Distance perception during self-movement

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A B S T R A C T

The perception of distance in open fields was widely studied with static observers. However, it is a fact that we and the world around us are in continuous relative movement, and that our perceptual experience is shaped by the complex interactions between our senses and the perception of our self-motion. This poses interesting questions about how our nervous system integrates this multisensory information to resolve specific tasks of our daily life, for example, distance estimation. This study provides new evidence about how visual and motor self-motion information affects our perception of distance and a hypothesis about how these two sources of information can be integrated to calibrate the estimation of distance. This model accounts for the biases found when visual and proprioceptive information is inconsistent.

1. Introduction

The perception of the space surrounding us is one of the most relevant problems for our brain to resolve on every moment, this is so because that information is critical for our correct interaction with the environment. In this process, vision tends to dominate spatial judgments, since it provides highly detailed spatial information, influencing our space perception and distance estimation, based on other senses like hearing or touch (Eimer, 2004). This is because our perceptual experience is in fact shaped by multiples and complex interactions between sensory modalities. There is an important body of literature about distance perception performed by static observers in open fields (e.g. Da Silva, 1985; Norman, Crabtree, Clayton, & Norman, 2005). The idea that underlies within these studies is that much of the behavior performed is visually guided from an approximately stable position (Loomis, Da Silva, Fujita, & Fukusima, 1992).

However, it is a fact that we and the world around us are in continuous relative movement, and that our perceptual experience is shaped by the complex interactions between our senses and the perception of our self-motion. In fact, one of the most important functions of the visual system is to help guide our actions while the body is moving, independently of the orientation of our gaze and in a way that is immune to any discontinuity of the visual input (e.g. a blink) (Land, 2012). Hence, all the sources of information must be integrated in an internal model of whole-body motion with respect to the physical environment (Land, 2012), which must be learned and updated through experience (Wolpert & Flanagan, 2001). As it is known, if one of these sources of information is in disagreement with the other ones, that source may be re-calibrated or updated, but it may also drive to some corrections in the others (Durgin et al., 2005). Experiments demonstrated that humans rapidly adjust the calibration of their motor actions to compensate for the changing circumstances (Rieser, Pick, Ashmead, & Garing, 1995). Interesting representative cases can be found in the practice of sports: these activities require a fine coordination of movements (run, jump, catch, etc.) and good distance estimations to place

objects in specific locations (a goal, a basket, a target, etc.). For example, when a basketball player has to throw the ball to the basket while she/he is moving forward, the distance to the basket at the moment of the execution is no longer the same as the one at the moment of the acquisition of the image used to estimate distance, thus, the estimation must be adjusted. The recalibration required for humans to successfully execute the skilled action – with the correct force and direction – may be understood as a compensation mechanism. The problem arises from the fact that the estimation of distance could be based on an instantaneous picture of the scene, which would become outdated at the moment of the execution in case the individual is moving.

$$D_f = D_i - v \cdot \Delta t \qquad (1)$$

Eq. (1) describes the problem. The subject was at a distance D_i of the target when the process of distance estimation was initiated, and at D_f at the moment of the execution of the action. In between, the observer moved $v \cdot \Delta t$, which is the distance to be compensated. v is the subject's speed, and Δt is the time elapsed between times i and f. There is no doubt that self-motion information is critical in this compensation mechanism. The self-motion information can be divided into two classes: the first, referred to internal derived signals, which is called *idiothetic* or *interoceptive*, as it is provided by internally generated sensations (any movement that induces forces and pressures and could be detected by specific systems like the vestibular system, the visceral graviceptors, or the mechanoreceptor on the skin, providing a quantitative estimation of accelerations and gravito-inertial forces); the second is called *allothetic* or *exteroceptive*, because it is provided by the stimulation of the senses (visual, auditory and tactile cues). In the case of vision, it is well-known that optic-flow contains information on navigation, self-orientation, and the three-dimensional world (Gibson, 1950; Harris et al., 2002; Koenderink & Doorn, 1976), and allows a rapid and efficient estimation of direction and speed of self-motion (Larish & Flach, 1990; Warren, 1982), which could also serve to discriminate the traveled distances.

It is known that interoceptive and exteroceptive information are combined in the representation of self-motion (Durgin & Gigone, 2007; Durgin et al., 2005; Durgin, 2009). The authors found that the perceived speed of motion-in-depth induced by a simulated flow field decreases when the observer walks on a treadmill. They proposed that locomotion perceived speed would be determined by a visual component, i.e. the visual speed contained in the optic-flow, minus some proportion of the non-visually perceived speed of self-motion as can be seen in Eq. (2).

$$v_p = v_{visual} - k \cdot v_{nonvisual} \qquad (2)$$

This idea was first proposed by Barlow and Földiák (1989) to explain the improvements in the perceptual discrimination that is observed when two different sources of visual information are correlated. According to Durgin and collaborators, this theory can also apply to the correlations between visual and non-visual information, where their findings regarding perception of speed of motion-in-depth are well explained. Consistent with this hypothesis are the results of Frenz, Lappe, Kolesnik, and Bührmann (2007) who found that perceived traveled distance is underestimated in virtual environments.

