Time dilation effect in an active observer and virtual environment requires apparent motion: No dilation for retinal- or world-motion alone

Luca Lo Verde

School of Psychology, The University of Sydney, New South Wales, Australia
Department of Neuroscience, Psychology, Pharmacology, and Child Health, University of Florence, Florence, Italy

✉

David Alais

School of Psychology, The University of Sydney, New South Wales, Australia

✉

David Charles Burr

School of Psychology, The University of Sydney, New South Wales, Australia
Department of Neuroscience, Psychology, Pharmacology, and Child Health, University of Florence, Florence, Italy

✉

Maria Concetta Morrone

Department of Translational Research on New Technologies in Medicine and Surgery, University of Pisa, Pisa, Italy

✉

Hamish MacDougall

School of Psychology, The University of Sydney, New South Wales, Australia

✉

Frans A. J. Verstraten

School of Psychology, The University of Sydney, New South Wales, Australia
Department of Experimental Psychology, Helmholtz Institute, Utrecht University, Utrecht, The Netherlands

✉

It is known that moving visual stimuli are perceived to last longer than stationary stimuli with the same physical duration (Kanai, Paffen, Hogendoorn, & Verstraten, 2006), and that motor actions (Tomassini & Morrone, 2016) and eye movements (Morrone, Ross, & Burr, 2005) can alter perceived duration. In the present work, we investigated the contributions of stimulus motion and self-motion to perceived duration while observers stood or walked in a virtual reality environment. Using a visual temporal reproduction task, we independently manipulated both the participants' motion (stationary or walking) and the stimulus motion (retinal stationary, real-world stationary and negative double velocity). When the observers were standing still, drifting gratings were perceived as lasting longer than duration-matched static gratings. Interestingly, we did not see any time distortion when observers were walking, neither when the gratings were kept stationary relative to the observer's point of view (i.e., no retinal motion) nor when they were stationary in the external world (i.e., producing the same retinal velocity as the walking condition with stationary grating). Self-motion caused significant dilation in perceived duration only when the gratings were moving at double speed, opposite to the observers' walking direction. Consistent with previous work (Fornaciai, Arrighi, & Burr, 2016), this suggests that the system is able to suppress self-generated motion to enhance external motion, which would have ecological benefits, for example, for threat detection while navigating through the environment.

Introduction

Accurate timing over the subsecond scale is essential for a range of perceptual and motor activities, but the mechanisms for encoding this timescale are poorly understood. Traditional ideas of a centralized clock (Treisman, Faulkner, Naish, & Brogan, 1990) to measure subsecond durations have been brought into question by evidence from a range of different studies. Perhaps the strongest evidence is that local adaptation to fast-moving stimuli selectively reduces perceived duration for stimuli presented in that spatial position (Johnston, Arnold, & Nishida, 2006). The selectivity is for position in space, not on the retina (Burr, Cicchini, Arrighi, & Morrone, 2011; Burr, Tozzi, & Morrone, 2007), and occurs only for translating stimuli, not rotating or expanding stimuli (Fornaciai et al., 2016).

Perceived duration is affected by many factors besides adaptation. There is a strong compression of time during saccadic eye movements (Morrone et al., 2005), pointing to a link between time perception and action. Furthermore, movement of the hand—and isometric contractions—also alters time, and the effects depend on the direction of the planned motor action: movement toward the body compresses perceived duration and movement away from it dilates perceived duration (Tomassini & Morrone, 2016), reinforcing the link between duration perception and action.

Perhaps the most robust effect on perceived temporal duration is its dependence on stimulus speed: Moving stimuli appear to be of longer duration than stationary stimuli (Brown, 1995; Kanai et al., 2006; Kaneko & Murakami, 2009). The effect increases with speed or temporal frequency (Brown, 1995; Kaneko & Murakami, 2009), and occurs in touch as well as in vision (Tomassini, Gori, Burr, Sandini, & Morrone, 2011). Thus, subjective duration seems to depend on the perceived rather than the physical speed of the stimulus (Tomassini et al., 2011). Indeed even implied motion in static scenes can increase apparent duration (Yamamoto & Miura, 2012).

Apparent speed is known to be reduced by self-motion, both active walking and passive motion (Durgin, Gigone, & Scott, 2005). Given the evidence linking motor actions and perceived duration, and the dependency of perceived duration on apparent speed, we measured the effect of stimulus motion (either on the retina or in the real world) under conditions where the observer was actively walking. The results reinforce previous work suggesting that it is the apparent speed, not the physical speed of the stimulus that induces the perceived expansion of duration.

