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There and back again: Revisiting the on-time effect

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ABSTRACT

In apparent motion, static stimuli presented successively in shifted locations produce a subjective percept of continuous motion. Reducing stimulus exposure (or on-time) was shown to consistently increase the perceived velocity of apparent motion (Vision Research 29 (1989), 335–347), yet surprisingly little investigation has followed up on the discovery of this illusion. In five experiments, we delineate the boundary conditions of the on-time illusion in order to clarify its underlying mechanisms. Subjects viewed multi-item apparent-motion displays, in which at some point, on-time duration either increased or decreased. Objective velocity remained unchanged, yet participants had to judge whether they perceived the motion to become slower or faster. We observed the on-time illusion during both fast and slow apparent motion. The effect was not modulated by stimulus luminance, thus precluding an energy-summation account of the illusion. It generalized from speed perception to time perception in a temporal bisection task. The illusion was specific to apparent motion, as it did not occur with veridical motion. Finally, the illusion persisted when on-time and off-time were not confounded, that is, when off-time remained constant. These findings are discussed in the framework of current models of motion perception.

In December 2012, the movie "The Hobbit: An Unexpected Journey" (henceforth: "The Hobbit"; Jackson, 2012) premiered in cinemas worldwide. The movie was recorded using high frame rate (HFR) technology, which allowed for the recording of 48 frames per second (fps) instead of the standard 24 fps. Many cinemas played the movie in the HFR version, whereas others played it in the standard frame rate. Interestingly, when viewed in HFR, some people reported experiencing the movie as played in fast forward, at least for the first several minutes (e.g., Ryan, 2012). That is, even though the HFR did not change the objective velocity of motion in the movie, subjective velocity was distorted and perceived to be higher than in the standard version.

Such velocity distortions are a widely researched phenomenon in veridical motion. However, films do not actually contain veridical motion. Instead, perceived motion in films is based on "stroboscopic apparent motion" (henceforth, apparent motion), which refers to the perception of continuous motion from static stimuli presented successively in spatially shifted locations. Apparent motion in the laboratory has traditionally been investigated with simple two-item displays (but also sometimes with multi-item displays, see Sperling, 1976). With two-item displays, two light flashes are presented in rapid succession at two separate locations, producing the illusion that the same light moves from one location to the other. Motion vividness (i.e., likeness of apparent motion to veridical motion) depends on the interplay between the spatial and temporal distances used (e.g., Gepshtein & Kubovy, 2007; Kahneman, 1967). For instance, Kahneman (1967) showed that for a given spatial distance, the main factor that determines motion vividness with short-duration stimuli (approximately 100 ms or less) is the stimulus-onset asynchrony (SOA) between the two items, whereas for long-duration stimuli the main factor is the inter-stimulus interval (ISI).

Distortions in perceived velocity refer to any systematic difference between objective velocity and subjective perception of velocity. Although the motion percept in apparent motion is illusory, objective velocity in apparent motion has been defined as the distance between two object locations divided by the SOA (Koffka, 1935; Kolers, 1972). Thus, distortions of motion perception in apparent motion can be evaluated against this objective measure.

In one of the very few published papers investigating subjective perception of apparent motion velocity, Giaschi and Anstis (1989) reported a velocity illusion in apparent motion. These authors defined a cycle of apparent motion as the time between the onset of one stimulus and the onset the next stimulus along the motion path. They divided each cycle into the "on-time", during which the

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stimulus is physically present and the "off-time" during which the screen is blank. Their main finding was that the shorter the on-time was, the faster the stimulus appeared to move. For instance, with 100 ms cycles, apparent motion was perceived to be faster by approximately 16% with 50 ms on-time (and 50 ms off-time) than with 100 ms on-time (and null off-time). As apparent motion is ubiquitous in everyday life, the on-time effect can have important practical implications. For example, this effect might provide a straightforward explanation to the perceived speed-up in the HFR version of the Hobbit movie because each individual static frame was exposed for shorter durations (i.e., shorter on-time) than in the standard version.

Curiously enough, however, very little research (e.g., Castet, 1995) followed up on Giaschi and Anstis's research. In this study we sought to revisit the on-time effect. Specifically, our objective was to delineate the conditions in which the illusion is observed.

1. Experiment 1

In Experiment 1 we examined whether the on-time effect, which was previously observed with low velocities (Castet, 1995; Giaschi & Anstis, 1989) generalizes to higher velocities and whether it is modulated by this factor. Displays consisted of a dot presented at successive locations in a rightward direction, with objective apparent-motion velocities of either 4.16°/s (low velocity) or and 8.33°/s (high velocity). On each trial, a reference and a test apparent-motion events were presented one after the other as a single motion event. On-time and off-time were equal during the reference part of the motion event, and at some point (marking the beginning of the test part) on-time became either longer or shorter (see Fig. 1).

Participants were informed that each motion event contained a single velocity change and had to judge whether they perceived this change to be speeding or slowing of the motion. We used multi-item displays (as did Castet, 1995) and our on-time duration manipulation was similar to Giaschi and Anstis's (1989): the SOA between successive flickers was fixed and on-time and off-time durations varied inversely (see Fig. 1). Thus, objective velocity (i.e., the distance covered by the dot in a given amount of time) as well as the number of flickers remained constant throughout each motion event. In addition, in both velocity conditions (low and high) the distance covered by the dot was the same.

In this experiment, a replication of the on-time illusion with multi-item displays should manifest as a larger proportion of "faster" responses on shorter than on longer on-time trials. Of main interest was whether the illusion, if found, would be modulated by apparent-motion speed.

1.1. Method

The study received ethical clearance from the Ethics Committee for Human Experimentation of Tel Aviv University. Informed consent was obtained from each subject after explanation of the nature of the study.

1.1.1. Participants

The participants were 12 Tel-Aviv University undergraduate students who participated for course credit or for the equivalent of $8.5 (mean age 25.9, SD = 2.95, 7 women). All reported normal or corrected-to-normal visual acuity.

1.1.2. Apparatus

Displays were presented in a dimly lit room on a 23″ LED screen, using 1920 × 1280 resolution graphics mode and 120 Hz refresh rate. Responses were collected via the computer keyboard. A chin-rest was used to set viewing distance at 50 cm from the monitor.