Many studies have investigated the effect of visual-proprioceptive mismatches produced, for example, when running on a treadmill. In this situation, vision does not provide us with information about locomotion while proprioception indicates that we are moving forward (Anstis, 1995; Durgin et al., 2005). There are two known aftereffects that appear after a while of running on a treadmill. When subjects attempt to run in place with their eyes closed, they drift forward inadvertently; and if they try to walk without vision to a distant visually previewed target, they overshoot it (Rieser et al., 1995). Similar aftereffects can be generated by running in place on solid ground or behind a golf-cart, with occluded vision (Durgin & Pelah, 1999). These effects seem to be the result of organismic recalibrations in response to situations in which the perceptual expectancies (resulting from the physical activity) are in conflict with the perceived information of self-motion, revealing the existence of a multimodal spatial sense that integrates the different idiothetic and allothetic sources of information (Durgin et al., 2005).

Previous works have shown that the aforementioned discrepancies induce biases in the perception of speed (Kong, Koh, Tan, & Wang, 2012) and movement discrimination (Yabe & Taga, 2008; Yabe, Watanabe, & Taga, 2011). We can borrow this approach and use it to study the problem posed in Eq. (1). So far, we do not know, whether such discrepancies affect – and how much – distance perception. Interestingly, if one combines Eqs. (1) and (2), as it is shown below in Eq. (3), two important predictions arise: first, appropriate visual stimulation (e.g. an optic-flow pattern inducing vection) will produce an underestimation of distance when the observer remains still; second, the distance estimation will be overestimated when the observer is producing proprioceptive signals compatible with locomotion (e.g. running) at the time she/he faces a static visual scene.

$$D_f = D_i - (v_{visual} - k \cdot v_{nonvisual}) \cdot \Delta t \qquad (3)$$

In this study, we present a series of experiments in the open-field to test these predictions. To produce motor proprioceptive information, observers performed the task while running on a treadmill. On the other hand, visual motion stimulation was produced by superimposing an optic-flow pattern to the view of the natural open field (more details will be found in the Methods section).

2. General methods

We used an indirect method of distance estimation to perform the experiments. It consisted in matching the distance to be estimated (sagital plane) with another in the frontal plane (Loomis et al., 1992). This method has shown to be informative about the perceived distance, as it captures the well known space compression shown in previous studies (Wagner, 1985), and is more precise in comparison to others such as verbal estimation (Santillán, Barraza, & Assaf, 2018). In that study, the authors show that both methods, indirect and verbal estimation, show the same space compression, in order of magnitude and shape, which validates the indirect method.
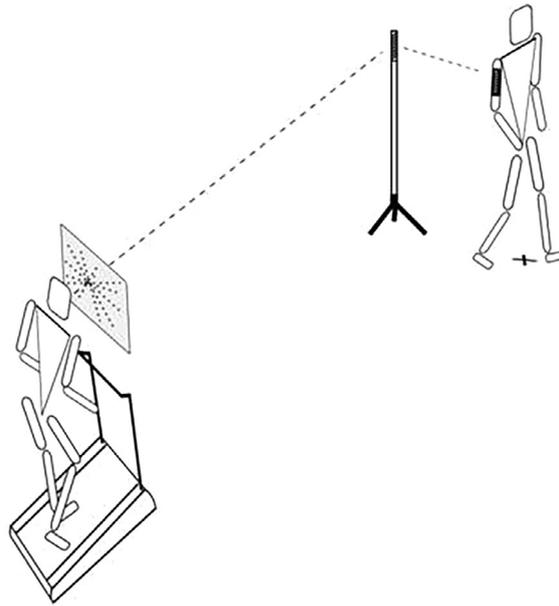
Fig. 1. Experiment layout showing the observer and assistant relative positions.

The protocol was approved by CEIUNT (Ethic Committee for Research of the National University of Tucumán, Argentina, Resolution: 1466/16), and followed all the procedures in order to protect the privacy and security of the participants, according to the tenets of the Declaration of Helsinki and the American Psychological Association for work with human subjects. An Informed Consent was obtained from all the participants.

2.1. Location and stimuli

The experiments were carried out in a flat and grassy open field of 18,000 m² the sports facility in the university campus. From the observation position, where the apparatus was located, there were 200 m free of obstacles that could be employed by the subjects as references for estimation in the range of distances used.

