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RESEARCH ARTICLE

Interactive footstep sounds modulate the perceptual-motor aftereffect of treadmill walking

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Abstract In this study, we investigated the role of interactive auditory feedback in modulating the inadvertent forward drift experienced while attempting to walk in place with closed eyes following a few minutes of treadmill walking. Simulations of footstep sounds upon surface materials such as concrete and snow were provided by means of a system composed of headphones and shoes augmented with sensors. In a control condition, participants could hear their actual footstep sounds. Results showed an overall enhancement of the forward drift after treadmill walking independent of the sound perceived, while the strength of the aftereffect, measured as the proportional increase (posttest/pretest) in forward drift, was higher under the influence of snow compared to both concrete and actual sound. In addition, a higher knee angle flexion was found during the snow sound condition both before and after treadmill walking. Behavioral results confirmed those of a perceptual questionnaire, which showed that the snow sound was effective in producing strong pseudo-haptic illusions. Our results provide evidence that the walking in place aftereffect results from a recalibration of haptic, visuo-motor but also sound-motor control systems. Self-motion perception is multimodal.

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Introduction

Over recent decades, several studies have investigated the aftereffect from jogging or walking (Anstis 1995; Philbeck et al. 2008) which is typically recognized as specific changes in the action performance induced following the experience of several minutes of walking/running on a treadmill. The effect, initially investigated by Anstis in 1995, can be explained simply as follows: When an individual is asked to run/walk in place with closed eyes after several minutes of treadmill running/walking, he/she inadvertently moves forward (Anstis 1995) and the amount of the displacement is directly proportional to the running/walking speed during the exercise. More recently, the effect was shown to have an impact also on gait initiation, by increasing the length and the velocity of the first walking step and by decreasing the duration of the double-stance phase (Lepers et al. 1999). The effect has been shown to generalize to different tasks: After treadmill walking, individuals maintain an inclined posture while staying still in a stance position (Zanetti and Schieppati 2007) and overshoot a previously seen target when asked to reach it with closed eyes (Rieser et al. 1995; Durgin et al. 2005).

The general interpretation for this effect has been related mainly to the conflict between visual and proprioceptive feedback: During treadmill walking, the proprioceptive system senses the body displacement, yet visual feedback, due to the absence of optic flow, and returns the information of not progressing forward. After stepping down from the treadmill and after removing visual information, the mismatch adapts the neural pathway that controls the body's frame of reference by generating its forward shift, which is visible and quantifiable, for instance, by the drift of the center of pressure (Zanetti and Schieppati 2007). When vision was manipulated during treadmill walking, the proportional increases in forward drift (calculated as the ratio between the two stepping-in-place tests: post-treadmill exercise/pre-treadmill exercise) was inversely related to the amount of optical flow supplied during the treadmill adaptation, while the provision of simulated optical flow was insufficient to reduce the amount of the aftereffect (Durgin and Pelah 1999). From this, it appeared that even if the amount of visual information available during adaptation modulated the recalibration, the presence of additional optical flow was insufficient to do so entirely on its own. This suggests that vision is not the only sense able to induce the aftereffect. Moreover, subsequent experiments that involved nonvisual locomotion during treadmill adaptation (Durgin et al. 2005) or walking on solid ground adaptation (Philbeck et al. 2008) clearly demonstrated that the aftereffect was not specifically dependent on visual feedback.

According to Durgin et al. (2005), the cause of the aftereffect is due to the multimodal nature of self-motion and the forward drift is the result of processes that seek to minimize the discrepancy between self-motion predictions and perceived self-motion. In one experiment, they asked individuals during both pre- and post-treadmill exercise to use earplugs (Durgin and Pelah 1999). When data for earplug use were compared to a hearing control group, they found that although the ratio (post-/pretest) that defines the proportional increase in forward drift remained the same, the absolute drift without audition was double the drift with audition. The authors interpreted the result as an indication of a major contribution of audition in body stabilization. From this, it will be interesting to find out the actual relevance of audition in self-motion perception by testing whether sound feedback plays a role in inducing an aftereffect. Answering this question would be of fundamental importance in sustaining a multimodality explanation for inducing the aftereffect.