Materials and methods

Participants

Seventeen observers (10 females, mean age ± SD 32 ± 14 years) participated in the experiment. All of the authors served as participants in the present study, while the remaining participants were naïve as to the purposes and aims of the study. They were recruited from the University of Sydney student population. All had normal or corrected-to-normal visual acuity and gave their informed written consent after recruitment. The experimental protocol was approved by the University of Sydney's Human Research Ethics Committee and respected the principles defined by the Declaration of Helsinki.

Stimuli

The virtual environment for the experiment was developed in Unity (Unity Technologies, San Francisco, CA) version 5.3.6 on a Windows-based PC. A HTC Vive (HTC Corporation, New Taipei City, Taiwan) tracked headset was used for stimulus presentation. The experiment was coded using a C# project in Microsoft Visual Studio 2017 (Microsoft Corporation, Redmond, VA). The Vive system was set up to track the position of the headset and controllers in a tracked area of 4 × 4 m, giving a diagonal path length of 5.6 m as observers walked from one corner to the other (Figure 1A). The virtual scene presented to the participants was a uniformly illuminated gray space with a fixation cube subtending 2° in width that was present at all times at the center of the display. In the walking condition, the cube receded in distance at a constant rate (see Procedure) from the starting point at one corner of the space to the diagonally opposite corner and served as a pacemaker for the observer's walking speed. In the stationary condition, the cube remained fixed. In both conditions, a matched pair of gratings was presented on either side of the observer, appearing at a random time around the middle of each trial (interval between 1.5 and 2.5 s after trial onset). The grating remained visible for 400, 600 or 800 ms. The gratings were maximum-contrast black and white square-wave gratings (0.05 $cycles \cdot deg^{-1}$ when viewed perpendicularly), were lateral to the observer by ±57 cm and parallel to the diagonal walking path. The gratings were shaped as isosceles trapezoids, to be consistent with the receding apparent size of the walls of a corridor flanking the walking path (Figure 1B).
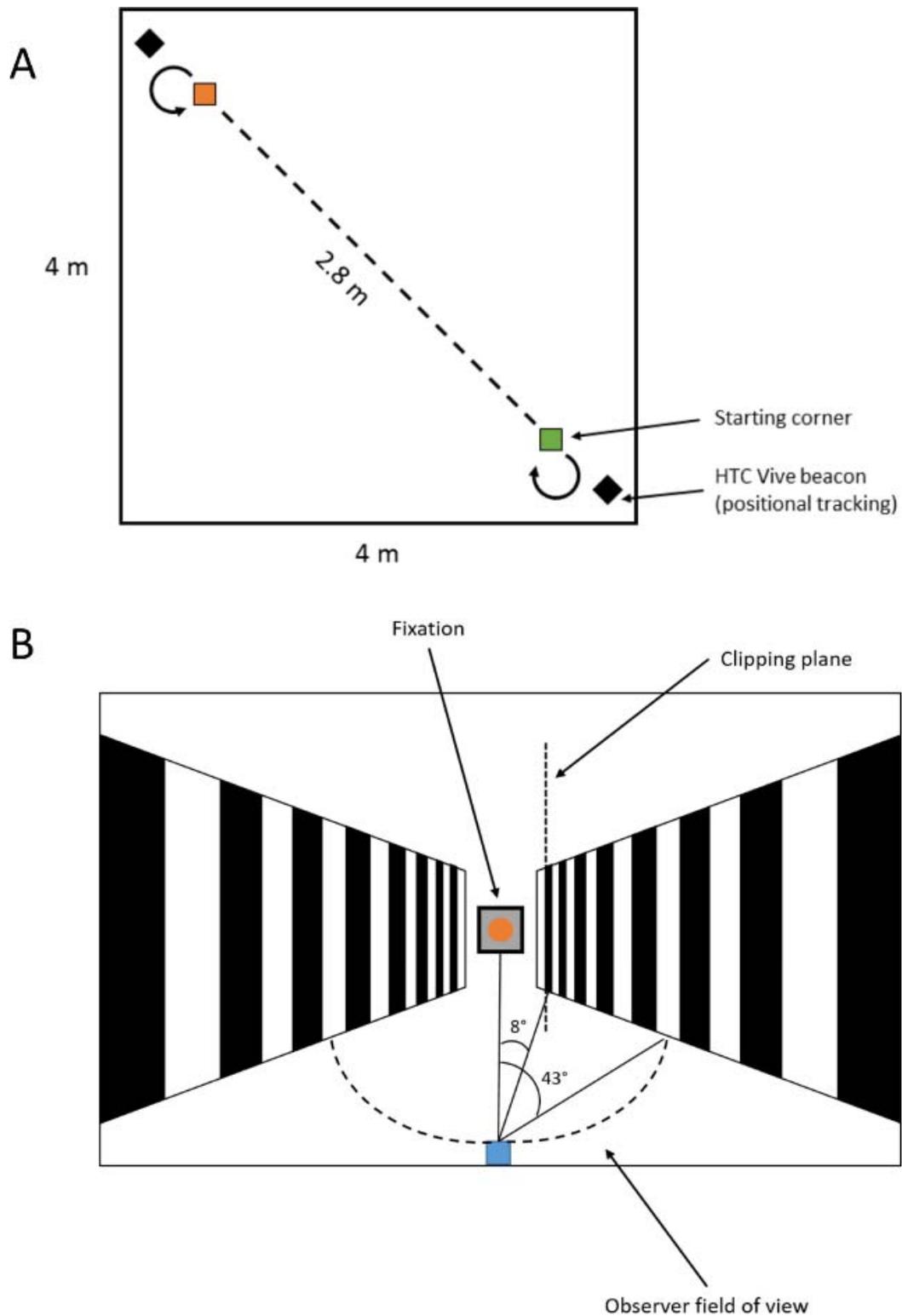
Figure 1. Schematic representation of the experimental setup and virtual scene presented to the observers. (A) Tracked area of the experiment. The participants were required to stand in a corner ("starting corner" in green) while wearing the VR headset. According to the experimental conditions, described further as follows, they had to either stand still while the stimuli were delivered through the headset, or to walk up to the destination corner (in orange) along the diagonal path of the square area. The experimental conditions were defined as follows: *SS*, stationary observer, stationary stimulus; *SM*, stationary observer, moving stimulus (moving in the world and on the retinae); *MS*, moving observer, stationary stimulus (moving on the retinae, not in the world; *MM*, moving