1.1.3. Stimuli

The fixation display was a gray 0.2° × 0.2° plus sign presented in center of the screen against a black background. The apparent-motion display consisted of two static bars and a dot, all white (110 cd/m^2). The two static vertical bars (1.7° of visual

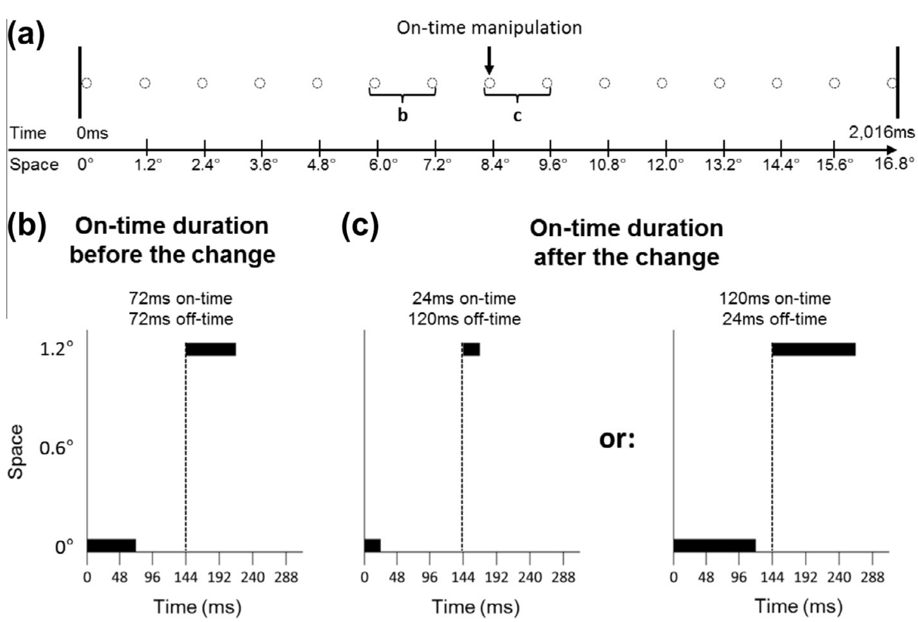

Fig. 1. Illustration of a trial with 4.16°/s velocity in Experiment 1; (a) a single dot appeared at fixed spatial intervals (outline circles represent the locations successively occupied by the dot) until the right-hand line marker was reached. Approximately at mid-screen on-time duration changed; (b) Space–time diagram of a single appearance of the reference motion (before the change), in which on-time duration was 72 ms; (c) Space–time diagram of a single appearance of the test motion (after the change), in which on-time duration was either 24 ms or 120 ms. The dashed vertical lines represent the SOA (144 ms).

angle and drawn with a 3-pixel stroke) marked the starting and end points of the apparent motion. These bars were positioned 8.4° to the left and right from fixation. The motion-inducing stimulus consisted of a dot subtending 0.15° in diameter. Stimulus-onset asynchrony (SOA) between successive appearances of the dot was 144 ms. The duration of each trial was either 2016 ms or 4032 ms.

On the shorter trials, velocity of the dot stimulus was 8.33° per second (8.33°/s), and it appeared at 14 successive locations distant from each other by 1.2°. On the longer trials, velocity was 4.16°/s, and the dot appeared at 28 successive locations distant from each other by 0.6°. The first and last locations of the dot overlapped with the starting and end lines. The on-time duration of the dot changed at some point during each trial. This change was randomly set to occur when the dot was in the spatial range of 2.4° to the left or right of the center of the screen: it could occur at 5 possible locations in the short-trial condition and at 9 possible positions in the long-trial condition. Prior to the change, both on-time and off-time were set to 72 ms. After the change, on-time changed to either 120 ms (with 24 ms off-time) or 24 ms (with 120 ms off-time). These conditions are illustrated in Fig. 1. The question screen consisted of the words "faster – 8" and "slower – 2" above and below the center of the screen.

1.1.4. Procedure

The fixation display was presented for 1000 ms and was followed by a 500 ms blank screen before the apparent-motion display, which lasted either 2016 ms or 4032 ms. At the beginning of the experiment, the experimenter ascertained that participants perceived the flickering dots as moving – although vividness of the apparent motion percept was not formally assessed (but see a control experiment reported in footnote 2).

Participants were instructed to follow the dot that moved from the starting to the end bar. Eye movements were not restricted. Participants were informed that the dot velocity would change at some point during each trial and were asked to judge whether they perceived this change to be speeding or slowing of the motion, by pressing either '8' or '2' on the numerical keypad, respectively, with their right hand. They were told that the change might be nearly undetectable on some trials and that they should guess if unable to detect it. Participants were further instructed to base each response on their immediate experience and to refrain from counting time or developing a response strategy, as is customary in temporal evaluation experiments (e.g., Grondin, Ouellet, & Roussel, 2004). At the end of the motion event, the question display prompted the participants to respond and remained visible until response. A new trial began 500 ms after the subject responded. Participants were fully debriefed at the end of the experiment.

1.1.5. Design

On-time in the test motion (120 ms vs. 24 ms) and velocity (8.33°/s or 4.16°/s) were within-subject factors. On-time was pseudo-randomized within each block of trials, whereas velocity was manipulated between blocks. Block presentation order was counterbalanced between participants. Each participant took part in one half-hour session, which included 20 practice trials followed by 200 experimental trials, divided into 4 blocks. Participants were allowed a self-paced rest between blocks.

1.2. Results and discussion

The data from participants who reported counting time or using a response strategy based on the properties of the stimuli were discarded without further analysis (2 participants). For each subject, the percentage of "faster-motion" responses was calculated for each condition of on-time duration and velocity. The mean percentages of "faster-motion" responses[1] (see Fig. 2) were entered in a 2 × 2 ANOVA with on-time duration and velocity (8.33°/s vs. 4.16°/s) as independent variables. The main effect of on-time was significant: participants were more likely to respond that the dot became faster when the on-time was 24 ms than when it was 120 ms, $F(1,9) = 25.50$, $p < .001$, $\eta_p^2 = .74$ ($M = 77.0\%$, SE = 9.7% vs. $M = 27.0\%$, SE = 7.9%). In addition, faster-motion responses were more frequent in the high-velocity (8.33°/s) than in the low-velocity condition (4.16°/s), $F(1,9) = 15.06$, $p = .004$, $\eta_p^2 = .63$ ($M = 57.2\%$, SE = 5.0% vs. $M = 46.7\%$, SE = 6.3%). These factors did not interact, $F(1,9) = 2.56$, $p = .14$, $\eta_p^2 = .22$.

In this experiment, on-time duration strongly affected subjective perception of apparent-motion velocity. When on-time became shorter, apparent motion was perceived to become faster, whereas the reverse phenomenon occurred when on-time became longer. The effect was not modulated by apparent-motion velocity, suggesting that the on-time illusion reported by Giaschi and Anstis (1989) is a robust phenomenon that can be generalized to multi-item apparent motion and velocities over 8°/s.

2. Experiment 2

According to Bloch's Law (Bloch, 1885) – the energy of a stimulus is summed across its duration, such that stimuli exposed for longer durations appear to be brighter than the same stimuli exposed for shorter durations. Thus, changes in time-averaged luminance (and in perceived contrast) correlate with changes in on-time. It is not clear whether this energy-based account can explain the on-time illusion. On the one hand, several studies have shown that high-contrast stimuli are perceived to move faster than low-contrast stimuli (e.g., Stone & Thompson, 1992), which leads to a prediction that is the opposite of the on-time effect. On the other hand, Thompson and Stone (1997) reported that increasing contrast in flickering stimuli reduces the perceived rate of the flicker, which could account for the on-time effect.