Before beginning each trial, the observer had her/his visual field blocked by a cardboard panel, while an assistant placed the target on the field. The target consisted of a white stake (1.65 m high) with a high-visibility orange fluorescent mark (20 cm) located on the top of the stake. When the panel was removed, the observer recovered full vision of the field and was able to see the target. Immediately after, the assistant stood next to the target and walked in the frontal plane until the observer said "stop" (please, see Fig. 1). The observer had the time the assistant was walking to make the distance estimation. We instructed the observers to stop the assistant when they perceived that the distance (in the frontal plane) between the assistant and the target was the same as the distance between her/himself and the target. The assistant could walk to the left or to the right from the target, depending on a list of randomly predefined directions. Once the observer performed the estimation, the assistant left a small and labeled mark (invisible from the point of view of the observer) to save the estimated distance. After each session, we measured the estimated distances, with a ruler which had an appreciation of 1 cm.

3. Experiment 1

The goal of this experiment was to investigate how motion information (visual and motor) affects the perception of distance. To do this, we performed an experiment in which we could produce separately visual and motor stimulation. This was needed in order to compare the distance estimations obtained in different test conditions with a reference condition, in which neither motor nor visual stimulation was used.

3.1. Method

The test conditions were three: 1) only visual stimulation (Visual Condition); 2) only motor stimulation (Motor Condition); 3) both, visual and motor stimulation (Combined Condition). Eq. (3) predicts that in the first condition, because of $v_{nonvisual} = 0$, distance will be underestimated respect to the reference.

$$D_f = D_i - v_{visual} \cdot \Delta t \tag{4}$$

On the other hand, for the second condition, because of $v_{visual} = 0$, distance should be overestimated respect to the reference.

$$D_f = D_i + k\, v_{nonvisual} \cdot \Delta t \tag{5}$$

Finally, for the condition in which both visual and motor stimulations are present, it is predicted that the perception of distance will be calibrated according to the resultant of combining the two speeds.

3.1.1. Participants

A total of 10 graduate students (four women and six men) participated voluntarily in this experiment. All were naïve as to the purpose of the experiment. Their age ranged between 20 and 25 with a mean age of 23. All of them had normal or corrected-to-normal vision.

3.1.2. Procedure

To produce motor stimulation, observers were adapted to treadmill locomotion. We set the speed at 4 and 8 km/h, and the observer run for two minutes without seeing the target before performing the task (the viewing of the target was blocked during motion adaptation). They continued to move on the treadmill while they made their adjustments. It is important to remark that previous studies confirmed that walking without vision for just one minute at a speed of 7 km/h is sufficient to produce adaptation (Durgin et al., 2005).

For controlled visual motion stimulation, we modified an LCD monitor in such manner that one could see through it, but keeping its capability of displaying images. To achieve this, we removed the physical structure of the monitor, including the backlight, and mounted it on an ad hoc structure. This modification allowed us to see the open field through the screen and perform the distance estimation task at the same time that a visual stimulus (optic-flow) was being presented on it. Because all sessions were performed during daylight and the transmittance of the display was low (32%), we had to build a black cabin from which the observer performed the task, otherwise the high level of light and reflections on the screen would not allow us to do it correctly. The monitor was located 20 cm from the observer, so that the visual field through it was approximately of 100 deg, 50 deg to each side of the target. The stimulus was a random-dot pattern simulating Motion-in-Depth (MID). It consisted in 100 dots randomly distributed in space. Each dot was randomly assigned a space coordinate (x, y, z) at the moment of stimulus initiation. To generate the optic-flow, we calculated the projection of each dot on the screen in each frame of the presentation, while the coordinate z was varied. It is important to note that only the position of the dots varied during motion presentation. Their size remained constant during the whole experiment. Due to these dots do not represent any familiar object, their size does not inform us about their distance (Gogel & Mertens, 1968). This produces a stimulus that, although it generates a compelling sensation of MID, it does not inform us about the veridical speed of self-motion. To set the Optic-flow speed, we performed a preparatory session in which the observers subjectively matched the speed-in-depth of the visual stimulus with their proprioceptive speed while running on the treadmill. This matching was performed for the two values of speed used in the experiment.

For this experiment, we used a PROTEUS MTM-5600 treadmill with digital speed selector. The monitor and cabin were present for all conditions.

