offset to examine whether this illusion is caused by the differential latency of response to stimulus onset and/or stimulus offset between moving and stationary stimuli. However, the onset RT and offset RT in response to the moving stimulus did not differ significantly from those to the stationary one. Therefore we concluded that erroneous perceptions of stimulus onset or offset were not sufficient to induce duration dilation.

Fourier analysis of stimulus configuration

Results of the first two experiments apparently contradict the findings of Kanai et al. (2006), who manipulated

the spatial and temporal frequencies of the stimulus just as we did and identified temporal frequency as the determining factor in the illusion. Specifically, they found that the higher the temporal frequency, the longer the apparent duration of the moving stimulus, irrespective of spatial frequency. To see whether this discrepancy originated from methodological differences, we replicated [Experiment 1](#) using the Gabor patch stimulus but substituting Kanai et al.’s (2006) method of reproduction. We still observed results similar to our earlier findings. Therefore, it is highly unlikely that the difference in experimental methods accounts for the contrasting conclusions.

Seeking another explanation for the discrepancy, we noticed that the two studies used different stimulus configurations. Whereas we used the Gabor patch throughout our experiments, Kanai et al. (2006) used an “expanding” concentric sinusoidal grating as the moving stimulus in their critical experimental conditions (specifically, in Experiments 3 and 4). The expanding grating is a wavelet-like pattern such as one sees on the surface of water after dropping in a stone. The luminance is sinusoidally modulated along radial directions isotropically, and this luminance modulation drifts outward over time. Contrast is tapered by a Gaussian that is concentric to the center of expansion. Using this kind of moving stimulus, Kanai et al. found that duration dilation was best described as an increasing function of temporal frequency.

Their expanding grating and our Gabor patch were different in many respects, including the direction of motion and stimulus size. We conducted a simple Fourier transform of both stimulus configurations to the spatial frequency domain. As can be seen in the power spectra and their transitions over time by a quarter cycle of phase ([Figure 9](#)), our Gabor patch was fairly well band-limited around the designated spatial frequency. In clear contrast, the expanding grating employed by Kanai et al. contained relatively broad spatial-frequency components at every phase and, intriguingly, a strong DC component (0 c/deg) at certain phases. Note that the DC component refers to the overall luminance of the stimulus relative to the background or mean luminance, and thus its systematic change as a function of phase indicates periodical modulation of overall luminance at the designated temporal frequency.

These power spectra indicate that the expanding grating would seem brighter or darker at certain phases, whereas the Gabor patch would not. This suggests that this expanding grating would generate flicker-like percepts. Hence, temporal frequency information contained in this configuration could become dominant, and one could explicitly perceive that information as flicker rate, or bright–dark switching within a unit of time. We are confident that this access to temporal frequency information was the most prominent distinction between the two studies, and that it brought about the apparent discrepancy in the results.

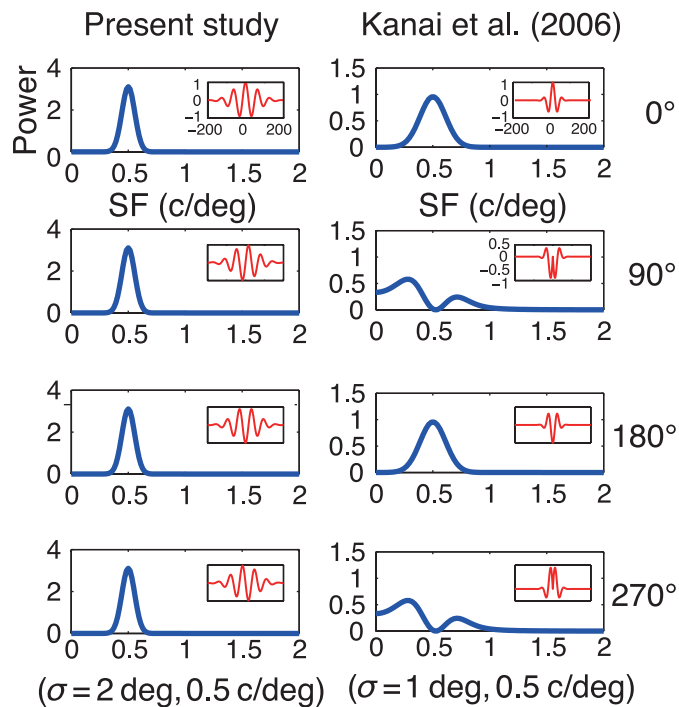


Figure 9. Spatial-frequency power spectra and their transitions over time. The four panels on the left are of our Gabor patch and the four panels on the right are of the “expanding” grating in Kanai et al. (2006). Plotted from top to bottom are the spatial-frequency profiles at four representative time slices of temporal modulation, with their respective phase angles indicated in the right-hand legend (0° , 90° , 180° , and 270°).

Possible neural mechanisms of time perception

We manipulated the temporal and spatial frequencies of the stimulus so that we could estimate the stages in visual information processing where the neural basis of this illusion might be located. From the results of the present study, we suggest that the neural correlate would be found in higher stages where an object’s speed is explicitly represented.

Visual information entering the retina first travels to the lateral geniculate nucleus (LGN) and then to the primary visual cortex (V1). At the level of V1, neurons show separable tunings for spatial and temporal frequencies (Priebe, Lisberger, & Movshon, 2006). The information about visual motion is then sent through the dorsal pathway to visual areas MT and MST. Neurons in MT are highly sensitive to motion direction, and some MT neurons are reportedly tuned for speed as well (Perrone & Thiele, 2001; Priebe et al., 2006). Therefore, we suggest that information in MT is responsible for the illusion of duration dilation induced by motion.