In Experiment 2, we therefore directly examined the role of time-averaged luminance in the on-time illusion. On half of the trials (compensated-luminance condition), we manipulated stimulus luminance so as to reduce the differences in time-averaged luminance between the reference and test motions. Thus, stimulus luminance was higher when on-time duration was shorter, and was lower when on-time duration was longer (see Di Lollo, 1980 for a similar manipulation). On the other half of the trials (non-compensated-luminance condition), the procedure was the same as in the previous experiment and time-averaged luminance was therefore left to vary with on-time. If time-averaged luminance accounts for part or all of the on-time illusion, this illusion should be reduced in the compensated-luminance condition – in fact, it might even be reversed because the values we chose were such that time-averaged luminance was actually smaller in the long than in the short on-time condition. Conversely, the illusion should be equally strong in the two conditions if on-time alone underlies the effect.

2.1. Method

2.1.1. Participants

Participants were 12 Tel-Aviv University undergraduate students (mean age 24.2, SD = 2.82; 7 women) who participated in

[1] Arcsine square-root transformation of the dependent variable did not change the results of any of the experiments. We report the untransformed data.

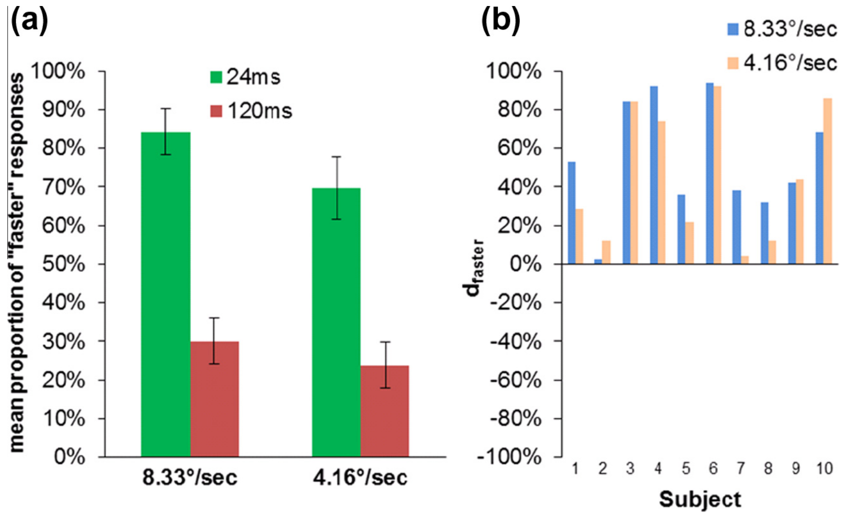

Fig. 2. Experiment 1. (a) Mean "faster-motion" responses as a function of on-time and velocity. (b) Mean difference in percentage of "faster-motion" responses between the 24 ms and 120 ms on-time conditions for each participant.

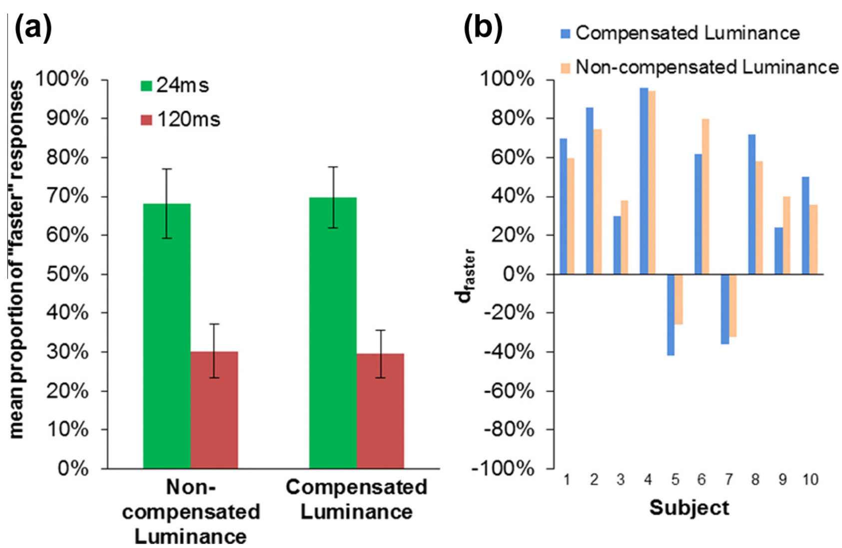

Fig. 3. Experiment 2. (a) Mean "faster-motion" responses as a function of on-time and luminance. (b) Mean difference in percentage of "faster-motion" responses between the 24 ms and 120 ms on-time conditions as a function of luminance for each participant.

the experiment for course credit or for the equivalent of $8.5. All reported normal or corrected-to-normal visual acuity.

2.1.2. Apparatus, stimuli, procedure and design

The apparatus, stimuli, procedure and design were similar to the 8.33°/s velocity condition of Experiment 1 except for the following changes. On half of the trials, the dot's luminance was set at 23 cd/m^2 (RGB [125,125,125]); "non-compensated-luminance" condition), whereas on the other half ("compensated luminance" condition), it was reduced to 4.5 cd/m^2 (RGB [50,50,50]) when on-time changed to 120 ms, and increased to 60 cd/m^2 (RGB [200,200,200]) when on-time changed to 24 ms. On-time during the test motion (120 ms vs. 24 ms) and luminance (non-compensated vs. compensated) were both within-subject variables. The four resulting conditions were equiprobable and appeared in pseudo-randomized order across the experiment.

2.2. Results and discussion

The data from 2 participants were discarded prior to analysis because they reported using explicit response strategies. For each subject, the percentage of "faster motion" responses was calculated for each condition of on-time and luminance. The mean percentages of "faster-motion" responses (see Fig. 3) were entered in a 2 × 2 ANOVA with on-time and luminance (non-compensated vs. compensated) as independent variables. As in Experiment 1, the main effect of on-time was significant, $F(1,9) = 8.75$, $p = .016$, $\eta_p^2 = .49$ ($M = 70.3\%$, SE = 8.3% vs. $M = 28.6\%$, SE = 6.4%). The main effect of luminance was not significant, $F < 1$, nor was the interaction between the two factors, $F < 1$.

The results of Experiment 2 closely replicated those of Experiment 1. When on-time was shorter, apparent-motion velocity was perceived to be higher. This illusion was unaffected by the luminance manipulation, suggesting that differences in time-averaged luminance cannot account for the on-time illusion. The results of a control experiment[2] also showed that the illusion does not result from differences in perceived motion vividness.

3. Experiment 3

In Experiment 3 we sought to extend the on-time illusion to the time-perception domain. Previous investigations (Castet, 1995; Giaschi & Anstis, 1989) measured observers' subjective perception of velocity. For a given distance, objective velocity of a motion event is inversely proportional to its duration. However, the relationship between subjective evaluations of velocity and duration do not always go hand in hand. For instance, using a temporal-judgment task Matthews (2011) showed that acceleration decreases the perceived duration of a motion event relative to that of a constant-velocity motion event, but that so does deceleration. So whether shorter on-times are associated with shorter perceived motion durations remains an open question.