→

←

observer, moving stimulus (moving in the world, not on the retinae); *MN*, moving observer, stimulus in the opposite direction (stimulus moving in the world and on the retinae, in opposite direction). (B) Schematic representation of the virtual scene that was presented to the observers. A fixation cube was present at all times. The stimuli consisted of matched pairs of maximum contrast black and white gratings, placed laterally at 57 cm on either side of the participant.

Procedure

Participants received instructions about the experiment and then were given time to familiarize themselves with the task and the virtual reality (VR) headset, controllers, and virtual environment. The interpupillary distance of the headset was adjusted for each individual. They were then asked to stand in the designated starting corner (the green square in Figure 1A) of the tracked area with the VR headset mounted on their head. Before each participant's first experimental session, we performed a training routine to walk subjects through the different experimental conditions, showing example trials of each condition, as well as on-screen written instructions on how to perform the trial. This resulted in five practice trials.

The conditions and general procedures are described in Figure 1 and relative caption. Observers fixated the cube located in front of them. Depending on the experimental condition of the trial, the participant was asked to stand still at the starting corner of the tracked area or to walk towards the diagonally opposite corner (shown as an orange square in Figure 1A). In the latter case, the fixation cube moved at a constant walking pace along the diagonal toward the opposite corner and the participant was asked to follow it while maintaining a distance behind it of about half a meter. The observers was thus either stationary or walking, and the brief grating stimulus could either be stationary or moving. The moving grating had the same direction and speed as the observer, as determined by the headset position in space as the participant walked across the space. This gives four conditions, and we included a fifth in which participants walked but the grating translated in the opposite direction to the participant, but with matched speed. We refer to these conditions as SS, SM, MS, MM, and MN: the first letter refers to the participant's motion (stationary or moving) and the second to the stimulus motion [static grating (S), grating moving in walk direction (M), or grating moving opposite the walk direction (N)]. In the conditions where the observer was stationary (SS & SM), they remained stationary in one of two corners of the tracked area, depending on where the participant finished the previous trial. In the conditions where the observer moved (MS, MM, & MN), the fixation cube led the participants towards the opposite corner of the tracked area. The cube defined the trajectory and speed of the movement by first uniformly accelerating from 0 to 0.8 $m \cdot s^{-1}$ over the course of 500 ms, then keeping the speed constant at 0.8 $m \cdot s^{-1}$ for 3.5 s before uniformly decelerating to a halt over 500 ms. The fixation cube always stopped about 1.4 m from the corner of the tracked area to prevent participants from accidentally leaving the area. For all five combinations of observer/stimulus motion, the grating stimuli were presented at a randomized time near the middle of each trial (random from a flat distribution spanning 1.5 to 2.5 s after trial onset), staying visible for either 400, 600, or 800 ms.