3.1.3. Design and data analysis

In this experiment, we tested 2 distances (Distance), 3 treadmill speeds (SpeedTM), and 3 optic-flow speeds (SpeedOF). The order in which the different distances were estimated was randomized. The independent variables were Distance (12 and 24 m), SpeedOF (0, 4, and 8 km/h), and SpeedTM (0, 4, and 8 km/h), whereas the Estimated Distance was the dependent variable. As each of the ten observers repeated the measurements five times for each combination of independent variables, we modeled the data by using a Linear Mixed Model (LMM), in which 'observer' was included as a random effect.
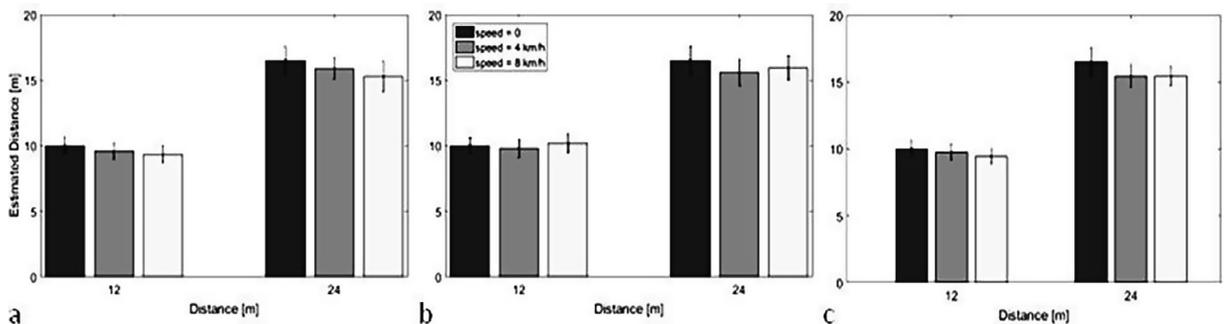

Fig. 2. Estimated distance for both target distances and the three values of speed. Results for the Reference Condition are in black and, the results obtained for speeds of 4 and 8 km/h, are in gray and white, respectively. Results are bounded with the SE. (a) Shows the results for Visual Condition so, speed refers to SpeedOF. (b) Corresponds to Motor Condition so, speed refers to SpeedTM. (c) Shows the result for Visual + Motor Condition. In this case, speed refers to both speeds.

3.2. Results and discussion

3.2.1. Effect of visual and motor stimulation

Fig. 2(a) presents the results for the Visual Condition. The plot shows the Estimated Distance for the three values of SpeedOF and the two values of Distance. The results for the Reference condition (SpeedOF = 0) are displayed in black, while the estimations for 4 and 8 km/h are in gray and white, respectively.

Results show that, consistently with the prediction, observers underestimate distance when the task is performed under a visual stimulation producing *vection*. A paired *t-test* indicates that for both distances (12 and 24 m) results obtained for speeds of 4 and 8 km/h are significantly different from those obtained without visual motion stimulation ($t(9) = 2.7548$, p = 0.0222 and $t(9) = 3.9349$, p = 0.0034 for 4 and 8 km/h respectively, for a distance of 12 m; $t(9) = 3.0535$, p = 0.0137 and $t(9) = 6.4903$, p = 0.0001 for 4 and 8 km/h respectively, for 24 m). Note that, all the estimated distances are by far smaller than the target's distance, which reveals the well-known compressive effect of distance perception of the in-depth dimension (Wagner, 1985). Moreover, data are alike those obtained in previous studies that used similar methods (Loomis et al., 1992; Norman et al., 2005), which suggests that the methodology is working properly.

Fig. 2(b) presents the results of the Motor Condition. The plot shows the Estimated Distance for the three values of SpeedTM and the two values of Distance. The results for the Reference condition (SpeedTM = 0) are in black, while the estimations for 4 and 8 km/h are in gray and white, respectively. Surprisingly, in this case results show that there is no effect of SpeedTM on the estimation of distance. For 12 m distance, neither the result for 4 km/h nor the one obtained for 8 km/h are significantly different from the reference condition (SpeedTM = 0; $t(9) = 1.7696$, p = 0.1105 and $t(9) = 1.1650$, p = 0.2739 for 4 and 8 km/h respectively). For 24 m distance, the estimated distance for 8 km/h is not significantly different from the reference condition ($t(9) = 1.9147$, p = 0.0878), but the one obtained for 4 km/h is significantly smaller ($t(9) = 3.6192$, p = 0.0055), which is exactly the opposite of our prediction (overestimation). No corrections for multiple comparisons were applied.

Fig. 2(c) shows the Estimated Distance for the three values of SpeedOF and SpeedTM and the two values of Distance. Results for the Reference condition (SppedOF and SpeedTM = 0) are in black, and the estimations for 4 and 8 km/h are in gray and white, respectively. Interestingly, the results of this experiment, practically replicates those found in the Visual Condition. According to our predictions, we should have found a null effect, as if motor and visual stimulation were compensating one to the other. However, we confirm that the effect of running does not appear in this experimental setup. The bar plot shows that there is an underestimation of distance when speed is different from zero, respect to the reference condition, as it was found in the Visual Condition.

3.2.2. Model fitting

Table 1 summarizes the result of fitting the model by using the LMM. For this analysis, we used distance ratios rather than absolute values of estimated distance to become independent from the compressive effect of distance perception of the in-depth dimension (Wagner, 1985). The random effects are shown in the upper part of the table; the lower part shows the fixed effects. The variable observer was included in the random term because our sample represents a much bigger universe of observers. Therefore, what matters here is to consider that over the model predictions there will be variability due to the variable Observer. We also included the slopes in the random term to avoid or minimize the possibility of spurious interpretations due to, for example, over-estimations in the evidence of differences.