We addressed it using a temporal-bisection task (e.g., Ortega & Lopez, 2008). Typically in this paradigm, participants are first familiarized with two reference durations, representing the "long" and the "short" durations in the context of the experiment. Then, in the test phase, a test stimulus of variable duration is presented on each trial and subjects have to decide whether its duration was more similar to the "long" or to the "short" reference. The bisection point represents the duration of subjective equality, that is, the stimulus duration that participants are equally likely to match to the short and to the long duration.

We used multi-item apparent motion displays as test stimuli, but unlike in the previous experiments, on-time duration remained constant throughout the motion event on any given trial (at either 24 ms or 120 ms). The reference stimuli were static dots presented prior to the experimental blocks for a long and a short duration. Note that the temporal-bisection task required the participants to monitor the entire motion event, whereas in the previous experiments, the change in velocity could be inferred from local on-time changes, namely, from the first cycle in which the on-time became either shorter or longer.

We expected on-time to affect temporal judgments. Specifically, we expected the duration of a motion event with the shorter on-time duration to be perceived as shorter than that of a motion event with the longer on-time duration. We thus predicted that the bisection point would be later for the shorter than for the longer on-time stimuli.

3.1. Method

3.1.1. Participants

The participants were 11 Tel-Aviv University undergraduate students (mean age 22.8, SD = 2.75; 8 women) who participated in the experiment for course credit or for the equivalent of $8.5. All reported normal or corrected-to-normal visual acuity.

3.1.2. Stimuli, procedure and design

The stimuli, procedure and design were similar to those of Experiment 1, except for the following changes (see Fig. 4). The "short" and "long" reference stimuli were a single dot presented in the center of the screen for 1400 ms and 2600 ms, respectively. They were presented three times each, in interleaved order, at the beginning of the experiment, with each occurrence being preceded by a textual display (e.g., "A short stimulus will now be presented. Please press any key when ready"). The reference stimuli were displayed again prior to each experimental block in order to refresh participants' memory (Ortega & Lopez, 2008).

During the motion events, the static lines were located 5.5° to the left and to the right of fixation (instead of 8.4°). On-time duration was either 120 ms or 24 ms throughout the motion event. There were five possible stimulus presentation durations: two that were equal to the reference durations (1400 ms or 2600 ms) and three intermediate durations (1700 ms, 2000 ms, and 2300 ms). The objective velocity of the stimulus and the distance between each of its successive appearances were computed so as to produce the same number of stimulus onsets. In both the short and long on-time conditions, the resulting velocities were 7.86°/s, 6.47°/s, 5.5°/s, 4.78°/s, 4.23°/s, corresponding to 10, 12, 14, 16 and 18 flickers, respectively. Immediately following the motion event, a question prompted the subject to respond as to whether the overall stimulus duration was similar to the "short" or to the "long" reference stimulus, by pressing either the '2' or '8' keys on the numerical pad, respectively, with their right hands. The question screen consisted of the words "long – 8" and "short – 2" above and below the center of the screen. This question remained visible until the participant's response and a new trial began after 500 ms.

Participants were instructed to remember the durations of the reference stimuli and indicate on each trial whether the experimental motion event was more similar to the long or to the short reference stimulus. On-time duration (120 ms vs. 24 ms) and trial duration (1400 ms, 1700 ms, 2000 ms, 2300 ms and 2600 ms) were within-subject factors. The resulting combinations were equiprobable and pseudo-randomized within each block of trials.

3.2. Results and discussion

The data from one subject were discarded prior to analysis because he reported using explicit response strategies. For each subject, the percentage of "long duration" responses (i.e. similar to the long stimulus) was calculated for each condition of on-time and motion duration. The mean percentages of "long" responses were entered in a 2×5 ANOVA with on-time and motion duration (1400 ms, 1700 ms, 2000 ms, 2300 ms, 2600 ms) as independent variables (see Fig. 5). The main effect of on-time was significant, $F(1,9) = 5.33$, $p = .046$, $\eta_p^2 = .37$, showing that participants were more likely to evaluate stimulus duration as being "long" when on-time was long than when on-time was short. The main effect of motion duration was also significant, $F(4,36) = 90.70$, $p < .001$, $\eta_p^2 = .91$, with the probability of participants judging the event as being "long" increasing with the actual motion duration. Post-hoc analyses using Tukey HSD test

[2] According to a Fourier analysis of the motion components in our design (Watson, Ahumada, & Farrel, 1986), motion vividness should be higher in the short than in the long on-time condition. If so, motion vividness could account for our results. To test this possibility, we ran a control experiment ($N = 10$) in which we measured the effects of our on-time manipulation on subjective motion vividness. Participants viewed the same stimuli as in Experiments 1 and 2. They were again informed that a change would occur during the trial and were required to report whether they perceived the motion to become more vivid or less vivid after the change. Conditions of on-time (24 ms vs. 120 ms) as well as of trial velocity (8.33°/s vs. 4.16°/s) and luminance (non-compensated vs. compensated) were intermixed within subject. We found no effect of on-time on perceived motion vividness, $F < 1$. The results revealed only a significant two-way interaction between trial velocity and on-time, $F(1,9) = 13.2$, $p = .005$ (all other $ps > .2$): while on high-velocity trials, on-time did not affect motion vividness ($M = 65.6\%$ vs. $M = 67.6\%$, respectively, $F < 1$), on low velocity trials, participants tended to report that the motion became more vivid when on-time became longer than when it became shorter, $M = 62.6\%$ vs. $M = 45.2$, respectively, $F(1,9) = 1.92$, $p = .19$. We can think of no straight-forward explanation for this interaction, but as the only effect of on-time on motion vividness was in the opposite direction of its effect on speed perception, the findings of this control experiment suggest that motion vividness does not account for our results. Please note that velocity was held constant within any given trial and so we did not expect any effect of this variable on participants' subjective impression of a *change* in vividness during the trial. However, we did expect luminance to affect perceived vividness. We speculate that absence of such an effect is specific to multi-element apparent motion, which maximizes the subjective quality of apparent motion (McKee & Welch, 1985; Sperling, 1976).

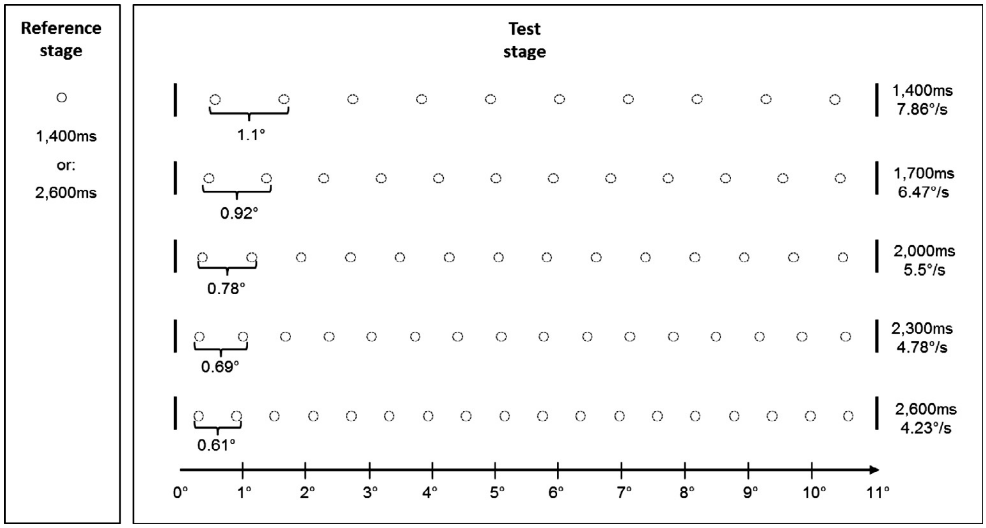

Fig. 4. Illustration of the reference stage and test stage of each block in Experiment 3. During the reference stage, a single dot appeared for either 1400 ms or 2600 ms. During the test stage a single dot appeared at fixed spatial intervals (outline circles represent possible locations) until the right-hand line marker was reached. On-time duration and velocity remained constant throughout the trial.