The experiment started once the participant was familiar with the procedure. Two data collection sessions were run for each observer, each containing 75 trials (five combinations of observer/stimulus motion over three time intervals, with five repetitions for each of these 15 conditions) for a total of 150 trials. One data collection session lasted approximately 15 minutes. Conditions and intervals were randomized within each experimental session as well as between observers. The trials were self-paced. Participants began a trial by fixating the cube and pulling the trigger on the hand-held HTC Vive controller. The cube had a central spot black spot that turned green in the case of a walking trial or red in the case of a stationary trial. In walking trials, the cube receded towards the diagonally opposite corner and the observer followed it or remained stationary otherwise. The grating was presented during the trial. After each trial, the fixation cube displayed a question mark, prompting the participant to respond. The participant's task was to reproduce the perceived duration of the grating stimulus presented during the trial by holding the trigger on the HTC Vive controller for a duration that matched their perceived duration of the grating. If the trial just completed was a walking trial, the cube then described a 180° circular path around the observer over the course of 3 s to turn the participant around and align them to face the opposite corner in preparation for the next trial. The experiment leader continuously monitored the observer's headset perspective and viewpoint to make sure that they were keeping their head still and that the headset cables did not become entangled.

Analyses

The reproduced times, obtained from the duration of the key presses on the Vive controllers, were imported

and analyzed in MATLAB (version 2016b; Math-Works, Natick, MA) through custom scripts. We computed the mean errors (reproduced time – physical time) across participants, for each condition and time interval. We also pooled the mean errors across time intervals by subtracting each reproduced time average from the relative presented time interval. We then performed multiple paired-samples Student's t-tests between the relevant subset of conditions. All the reported p values are corrected for multiple comparisons using the Benjamini-Hochberg procedure for false discovery rate (Benjamini & Hochberg, 1995).

Results

Participants reproduced the apparent duration of a stationary or moving grating stimulus, presented in the middle of a trial where they either stood stationary, or walked at a constant speed of 0.8 m $\times$ s^{-1}. There were five experimental conditions, as described in the Materials and methods and in Figure 1.

Figure 2 shows the results averaged over all 17 participants. Figure 2A plots average reproduction duration as a function of physical duration, separately for the five conditions. For all conditions, there was a tendency to overestimate duration, particularly at the shorter durations. The slopes of the functions are slightly lower than unity, reflecting the well-known regression to the mean that occurs when estimating duration under these conditions (Cicchini, Arrighi, Cecchetti, Giusti, & Burr, 2012; Jazayeri & Shadlen, 2010).