The table confirms statistically our description of the results, which is that between the two speeds considered, only SpeedOF is significant, which reflects the effect obtained in the Visual Condition and the lack of effect observed in the Motor Condition. The

Table 1

Results of fitting the model by using the LMM in Experiment 1 data.

Random effects			
Groups	Name	Variance	Std. Dev.
Obs.	(Intercept)	2.891e−03	0.053769
	Distance	6.721e−06	0.002592
	SpeedOF	3.075e−05	0.005545
	SpeedTM	7.427e−05	0.008618
Residuals		2.693e−03	0.051892

| Fixed effects					
	Estimate	Std. Error	df	t value	Pr (> |t|)
(Intercept)	1.001e+00	2.182e−02	18.92	45.865	<2e−16
Distance	−6.181e−04	1.092e−03	22.32	−0.566	0.576883
SpeedOF	−7.529e−03	3.176e−03	78.07	−2.371	0.020223
SpeedTM	7.717e−03	3.800e−03	31.35	2.031	0.050831
Dist:SpeedOF	2.363e−05	1.396e−04	856	0.169	0.865611
Dist:SpeedTM	−4.784e−04	1.396e−04	856	−3.428	0.000637
SpeedOF:SpeedTM	−9.104e−04	5.128e−04	856	−1.775	0.076207
Dist:SpeedOF:SpeedTM	6.608e−05	2.703e−05	856	2.445	0.014689
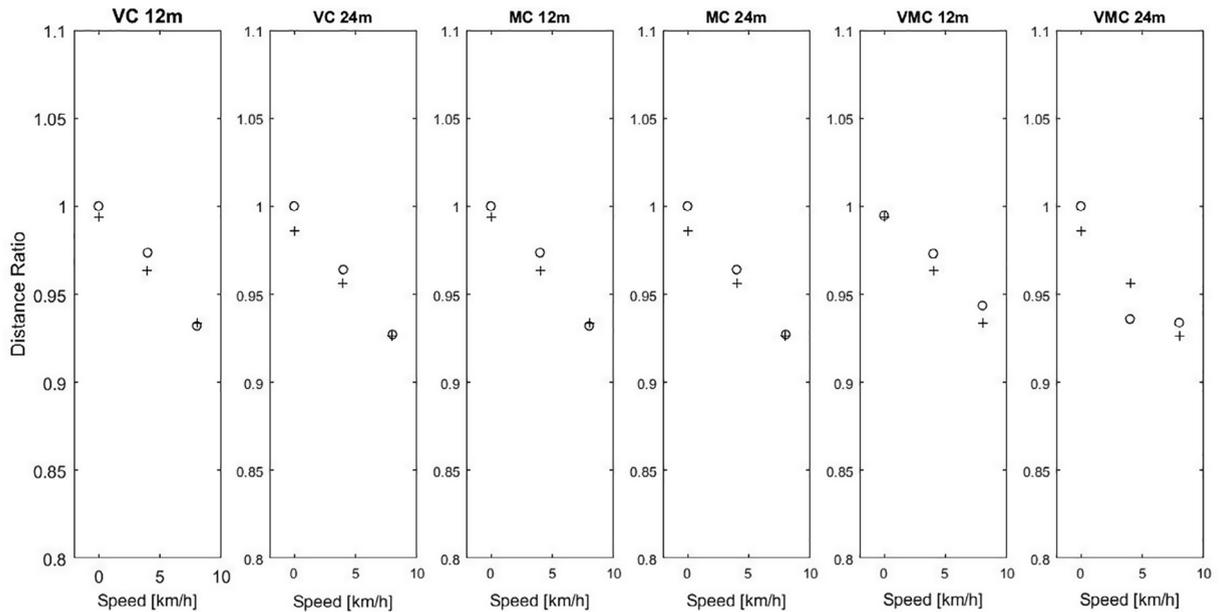
Fig. 3. All panels present the Estimated Distance Ratio as a function of Speed. Values smaller than 1 mean that distance was underestimated. Each panel is identified by the acronym of each condition and the target's distance. VC, MC, and VMC correspond to Visual Condition, Motor Condition, and Visual + Motor Condition, respectively. The experimental data are shown with open circles and crosses show the model's predictions.

Tukey test for multiple comparisons of means confirms the significances reported by the *t-tests*.

Fig. 3 shows the experimental data (open circles) and the model fitting (crosses) for the three conditions and the two studied distances. It is clear that the model fits very well the data, particularly for Distance = 12 m. In both, Visual and Visual + Motor Conditions, it appears that, for Distance = 24 m, the model predicts an effect a little less pronounced than what the experimental data shows.

The lack of proprioceptive effect in the perception of distance, found in Motor and Combined Conditions, is puzzling given that it contradicts what is expected from the visual aftereffects produced by running on a treadmill (Anstis, 1995; Durgin et al., 2005; Rieser et al., 1995). It was shown that these aftereffects induce mistakes in the perception of distance that are consistent with the hypothesis proposed in this study. Therefore, we decided to test our hypothesis, specifically for the Motor Condition in a separate experiment.