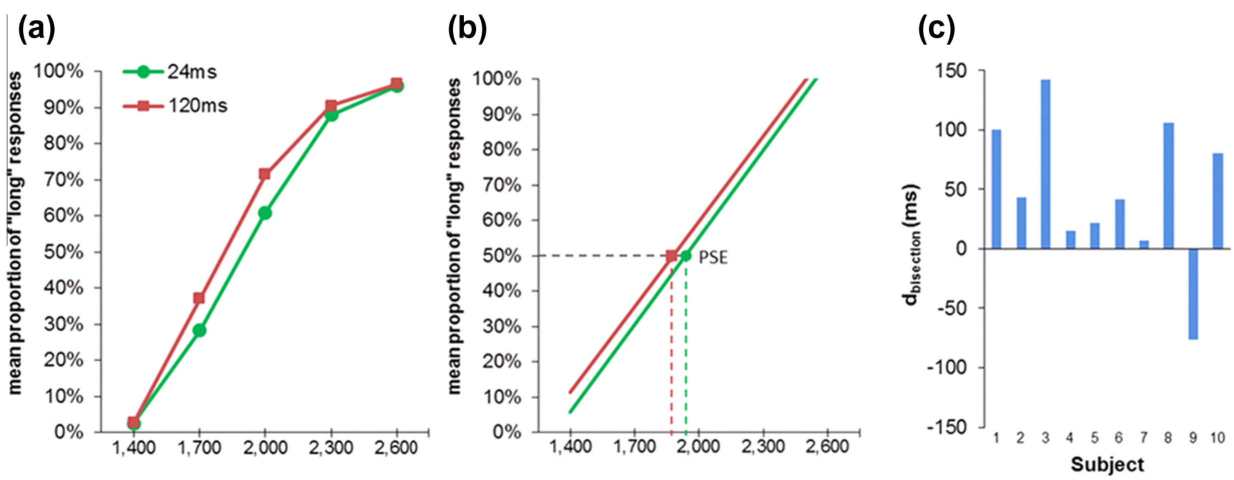

Fig. 5. Experiment 3. (a) Mean percentage of "longer duration" responses as a function of on-time and motion duration. (b) Linear prediction of "longer duration" responses as a function of on-time and motion duration. The dashed lines represent the point of subjective equality (PSE) for each condition. (c) Mean difference between the bisection point in the 24 ms condition and the bisection point in the120 ms on-time condition, for each participant. Positive values indicate later bisection points in the 24 ms on-time condition. A later bisection point indicates a shorter perceived duration.

confirmed that 1700 ms events produced more "long" responses than 1400 ms events, 2000 ms events more than 1700 ms events and 2300 ms events more than 2000 ms events, all $ps < .005$. The difference between 2600 ms and 2300 ms events was not significant, $F(1,9) = 4.78$, $p > .05$ and neither was the interaction between the two factors, $F(4,36) = 1.51$, $p = .22$, $\eta_p^2 = .14$.

Next, the bisection point was calculated for each participant using the least squares method (Maricq, Roberts, & Church, 1981).[3] As expected, we observed an earlier bisection point when on-time duration was 120 ms than when it was 24 ms, $F(1,9) = 5.98$, $p = .037$, $\eta_p^2 = .40$ ($M = 1902.0$, SE = 43.18 vs. $M = 1950.56$, SE = 38.33). In other words, longer on-time motion events were subjectively perceived to last longer than shorter on-time motion events.

The results show that stimulus on-time during apparent motion does not only influence motion perception but also biases temporal judgments. This finding therefore extends the generalizability of the on-time illusion. In addition, as the bisection paradigm required monitoring of the entire motion event, this result confirms that the on-time effect does not solely rely on the detection of local change in a single cycle of apparent motion.

An alternative account of our results is that they might reflect distortions in perceived distance rather than perceived duration.[4] This possibility is unlikely, however, because Giaschi and Anstis (1989; p. 341) showed that the velocity illusion does not result from a difference in subjective spatial distance in the short vs. long on-time condition.

Another possible explanation is that despite the equal number of flickers, longer exposures to the stimulus also increase the activity of an internal time accumulator (Zakay & Block, 1995). Accordingly, the duration of the test stimulus would be subjectively extended regardless of its perceived velocity. This account could be tested in future research by examining the effect of on-time on perceived duration of a static flickering stimulus.

[3] The reported effects remained significant after log transformation. We also calculated the bisection points by fitting a logistic function to the data of each participant. The results were similar albeit slightly weaker ($p = .06$, $\eta^2_p = .34$).

[4] We thank an anonymous reviewer for this suggestion.

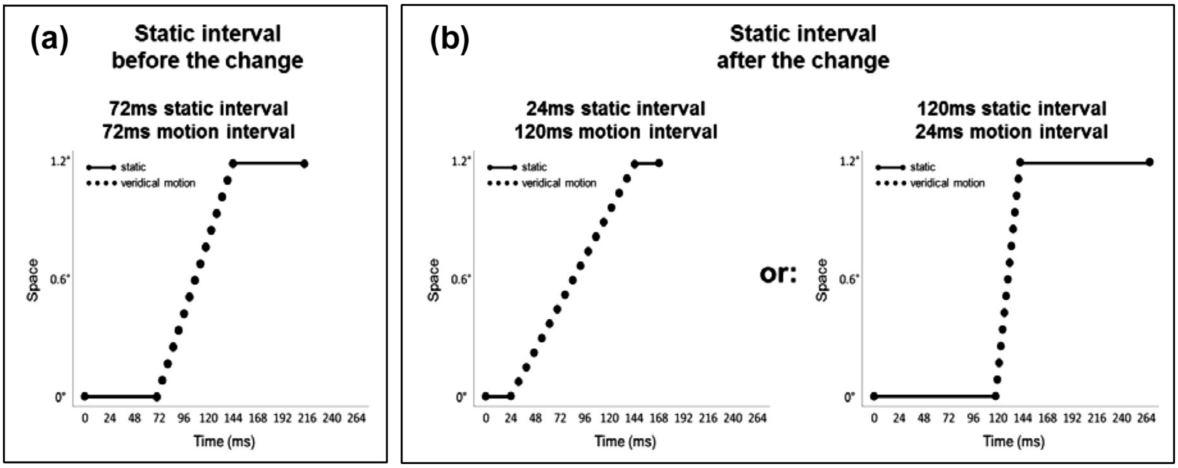

Fig. 6. Space–time diagram of the veridical motion conditions in Experiment 4. The black bars represent static on-times and the dotted lines represent veridical motion. A steeper space–time slant represents higher velocity of veridical motion. (a) Reference motion (before the change), in which the static interval was 72 ms; (b) Test motion (after the change), in which the static interval was either 24 ms or 120 ms.