The main result is the effect of motion on duration estimation, brought out in Figure 2B, which plots average reproduction error (reproduced minus physical duration) as a function of physical duration. Figure 3 shows the data of Figure 2B collapsed over physical duration, which shows the results most clearly. Even for stationary stimuli there was an overestimation in perceived duration, of about 80 ms. As this condition can be considered as the standard to compare the others against, we will consider this to be baseline, to compare the motion conditions against. The first condition of stationary observer and moving stimulus (SM) showed a clear effect of apparent duration, with a significant increase of about 100 ms, on average. This is the standard condition used by previous researchers (Kanai et al., 2006), and the results are comparable. However, for the moving observer, the results were different. Neither stationary stimuli (MS), which have motion on the retina, nor moving stimuli (MM) with motion in the real world showed any systematic motion-dependent change in apparent duration. Only the condition MN (moving observer, opposite-moving
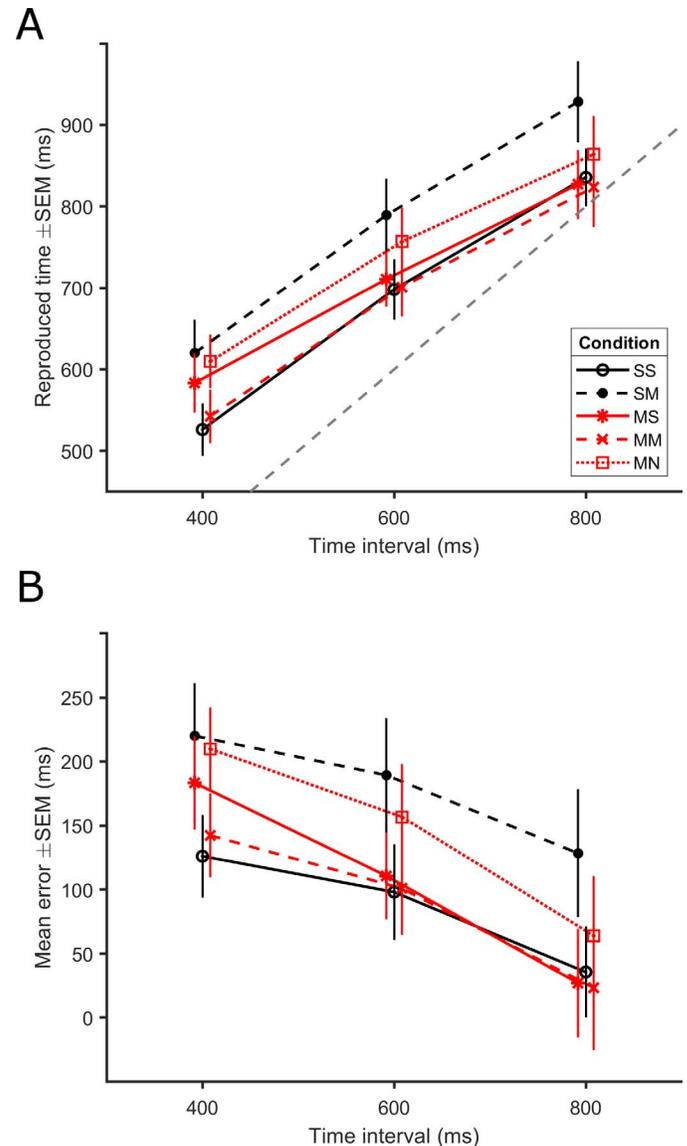
Figure 2. Average time reproduction results across participants. Conditions in which the observers were standing still are represented by the black lines and points, while conditions with walking observers are represented in red. (A) Average reproduction durations as a function of presented physical durations and experimental condition (see Materials and methods and Figure 1 caption for the condition labels descriptions). Bars represent ± 1 SEM. The dashed gray line represents equality between physical and reproduced duration. (B) Average reproduction errors across participants as a function of presented physical durations and experimental condition. Error bars represent ± 1 SEM.

grating) showed a significant increase in perceived duration relative to the baseline (SS) condition. SM and MN were both significantly different from the control condition SS (paired t-tests: $p = 0.00032$ and $p = 0.0025$, respectively) but are not significantly different from each other (SM vs. MN: $p = 0.157$). In other
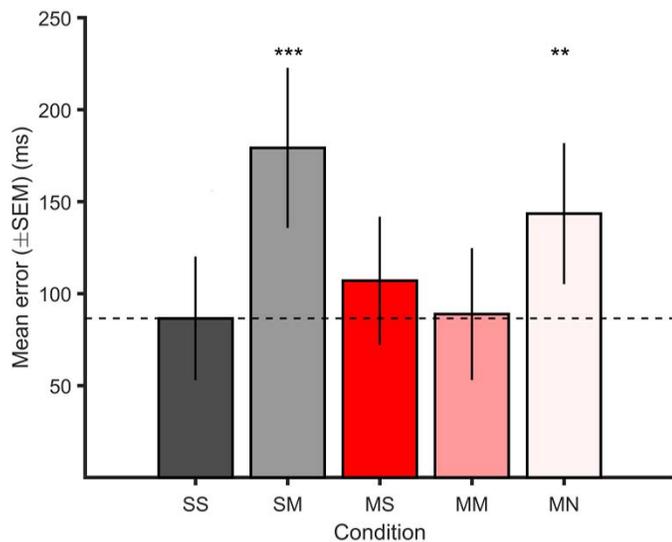
Figure 3. Average reproduction errors as a function of experimental condition, collapsed across physical presented durations. Error bars represent ±1 *SEM*. The dashed horizontal line represents the control condition (SS) mean reproduction error. The asterisks represent statistically significant difference from the baseline condition (paired Student's *t*-tests, ***$p \leq$ 0.001; **$p \leq$ 0.01; *$p \leq$ 0.05).

words, the only conditions that led to overestimate of duration were those where there was both external and retinal motion.