4. Experiment 2

Control for Motor Condition: the goal of this experiment was to investigate the effect of proprioception on the perception of distance in an experimental setup free of any external spatial reference that could affect the distance evaluation. These static references, in addition to provide external cues to the estimation of distance, may be propping up the problem of using a treadmill to induce motion proprioceptive information related to self-motion. As Durgin et al. (2005) established, running on a treadmill does not provide a neutral context for the perception of self-motion. Whether the eyes are open or closed, the primary spatial framework for the control of locomotion becomes the treadmill itself. This reference is necessary to maintain the position avoiding getting expulsed out of the treadmill, and is always accompanied by the conflicting perception that one is not actually going anywhere. In this control experiment, the task was performed in the open field without any additional reference to those provided by the field. The treadmill was located in the same place but now, the monitor and the cabin were removed so that observers had a view free of obstacles.

4.1. Method

4.1.1. Subjects

A total of 15 naïve subjects (nine men, six women) took part in this experiment. They were students from the university community that participated as volunteers. Their age ranged between 20 and 27 with a mean age of 25. All of them had normal or corrected-to-normal vision.

4.1.2. Procedure

The experiment was carried out in the same flat and grassy open field, at the sports facility in the university campus. The procedure and stimuli were the same as those used in the Experiment 1.
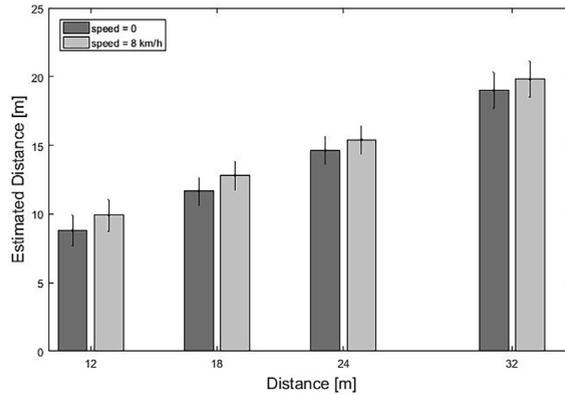
Fig. 4. Estimated distance for the four target distances and both values of speed. The results for Reference Condition are shown in gray and white bars show the results obtained in the Motor Condition. The results are bounded with the SE.

4.1.3. Design and data analysis

This experiment was performed for 4 distances (12, 18, 24, and 32 m) and 2 speeds (0 km/h and 8 km/h). The order in which the different distances were estimated was randomized. As each of the fifteen observers repeated the measurements five times for each combination of independent variables, we modeled the data by using a Linear Mixed Model (LMM), in which Observer was included as a random effect.

4.2. Results and discussion

4.2.1. Effect of motor stimulation

Fig. 4 shows Estimated Distance for both speeds and the four values of distance. As it can be noted, observers overestimated distance in this experimental setup. Moreover, results show that the difference between the estimated distances for test and reference is consistent along the whole range of studied distances. A paired *t-test* indicates that, for all studied distances, the estimated distance while the observer is running on the treadmill is significantly larger than the obtained in the reference condition ($t(14) = 3.3824$, p = 0.0044; $t(14) = 5.3614$, p = 0.0001; $t(14) = 3.9445$, p = 0.0014; $t(14) = 2.2891$, p = 0.0381, for 12, 18, 24, and 32 m distance respectively).

4.2.2. Model fitting

Table 2 summarizes the result of fitting the model by using the LMM. In this case, we performed the analysis by using the absolute values of estimated distance to fit the data because the model did not converge when using the ratios, perhaps, because we only have two values of speed (independent variable) and there is a slight dependency of estimated distance on speed.

The table confirms statistically our description of the results. In this case, the strongest effect corresponds to Distance and, the effect of SpeedTM is significant. As in the previous experiment, there is no interaction between SpeedTM and Distance.

Fig. 5 shows the experimental data (open circles) and the model fitting (crosses) for the four studied distances. It is clear that the model fits very well the data for all distances, which tell us to interpret the coefficient for SpeedTM as the processing time of visual information, i.e. Δt of Eq. (3).

Table 2

Results of fitting the model by using the LMM in Experiment 2 data.