4. Experiment 4

Apparent motion inherently includes two types of signals: (1) a motion signal produced by two consecutive flickers, which has an objective velocity (calculated as the space between two flickers divided by the SOA between them) and (2) a static signal, produced by the exposure to a single flicker, which has null velocity. Note that the on-time manipulation implemented by Giaschi and Anstis (1989) as well as here, affects the two signals in competing directions: while a long on-time increases the static signal relative to a short on-time, it also increases the objective velocity of the motion signal during the off-time because the same distance is crossed in a shorter time (since the blank off-time is shorter). Giaschi and Anstis (1989) suggested that longer exposure to static stimuli reduces perceived velocity by disrupting the motion signal. Thus, they assigned a crucial role to the static signal in the on-time illusion during apparent motion.

Apparent motion is indistinguishable from veridical motion only when the spatial distance between two flickers is very small (De Silva, 1929, cited in Larsen et al., 2006). Otherwise, even a highly vivid apparent motion event can be distinguished from a veridical motion event, which suggests that the motion signal is less salient during apparent motion than during veridical motion.

In Experiment 4 we manipulated the salience of the motion signal and examined its influence on the on-time illusion. The experiment included two conditions: the apparent-motion condition was similar to the 8.33°/s condition of Experiment 1 and the veridical-motion condition differed from it in that during the off-time, the dot actually moved across all intervening locations instead of disappearing. A motion cycle thus included a static segment and a veridical-motion segment[5] (see Fig. 6).

We expected exposure to null velocity (i.e., on-time) to have a smaller effect (and the illusion to be smaller) in the veridical than in the apparent-motion condition. In this experiment we refer to the critical manipulation as a manipulation of "static-exposure duration" rather than of "on-time" because the latter term does not accurately describe the veridical-motion condition.

[5] Note that a computer screen cannot present veridical motion, strictly speaking. However, unlike in the apparent motion condition, the successive locations of the dot overlapped by at least 10% and followed each other by at very short time interval (8 ms, without off-time). Under these conditions, the event is experienced as veridical motion (De Silva, 1929, cited in Larsen et al., 2006).

4.1. Method

4.1.1. Participants

The participants were 10 Tel-Aviv University undergraduate students (mean age 22.4, SD = 0.92; 8 women) who participated in the experiment for course credit or for the equivalent of $8.5. All reported normal or corrected-to-normal visual acuity.

4.1.2. Apparatus, stimuli, procedure and design

The apparatus, stimulus, procedure and design were similar to the 8.33°/s velocity condition in Experiment 1 except that half of the trials were veridical-motion trials, in which the dot stimulus was alternately static and moving. During the reference motion, the dot appeared at one position for 72 ms and moved smoothly to its end position for 72 ms. During the test motion, the dot either appeared at one position for 24 ms and moved for 120 ms, or appeared at one position for 120 ms and moved for 24 ms (see Fig. 6). Note that as average stimulus speed was held constant (8.33°/s) and the dot moved through the same distance in either a short or a long time interval, objective speed during the motion intervals varied with static-exposure duration. It was 50°/s on 120 ms static-interval trials (as it moved through 1.2° of visual angle in 24 ms), and 10°/s on 24 ms-static interval trials (as it moved through 1.2° in 120 ms). The instructions emphasized that velocity evaluations were to be based on average speed and not on local changes in speed.

4.2. Results and discussion

For each subject, the percentage of "faster motion" responses was calculated for each condition of static interval and motion type. The mean percentages of "faster-motion" responses (see Fig. 7) were entered in a 2 × 2 ANOVA with static interval (24 ms vs. 120 ms) and motion type (apparent motion vs. veridical motion) as independent variables. The main effect of motion type was significant, $F(1,9) = 5.34$, $p = .046$, $\eta_p^2 = .37$. Participants were more likely to respond that the stimulus became faster in the apparent-motion condition than in the veridical motion condition (M = 55.78%, SE = 3.67% vs. M = 45.41%, SE = 2.54%). The main effect of static interval was not significant, $F < 1$, but the two-way interaction between the two factors was significant, $F(1,9) = 33.30$, $p < .001$, $\eta_p^2 = .79$. Follow-up comparisons revealed that for apparent motion, 24 ms static intervals again produced more "faster

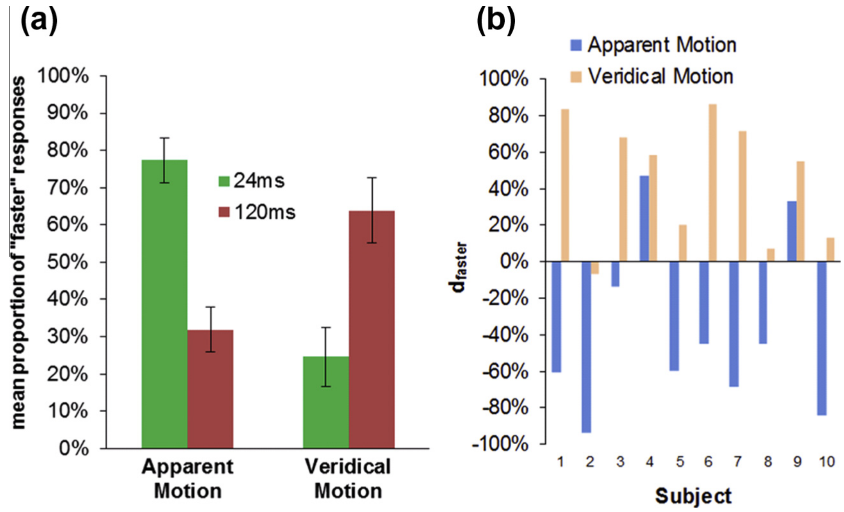

Fig. 7. Experiment 4. (a) Mean "faster-motion" responses as a function of static stimulus interval and motion type. (b) Mean difference in the percentage of "faster-motion" response between the 24 ms and 120 ms static stimulus intervals conditions for each participant.

motion" responses than 120 ms static intervals, $F(1,9) = 17.80$, $p = .002$, $\eta_p^2 = .66$ ($M = 77.04\%$, SE = 5.9% vs. $M = 31.88\%$, SE = 6.0%), whereas the opposite pattern was observed for veridical motion: 24 ms static intervals produced fewer "faster motion" responses than 120 ms static intervals, $F(1,9) = 6.88$, $p = .028$, $\eta_p^2 = .46$ ($M = 25.59\%$, SE = 7.94% vs. $M = 63.90\%$, SE = 8.71%).