Figure 4 shows the data for all 17 observers, for the key conditions: SS (the control, plotted on abscissa), SM (Figure 4A), and MN (Figure 4B). There is considerable variability in the behavior of individual observers, varying from slightly under-reproducing the duration of the standard SS, by up to 100 ms, to over-reproducing by as much as 400 ms. Despite these large individual variations, the pattern of perceiving the SM and MN conditions as longer than the SS condition held for almost all observers and most points lie above the equality line. This shows that the increase in apparent duration was a commonly shared phenomenon, not due to outliers.

The data show that only two motion conditions cause a systematic time dilation. First, when the observer is stationary and the grating moves (SM), and second, when the observer is walking but the grating moves in the other direction (MN). Both of these conditions create quite a strong sensation of motion, and are the only conditions in which there is motion both in the world and on the retina (albeit in the opposite direction in condition MN). We attempted to quantify this by asking a subset of observers (four of the original participants) to rate the apparent strength of the sensation of motion (on a seven-point Likert scale) experienced in the five motion conditions, including SS as a control, where neither observer nor
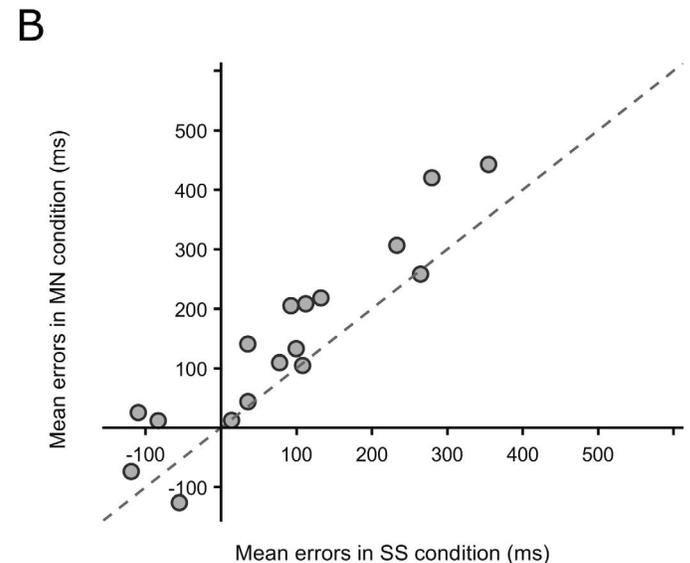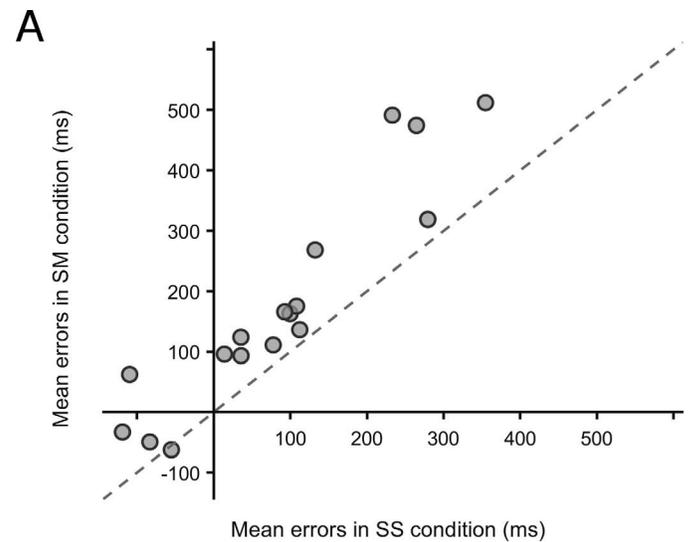

Figure 4. Single observers comparison between mean errors in the key conditions. (A) Single observers mean reproduction errors in the SM condition versus baseline (SS). Each point represent the errors in the two conditions for a given participant. The dashed gray line represents equality between these two measures. (B) single observers mean reproduction errors in the MN condition versus baseline (SS).

stimulus moved. The results are shown in Figure 5. The strongest sense of motion was in conditions SM and MN, and only for these two conditions was the score significantly higher than 1.