Random effects			
Groups	Name	Variance	Std. Dev.
Obs.	(Intercept)	2.214226	1.48803
	Distance	0.009854	0.09927
	Speed	0.002143	0.04629
Residuals		1.740967	1.31946

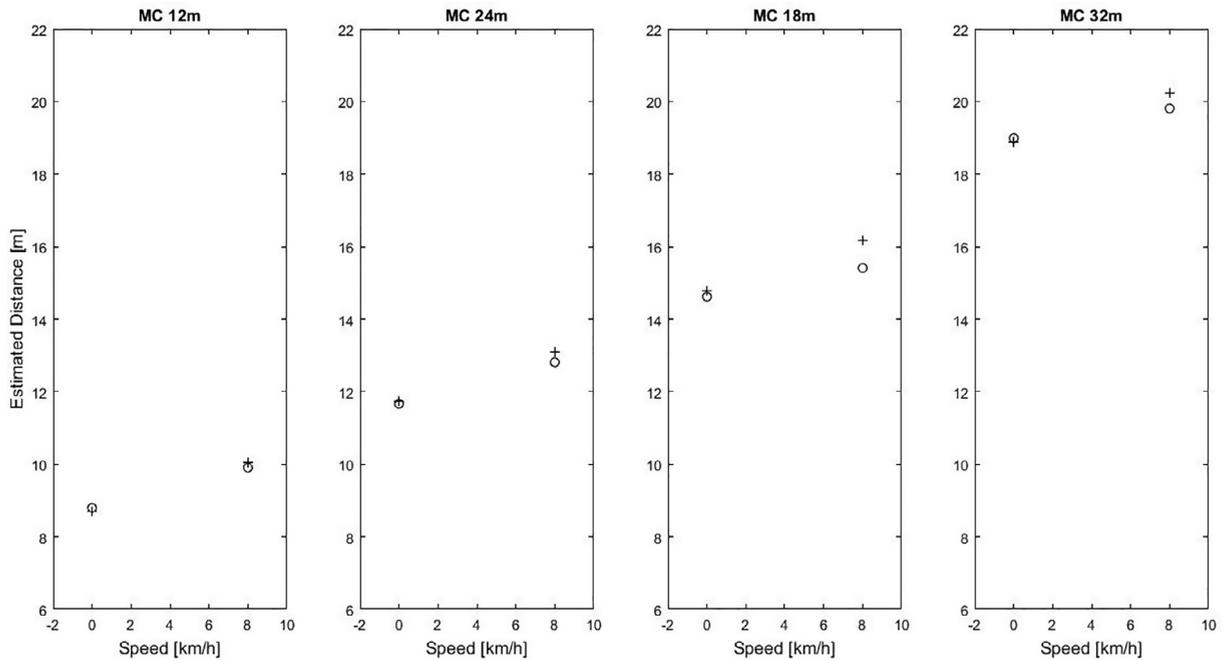| Fixed effects					
	Estimate	Std. Error	df	t value	Pr (> |t|)
(Intercept)	2.567210	0.449905	18.131	5.706	2.01e−05
Distance	0.509624	0.027621	16.180	18.451	2.71e−12
Speed	0.169756	0.043074	293.23	3.941	0.000101
Distance:Speed	− 0.002293	0.001820	553.99	− 1.260	0.208176

Fig. 5. All panels present the Estimated Distance as a function of Speed. Each panel is identified by the acronym MC that corresponds to Motor Condition, and the target's distance. The experimental data are shown with open circles and crosses show the model's predictions.

These results could be suggesting that the experimental setup used in the first experiment is not appropriate to test this effect. In fact, although we have an extensive open field outside the test cabin used in the first experiment, observers viewed this field through a rectangular frame, which could be introducing cues and external references that would be affecting their estimates. This may certainly be a good explanation if it were not that in the Visual Condition the setup worked. We understand that the answer can be found in the way different visual cues and visual and proprioceptive information are integrated. Although classically, vision has been thought to dominate those processes in which perception is based on visual and proprioceptive information (Welch & Warren, 1986), models of intersensory integration (van Beers, Sittig, & van der Gon Denier, 1996; van Beers, Sittig, & van der Gon, 1999) suggest that information from the two senses is weighted optimally to produce perception. Experimental results about target manual localization indicate that accuracy is critically affected by conflicting visual information (van Beers et al., 1999). In our experiment, the spatial cues provided by the frame would be pulling the distance perception to the reference condition, reducing the effect of the proprioceptive information and thus, washing the bias. On the other hand, different visual cues may be combined cooperatively in a way that, when there is conflicting information, the visual system makes assumptions that better explain the scene (Jacobs, 1999). An example of this cooperative mechanism can be found in the way the static spatial cues cooperates with optic-flow in the perception of heading (Van den Berg & Brenner, 1994). In other words, although the frame could provide strong references for distance estimation, it does not disable the information provided by optic-flow, perhaps, because people is familiar with such situation when riding a car, for example. Conversely, running with a window in front of us is a situation that we can rarely find in real life, this even comes into conflict with proprioceptive information, which, as we know, must be contextualized by the brain to make a correct interpretation.

This would explain why the effect of running on the treadmill did not appear in the previous experiment and clearly does in this, in which the open field was free of any external spatial reference that could affect the estimation of distance.