The results of Experiment 4 show that the on-time illusion is specific to apparent motion, since when the empty intervals were replaced with veridical motion longer exposures to static signals were actually associated with a subjective percept of *faster* motion. These results suggest that during apparent-motion perception, the visual system relies more heavily on the physically available data (on-time) than on inferred data (that is, velocity during off-time) and longer static intervals are therefore associated with slower perceived velocity. By contrast, during veridical motion, the physically present motion signal drives velocity perception and longer static intervals, which also imply faster veridical-motion intervals, are associated with faster perceived velocity.

5. Experiment 5

In the introduction, we reported a real-life velocity illusion in the HFR version of the movie "The Hobbit". However, the two versions of the Hobbit did not differ in on-time alone but also in the SOA between successive images. In all our experiments so far, on-time was increased by decreasing off-time while maintaining a constant SOA. The reason for adopting such a design was to ensure that the on-time effect was not confounded with the number of dot onsets during the motion interval. Having established that the on-time effect occurs with a constant SOA we now moved to generalize the effect to a situation in which on-time varies with SOA while off-time is held constant (see Fig. 8 for a description of the experimental conditions).

5.1. Method

5.1.1. Participants

Participants were 13 Tel-Aviv University undergraduate students (mean age 24.86, SD = 6.49; 9 women) who participated in the experiment for course credit. All reported normal or corrected-to-normal visual acuity.

5.1.2. Apparatus, stimuli, procedure and design

The apparatus, stimuli, procedure and design were similar to the 8.33°/s velocity condition of Experiment 1 except for the following changes. On half of the trials, the stimulus off-time duration was held constant at 72 ms, whereas on the other half it was held constant at 24 ms. On-time during the test motion (120 ms vs. 24 ms) and off-time duration throughout the trial (72 ms vs. 24 ms) were both within-subject variables. The four resulting conditions were equiprobable and appeared in pseudo-randomized order across the experiment.

5.2. Results and discussion

The data from one participant were discarded prior to analysis because she reported using explicit response strategies. For each subject, the percentage of "faster motion" responses was calculated for each condition of on-time and off-time across the trial. The mean percentages of "faster-motion" responses (see Fig. 9) were entered into a 2 × 2 ANOVA with on-time duration during test motion (24 ms vs. 120 ms) and off-time duration across the trial (24 ms vs. 72 ms) as independent variables. Both main effects were significant, $F(1,11) = 14.45$, $p = .003$, $\eta_p^2 = .57$ and $F(1,11) = 11.29$, $p = .006$, $\eta_p^2 = .51$, respectively. Subjects were more likely to report that the motion became faster when on-time became shorter ($M = 74.8\%$, SE = 10.4%) than when it became longer ($M = 21.1\%$, SE = 10.2%), and with 72 ms than with 24 ms off-time durations ($M = 54.4\%$, SE = 2.2% vs. $M = 41.5\%$, SE = 4.7%, respectively). Finally, the two-way interaction between the two factors was significant, $F(1,11) = 18.22$, $p = .001$, $\eta_p^2 = .62$, indicating that the on-time effect was larger when off-time across the trial was fixed at 72 ms, $F(1,11) = 29.12$, $p < .001$, $\eta_p^2 = .72.5$ ($M = 89.4\%$, SE = 5.7% vs. $M = 19.4\%$, SE = 7.5%) than when it was fixed at 24 ms, $F(1,11) = 5.39$, $p = .04$, $\eta_p^2 = .33$ ($M = 60.2\%$, SE = 10.2% vs. $M = 22.7\%$, SE = 7.0%).

The on-time effect was replicated when off-time was held constant, confirming that the illusion is driven by on-time rather than by off-time. However, off-time across the trial modulated the on-time effect: the illusion was larger in the 72 ms than in the 24 ms off-time condition. A reasonable explanation for such modulation is that the on-time illusion in the short off-time condition was offset by the "filled-duration illusion", whereby increasing the number of events within a given time interval is associated with the subjective lengthening of the duration of this interval

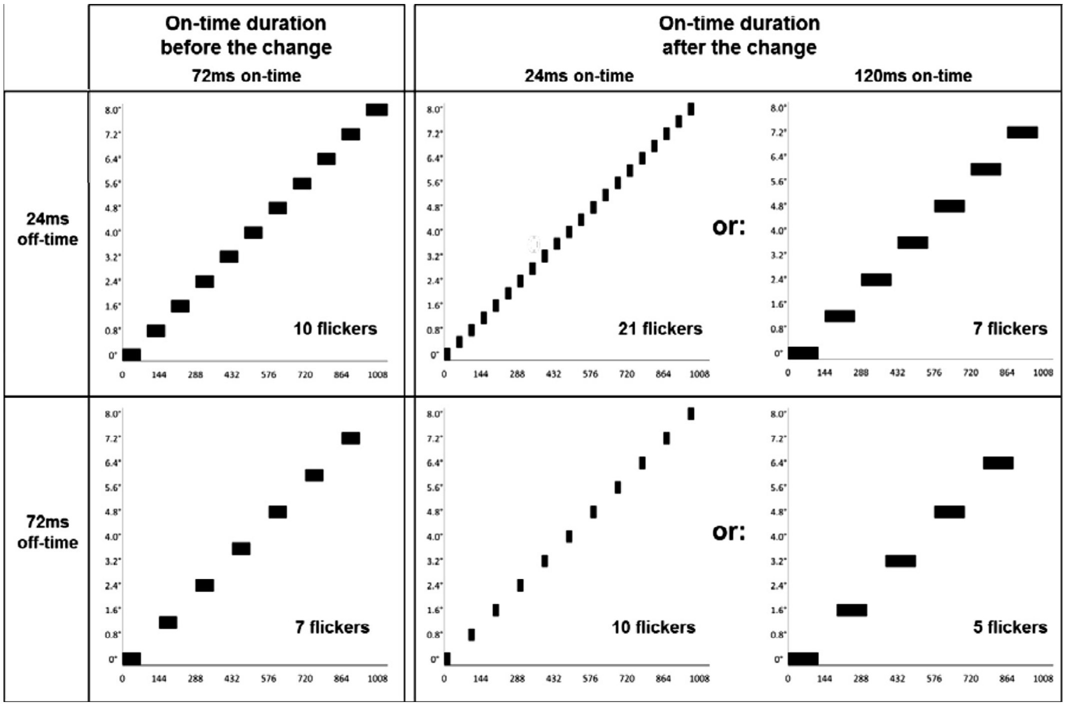

Fig. 8. Description of the four experimental conditions in Experiment 5, and the resulting number of flickers following the change in on-time duration.