Discussion

The results of this study show that movement within the environment affects motion-induced expansion of perceived duration. For stationary observers, move-
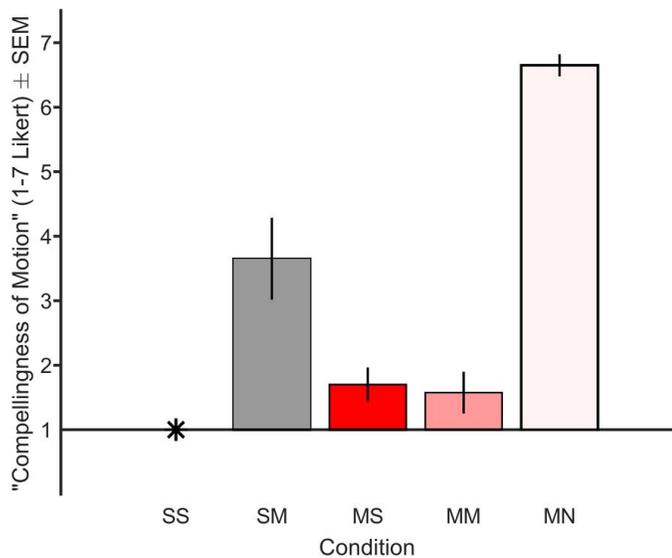
Figure 5. Subjective strength of motion sensation as a function of the experimental condition. A subset of the observers ($n = 4$) were asked to report the perceived sensation of motion on a seven-point Likert scale (1 = no motion; 7 = strongest motion) for each of the experimental conditions. For the baseline condition (SS), all of the subjects consistently reported a motion sensation of 1. The error bars represent ±1 *SEM*.

ment of the stimuli caused a robust expansion of duration. This SM condition replicates the observation made in several previous studies conducted in non-virtual environments (Brown, 1995; Kanai et al., 2006; Kaneko & Murakami, 2009). However, our data show that stimuli with the same image motion on the retina, caused by walking through a stationary world (MS condition), did not result in an expansion of perceived duration. Nor did the MM condition, where the stimuli moved in the real world, but in the direction of the observer, so that there was no retinal motion. The only condition in which the observer moved which caused duration expansion was MN, where the stimulus moved against the direction of walking, so it moved both in the real world and on the retina. According to observers' subjective ratings of motion strength, this was the only condition that elicited a strong perceptual sensation of motion. This is consistent with previous work (Durgin et al., 2005) showing that motion perception is underestimated when observers are in motion. It seems that to elicit a sensation of motion in a moving observer, it is necessary to have motion both on the retina and in the world. Furthermore, the pattern of results across the various conditions indicates that motion-induced expansion of perceived duration depends not on the physical speed of the motion stimulus but on the perceived sensation of motion, either on the retina or in the world.

Our participants moved actively in the environment. At this stage we cannot be certain which of the two factors contributed most to the lack of motion-induced duration expansion: the motion of the observer, or the physical act of walking. Previous work shows that estimation of apparent speed is influenced by both: by passive motion of the environment and by active stationary walking on a treadmill (Durgin et al., 2005). Both have effects of similar magnitude, which seem to be additive. It would be interesting in future to disentangle the two.

Our results raise several issues. First, it would appear that self-movement through a rich but static visual environment, which causes clear motion of the retinal images, does not result in a strong sense of apparent motion, as revealed by the motion strength ratings in Figure 5 and by the lack of expansion of apparent duration in the MS condition. Nor, indeed, does this condition result in a strong motion aftereffect (Harris, Morgan, & Still, 1981). These observations make sense because it is clearly advantageous for the system to distinguish retinal motion generated by self-motion from that generated by motion of the external environment, although it is far from clear how the system achieves this. Much work has been done on this for the specific case of eye movements, both smooth pursuit and saccadic movements (Morrone et al., 2005; Schütz & Morrone, 2010), but the problem becomes more complex when eyes, head, and body are all moving freely. It is still unclear to what extent the various vestibular and kinesthetic inputs, combined with long-term association, contribute to distinguishing self-generated from externally generated retinal motion.

Our results also relate to those of Fornaciai and colleagues (Fornaciai et al., 2016), who showed that time compression induced by motion adaptation occurs only for linear motion, not for expansion or rotation. This observation has a particular ecological significance because self-motion generates an optic flow on the retina that is primarily expansion and it is advantageous that this form of motion, occurring every time we walk or run, does not affect perceived time, either directly or indirectly via adaptation.

We know little about the mechanisms for perceiving event duration, or why they are distorted by motion. These results provide further evidence of how action and motion are tightly coupled to lead to a veridical perception of speed, and this is reflected in perception of apparent duration. The current study makes an important contribution in showing that it is apparent motion, not real motion (either in the world or on the retina) that causes the time dilation effect. This provides a useful constraint in the search for the mechanisms underlying perceived duration and dilation of visual stimulus events.