5. Conclusions

This article presents a series of experiments that explore how distance perception, in an open field environment, is affected by different signals indicating locomotion, such as motor proprioceptive information or optic-flow. In the first experiment, ten observers performed indirect distance estimations standing or running on a treadmill through a transparent LCD screen where an optic-flow pattern could be displayed. We found that distance was underestimated when optic-flow was displayed on the screen and observers were standing on the treadmill (Visual Condition). On the contrary, the results obtained from observers running on the treadmill (Motor Condition) did not show any effect on the distance perception. Finally, we asked the observers to estimate distance in a combined-test condition (Visual + Motor) and compared it with the reference. We found that these results replicate those found in the Visual Condition, suggesting that running on the treadmill did not produce any bias in the perception of distance with this experimental setup. After this, we performed a control experiment to test whether the lack of effect obtained in the Motor Condition was due to the presence of the frame of the monitor, which introduced a strong spatial reference for distance estimation. In this experiment we carried out the Motor Condition without any obstacle that could serve as a reference. In this case, we found that

distance was overestimated in the test conditions; respect to the reference as was predicted by the model.

The main motivation for these experiments was the hypothesis that, since visual processing is not instantaneous, tasks involving distance estimations performed while moving, require a compensation for the distance traveled during visual processing. This kind of mechanism resembles the well-known flash lag effect. According to the explanation proposed by Nijhawan (1994), the lag is the result of a trajectory extrapolation to compensate for the neural delays. Such a model would require a speed measure to be used in the extrapolation (Barraza & Derrington, 1999; Cantor & Schor, 2007). In the case of the flash-lag effect, it is clear that the relevant speed is that of the moving object. However, in our problem, actions would not be calibrated in terms of the physical speed but in terms of the perceived speed of self movement. This is determined by both visual and motor proprioceptive components, according to the model proposed by Durgin and collaborators (Durgin & Gigone, 2007; Durgin et al., 2005; Durgin, 2009). Starting from this hypothesis, one can expect, effectively, that motor proprioceptive information induces a positive bias in the perception of distance, just like an optic-flow pattern producing the perception of motion in depth, would induce a negative bias. Results presented here confirm these predictions. However, in this context, any interpretation of these results must necessarily include an analysis about how such interpretation depends on the observer's task.

According to our rationale, the biases obtained in the test conditions, obeys to the fact that visual and motor proprioceptive information are inconsistent. But, underlying this interpretation it is the assumption that there is, effectively, a "perceptual" difference of distance between the two conditions. Favoring this interpretation is, the consistency in the sign of the bias found for running and visual conditions. Moreover, there is the fact that, accompanying the main effect, we have obtained the typical compressive effect in distance perception, which is assumed as a perceptual effect. What other explanation would be suitable to explain our results? One possibility could be that running observers tended to overestimate distance (with respect to that in static condition) due to the energy expenditure, for example. According to action-specific perception account (Philbeck & Witt, 2015; Witt, 2011) people perceive the surrounding environment in terms of their ability to act in it. Such action abilities depend on a series of factors including energetic potentials. For example, people who throw heavy balls, perceive targets farther away compared with observers who throw light balls (Witt, Proffitt, & Epstein, 2004). However, this effect would produce a difference between estimates, proportional to the distance to be estimated since, according to action-specific perception account; meaning that the further away the target, the greater the effort to reach it and thus, the bias will be higher, unlike to what actually happens. In addition, this explanation is not suitable for the Visual Condition, in which there is not a motor action and thus, energy expenditure.

Another aspect that deserves to be discussed is whether our interpretations are tied to certain assumptions about the mechanisms involved in distance perception. For example, it was suggested that the perception of egocentric distance is determined by the gaze declination from horizon (Li, Phillips, & Durgin, 2011). An overestimation of this angle would produce an underestimation of distance. However, when exocentric extents along the ground are compared to frontal extents arranged to form an L-shape, observers seem to use optical slant rather than gaze declination. Li et al. (2011) used an L-shape layout to estimate egocentric distance indirectly, similarly to the method used in this work, and found that the distance underestimation is quantitatively consistent with the overestimation of gaze declination. The question would be, how could the external motion stimulation affect such information in a way that produces over- and underestimations of distance, depending on whether the stimulation is visual or motoric? According to our hypothesis, the effects shown in our experiments are explained by a compensation mechanism for the change of position that occurs during our movement, while estimating distance. Could we think about an effect on the perception of gaze declination as well? This is an interesting question that should be addressed in future works.

To sum up, we showed experimental evidence about the existence of a mechanism of compensation for distance estimation during movement, and how the visual system combines proprioceptive and visual information in the estimation of distance. Our data shows that the perception of distance during self movement would be calibrated in terms of the perceived speed of translation, which results from the modulation of the perceived visual speed (optic-flow) by the proprioceptive motor information (Durgin et al., 2005). Future studies should explore this mechanism in experiments including perception and action. Just as we find a bias in the perception of distance during movement, it is a greater challenge to show how proprioceptive or visual information affect the calibration of motor actions.

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