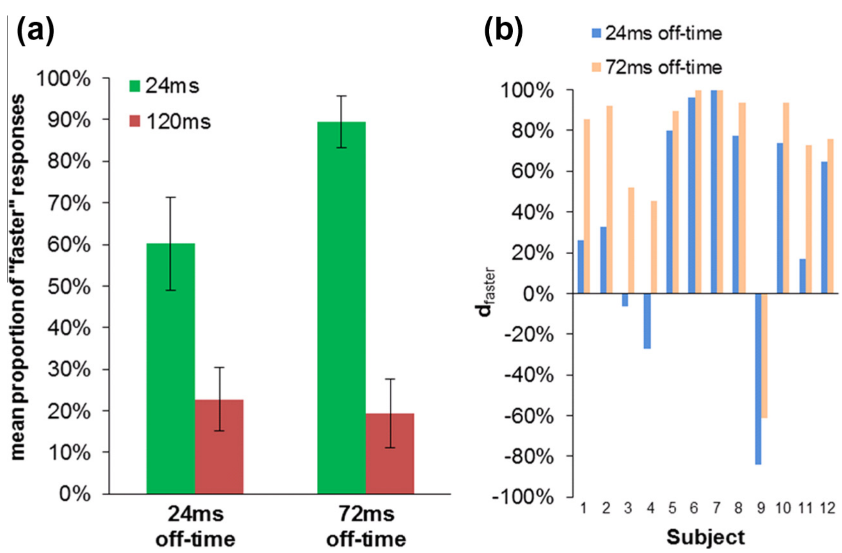

Fig. 9. Experiment 5. (a) Mean "faster-motion" responses as a function of on-time duration after the change and off-time duration across the trial. (b) Mean difference in the percentage of "faster-motion" response between the 24 ms and 120 ms on-time conditions as a function of off-time for each participant.

(Buffardi, 1971; Grondin, 1993). Indeed, in this experiment, the number of flickers during the test motion was larger in the 24 ms than in the 72 ms off-time condition. More specifically and as is clear from Fig. 9, the smaller on-time illusion in the short off-time condition occurred only for the 24 ms on-time condition, in which the number of events was much larger than in the other conditions (see Fig. 8): accordingly, the statistical comparison of the percentage of "shorter" responses against 50% showed no bias for this condition, $t(11) = 1.01$, $p = .33$, and a significant bias in all the remaining conditions, all $ps < .003$. Note that our original motivation for keeping a constant SOA across on-time conditions in our previous experiments was precisely to avoid the contamination of the on-time illusion by the filled-duration illusion.

6. General discussion

The present study demonstrates that the on-time effect is a highly consistent illusion in apparent motion. The less time a stimulus remains visible on each of its appearances during apparent motion, the faster its perceived velocity (Giaschi & Anstis, 1989). Despite the prevalence of apparent motion in our daily lives, this effect has gone relatively unnoticed by the scientific community. In five experiments we revisited the on-time illusion in order to delineate its boundary conditions. We found that it occurs with both low and high velocities during multi-item apparent motion (Experiment 1) and that it does not result from changes in time-averaged luminance of the apparent-motion stimuli

(Experiment 2), from changes in motion vividness (control experiment reported in footnote #2) or from monitoring of local changes in on-time (Experiment 3). We generalized the illusion to the domain of time perception by using a temporal judgment paradigm as a converging operation (Experiment 3). We showed that the on-time illusion is specific to apparent motion and does not occur during veridical motion (Experiment 4). Finally, we showed that it also occurs when off-time remains constant (Experiment 5).

The on-time illusion has been accounted for within the framework of a neural network model by Grossberg and Rudd (1992), which explains various apparent motion phenomena. This model postulates that responses from low-level units (V1, V2) go through several computational filters resulting in an output of activation waves in the high-level units (MT+). According to the model, a two-flash apparent motion produces acceleration away from the location of the first flash and deceleration into the location of the second flash. This means that the maximal activation of the second flash occurs at approximately half of its on-time duration (Grossberg & Rudd, 1989; figure 11). Thus, flashes with longer on-time duration produce more deceleration of the motion signal and shallower space–time slants in a space–time diagram (Grossberg & Rudd, 1992; figure 29), thereby explaining the on-time effect. It follows from this model that the on-time effect should be modulated by neither objective velocity nor off-time (Grossberg & Rudd, 1992, figure 31). Our results only partially confirmed these predictions: objective velocity did not influence the on-time effect (Experiment 1) but increasing off-time enhanced the illusion (Experiment 5).

The on-time illusion has also been accounted for within the framework of a Fourier motion-energy model (see Krekelberg, 2008; Nishida, 2011 for reviews), according to which speed encoding is based on an antagonistic comparison of the activity in two broadly tuned, low-pass and high-pass, temporal filters (see Smith & Edgar, 1994). It was suggested that increasing on-time within a constant cycle reduces the relative amplitude of the high temporal frequencies at a given speed, therefore leading to an underestimation of apparent speed (Castet, 1995).

Castet replicated the speed overestimation characteristic of the illusion by manipulating the relative on-time duration within a cycle, either by varying the ISI and keeping on-time constant (Castet, 1995; Experiment 1), or by varying the on-time while keeping the SOA constant (Castet, 1995; Experiment 2). It is noteworthy, however, that in Castet's Experiment 1, the illusion occurred only with low apparent motion velocity (2°–4°/s) but not with high velocity (8°/s). This finding appears to be at odds with our conclusion that the on-time effect is not modulated by apparent-motion velocity. The author suggested several possible accounts for this interaction, one of which focused on the observation that in their experiment higher physical speeds were generated by decreasing the ISI or "off-time" (see Castet, p. 1379 for a detailed explanation of how decreasing off-time should affect subjective speed within the model). The results of the present Experiment 5 support this conjecture and confirm that off-time rather than motion velocity per se modulates the illusion's strength: the illusion was indeed stronger with long than with short off-times when velocity was kept constant.

Several models that attempt to account for diverse motion illusions describe the motion percept as emanating from the weighted average of a collection of motion signals (e.g., Howe et al., 2006). Likewise, the on-time effect can be expressed as resulting from a weighted average of the speeds associated with a static (no-motion) signal and a motion signal. Accordingly, the on-time effect should be strongly influenced by the time window during which the static signal is accumulated. In order to account for the Flash-Lag illusion (MacKay, 1958), Eagleman and Sejnowski (2000) postulated such a time window by suggesting that a stimulus is sampled for approximately 80 ms prior to its conscious localization. Several predictions follow from applying this account to apparent motion. As the second flash should be sampled for a maximum of 80 ms prior to velocity calculation, the influence of the static signal carried by the second flicker should have an upper limit. In other words, the illusion should saturate when on-time exceeds a certain threshold. In addition, for multi-item displays, a flicker with a long enough on-time should produce a sensation of periodical motion, as the static signal would be sampled for a sufficient duration to catch up with the delayed motion percept.

To conclude, this study considerably widened the scope of the on-time effect, a largely ignored velocity illusion in apparent motion. Unlike other motion illusions (see e.g., Howe et al., 2006; Nishida, 2011), little research has relied on the on-time effect to test models of motion perception. Yet, this effect is robust and lends itself to a variety of manipulations that can yield clear predictions. We therefore suggest that this illusion can be a useful tool to further elucidate the mechanisms underlying motion perception. In addition, as new media technologies are introduced, understanding such effects can have important practical implications.

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