Magnocellular pathway, which mainly conveys information from the retina to the dorsal stream including area

MT, is known to prefer low spatial frequencies and high temporal frequencies (Merigan, Byrne, & Maunsell, 1991). The possibility that the temporal frequency dependence and spatial frequency dependence in our experiments occur independently through this pathway still technically remains to be considered. However, if they were truly independent, it would be a surprising coincidence that we obtained the partial regression coefficients for spatial frequency and temporal frequency of roughly the same size (with no significant difference) favoring the speed hypothesis, in both Experiments 1 and 2. We regard this as evidence for speed dependence as the most parsimonious account.

Some researchers (Goldstone & Lhamon, 1976; Lhamon & Goldstone, 1975; Kanai et al., 2006) have demonstrated that visual flicker, which contains no directional motion, also expands perceived duration. In this case, we do not need to distinguish between speed and temporal frequency. For simple flicker, it is not difficult to imagine that the speed-processing stage will respond to flicker more vigorously with increasing flicker rate. Thus, we can explain both motion-induced and flicker-induced duration dilations if we assume that the illusion depends on the output from this stage regardless of the stimulus property.

It is apparent that one can calculate duration in the absence of visual information, so a vision-specific neural mechanism (e.g., V1 or MT) does not necessarily play a central role in time perception itself. Rather, a general mechanism for time perception might reside elsewhere and interact with a vision-specific mechanism specialized for speed.

Models and future explorations

The change model (or change/segmentation model; e.g., Brown, 1995; Poynter, 1989) predicts that durations of stimuli containing many changes seem longer than those of stimuli containing fewer changes. From this point of view, as many researchers have pointed out, it is understandable that one would overestimate the duration of moving objects because they change in spatial location more than do stationary objects (Brown, 1995). In the present study, we used Gabor patches as moving stimuli. Although the inner elements drifted within the patches, the patches never changed their spatial location. Nonetheless, we observed the duration dilation typically associated with motion. This finding implies that duration dilation does not require a change in the stimulus location. Luminance modulation of the stimulus is not sufficient to account for duration dilation because the illusion depends not on temporal frequency but on speed. These new findings suggest that the classical view of the change model needs some modification as applied to the sub-second range of stimulus duration.

We propose the following revised model of duration dilation and time perception. When one is experiencing a

visual event, the visual system processes information with a certain “tick rate” that represents the lapse of time in the ongoing event. This tick rate of the “internal clock” is altered as required by the stimulus situation. As the rate becomes higher, more precise temporal information about the event is available. We argue that the rate of the clock becomes higher for moving/flickering objects than for stationary ones because such an adaptation would provide an ecological advantage in the prevention of accidents, avoidance of predators, and so forth. This model is similar to the classical pacemaker-accumulator model (e.g., Treisman, Faulkner, Naish, & Brogan, 1990). The difference is that whereas the classical model assumes the existence of a general pacemaker, which generates pulses to gauge universal time beyond sensory modalities, the model proposed here does not require such a general clock but simply assumes an internal clock that can be specific to visual modality. The idea of modality specific clock could explain the absence of transfer of duration dilation effects between two modalities (Morrone et al., 2005).

The key to our model is the argument that a mechanism for time perception estimates the duration of the stimulus by referring to the number of internal “ticks” counted during the presence of the object. Therefore, when the number of ticks increases, the duration of the object is estimated to be longer.

Our model assumes that the internal clock increases its tick rate depending on information from the speed-processing stage. As stimulus speed increases, the ticks become more rapid, possibly to adapt to the rapidly changing nature of a moving object. Eagleman (2004) reported that the duration of a flash was underestimated more when it was presented in slow motion than when it was presented at normal speed. In terms of our hypothesis, we might suggest that the tick rate of one’s internal clock is degraded during slow motion presentation, causing fewer ticks and therefore shrinkage of the estimated duration of the event. When the stimulus is simple flicker, the speed-processing stage responds more vigorously with increasing flicker rate so the ticks increase depending on the temporal frequency rather than on speed. Hence, flicker induces duration dilation depending on its temporal frequency.

Some of the assumptions and predictions of this model require further exploration. For example, as the tick rate increases, the spatial resolution of the visual system is expected to degrade. Yeshurun and Levy (2003) found that transient spatial attention increases spatial resolution while sacrificing temporal resolution in a parallel manner. In both cases, it seems that our limited resources make it difficult to improve multiple resolutions simultaneously. This is currently an open question because we did not test spatial sensitivity in this study. In addition, the term “speed” should be defined more narrowly. We assume that the tick rate of the internal clock increases depending on speed, but it is not clear whether this refers to physical

speed or perceived speed. These explorations will clarify the plausibility of the proposed model and the underlying mechanism of time perception.

Conclusions

Our perception of time is easily distorted by a variety of factors, one of which is visual motion. In this study, we have demonstrated that visual motion expands the duration of perceived time, and that this effect is best characterized as a function of the speed of motion rather than one of temporal frequency. Because speed information is processed at higher stages of visual information processing, this illusion arguably has its neural basis at these higher stages, and this neural information plays an important role in time perception.

Acknowledgments

Part of this study has appeared in the form of conference proceedings (Murakami & Kaneko, 2008). I.M. was supported by Nissan Science Foundation.

Commercial relationships: none.

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Footnote

¹Bayesian Information Criterion (BIC) is a criterion for model selection. It penalizes the more complex models, and the smaller BIC values indicate the better models (see Schwarz, 1978).

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