Acknowledgments

Commercial relationships: none.
Corresponding author: Luca Lo Verde.
Email: luca.loverde@unifi.it.
Address: Department of Neuroscience, Psychology, Pharmacology, and Child Health, University of Florence, Florence, Italy.

References

Benjamini, Y., & Hochberg, Y. (1995). Controlling the false discovery rate: A practical and powerful approach to multiple testing. *Journal of the Royal Statistical Society B*, 57(1), 289–300. https://doi.org/10.2307/2346101

Brown, S. W. (1995). Time, change, and motion: The effects of stimulus movement on temporal perception. *Perception & Psychophysics*, 57(1), 105–116. https://doi.org/10.3758/BF03211853

Burr, D., Cicchini, G. M., Arrighi, R., & Morrone, M. C. (2011). Spatiotopic selectivity of adaptation-based compression of event duration. *Journal of Vision*, 11(2):21, 1–9; author reply 21a, https://doi.org/10.1167/11.2.21. [PubMed] [Article]

Burr, D., Tozzi, A., & Morrone, M. C. (2007). Neural mechanisms for timing visual events are spatially selective in real-world coordinates. *Nature Neuroscience*, 10(4), 423–425. https://doi.org/10.1038/nn1874

Cicchini, G. M., Arrighi, R., Cecchetti, L., Giusti, M., & Burr, D. (2012). Optimal encoding of interval timing in expert percussionists. *Journal of Neuroscience*, 32(3), 1056–1060. https://doi.org/10.1523/JNEUROSCI.3411-11.2012

Durgin, F. H., Gigone, K., & Scott, R. (2005). Perception of visual speed while moving. *Journal of Experimental Psychology: Human Perception and Performance*, 31(2), 339–353. https://doi.org/10.1037/0096-1523.31.2.339

Fornaciai, M., Arrighi, R., & Burr, D. (2016). Adaptation-induced compression of event time occurs only for translational motion. *Scientific Reports*, 1–13. https://doi.org/10.1038/srep23341

Harris, L. R., Morgan, M. J., & Still, A. W. (1981, September 10). Moving and the motion after-effect. *Nature*, 293(5828), 139–141. https://doi.org/10.1038/293139a0

Jazayeri, M., & Shadlen, M. N. (2010). Temporal context calibrates interval timing. *Nature Neuroscience*, 13(8), 1020–1026. https://doi.org/10.1038/nn.2590

Johnston, A., Arnold, D. H., & Nishida, S. (2006). Spatially localized distortions of event time. *Current Biology*, 16(5), 472–479. https://doi.org/10.1016/j.cub.2006.01.032

Kanai, R., Paffen, C. L. E., Hogendoorn, H., & Verstraten, F. A. (2006). Time dilation in dynamic visual display. *Journal of Vision*, 6(12):8, 1421–1430, https://doi.org/10.1167/6.12.8. [PubMed] [Article]

Kaneko, S., & Murakami, I. (2009). Perceived duration of visual motion increases with speed. *Journal of Vision*, 9(7):14, 1–12, https://doi.org/10.1167/9.7.14. [PubMed] [Article]

Morrone, M. C., Ross, J., & Burr, D. (2005). Saccadic eye movements cause compression of time as well as space. *Nature Neuroscience*, 8(7), 950–954. https://doi.org/10.1038/nn1488

Schütz, A. C., & Morrone, M. C. (2010). Compression of time during smooth pursuit eye movements. *Vision Research*, 50(24), 2702–2713. https://doi.org/10.1016/j.visres.2010.07.022

Tomassini, A., Gori, M., Burr, D., Sandini, G., & Morrone, M. C. (2011). Perceived duration of visual and tactile stimuli depends on perceived speed. *Frontiers in Integrative Neuroscience*, 5(September), 1–8. https://doi.org/10.3389/fnint.2011.00051

Tomassini, A., & Morrone, M. C. (2016). Perceived visual time depends on motor preparation and direction of hand movements. *Scientific Reports*, 6, 1–12. https://doi.org/10.1038/srep27947

Treisman, M., Faulkner, A., Naish, P. L. N., & Brogan, D. (1990). The internal clock: Evidence for a temporal oscillator underlying time perception with some estimates of its characteristic frequency. *Perception*, 19(6), 705–742. https://doi.org/10.1068/p190705

Yamamoto, K., & Miura, K. (2012). Time dilation caused by static images with implied motion. *Experimental Brain Research*, 223(2), 311–319. https://doi.org/10.1007/s00221-012-3259-5