One of the most salient auditory cues for self-motion perception is the sound generated by footsteps. Following the recent literature, it is known that injecting interactive footstep sounds during walking can modify step kinematics in both clinical (Baram and Miller 2007; Baram and Lenger 2012; Rodger et al. 2013) and nonclinical contexts (Turchet et al. 2013a). It is important to notice that interactive simulations of footstep sounds are stimuli valid from an ecological point of view (Gaver 1993a, b). This is relevant since outside the laboratory, the environment presents multi-sensory stimuli that share spatial and temporal concordances and variations, which might contribute to their binding into specific and unitary events.

In the study reported in Turchet et al. (2013a), it was ascertained that locomotion speed was significantly affected when walkers were interactively provided with sounds simulating steps on a terrain different from the one they were walking upon. Specifically, participants walked faster on an asphalted road when auditory feedback was not provided than when walking in the presence of footstep-simulated sounds resembling a surface material different from asphalt in terms of compliance. Moreover, there was a scaling effect from higher to lower material compliance such that individuals walked faster when the simulated sound resembled wood than with gravel and snow. Locomotion speed was not affected in the presence of the sonic simulation of a wooden surface, which in terms of compliance is similar to asphalt. This effect was explained by the combination of the presence of conflicting information between auditory and foot-haptic modalities, along with an adjustment of locomotion to the physical properties evoked by the sounds simulating the ground material. Furthermore, results of a perceptive questionnaire, as well as the comments reported by the participants, indicated that the auditory cues involved created haptic sensations that have no basis in the mechanical signals perceived by the feet (such as effort, or the sensation of sinking into the ground). This phenomenon presents strong analogies with what has been termed *pseudo-haptic feedback*, in which visual cues can create haptic sensations of stiffness in the absence of haptic interfaces (Lécuyer 2009).

Analogous illusions induced by such auditory cues were also found in Turchet et al. (2013b). In this study, participants were provided with synthetic sounds simulating different surface materials while jumping on an elastic trampoline. Some types of auditory feedback were shown to be effective in altering the haptic perception due to the foot–membrane contact. Specifically, liquid sounds increased the sensation of sinking into the trampoline's membrane, while hardness was significantly increased by sounds simulating solid materials.

Knowing that sound can influence our way of walking through changes in movement kinematics, it is reasonable to expect that interactive sound feedback may contribute to recalibrating the perception of self-motion that could be observed in changes in aftereffect strength. Usually, the variable that defines the aftereffect is the distance travelled while walking in place (Anstis 1995; Durgin et al. 2005; Philbeck et al. 2008; Brennan et al. 2012). In this study, we investigated whether providing interactive auditory feedback simulating footsteps on terrains having different levels of compliance can influence step kinematics along with the forward drift during the walking-in-place task. In particular, we tested whether different sounds were capable of influencing forward body reference shift in combination with lower leg joint angles, step lengths, and times of foot contact.

For this purpose, we performed an experiment where footstep sounds were provided interactively to the walkers by means of a system consisting of shoes augmented with pressure sensors that drove a footstep sound synthesis engine. We also asked participants to fill in an ad hoc questionnaire [by means of a visual analog scale (VAS) score] to assess post-perceptual appreciations of the simulated surfaces and to correlate these with walking performance.

Based on recent research, we are expecting to observe an aftereffect in all the experimental conditions, and while following the interactive sound literature, we are expecting to find different joint angles and step kinematics depending on the type of sound delivered. More importantly, as a main new result, we are expecting to measure different percentages of forward drifts (calculated as a ratio of post-/pretest) for each sound condition. We anticipate a scaling effect in the amount of forward drift from higher to lower surface material compliance. This result would support the idea that auditory feedback adds to vision in inducing an aftereffect, sustaining therefore the multimodal nature of the effect.

Methods

Participants

Twelve participants, two males and ten females, between 23 and 36 years of age (mean = 27.58, SD = 3.91), took part in the experiment. All participants reported normal hearing and no locomotion impairments.

The procedure, approved by the local ethics committee, was in accordance with the ethical standards of the 1964 Declaration of Helsinki.

Apparatus

The apparatus consisted of a treadmill (HP/cosmos/Saturn 300/100r), a laptop delivering a sound synthesis engine connected to a pair of sandals augmented with pressure sensors, an Arduino UNO board, a wired closed headphone set with a noise cancelling system (Sennheiser PXC 450), and a motion capture system (Vicon MX) composed of 8 infrared cameras placed in order to track an area of calibration of 4 × 4 m. Cameras were set to collect data at a sampling frequency of 100 Hz. The treadmill was positioned near to the calibrated area, which was entirely covered by a thin carpet.

The sandals' shape was adjustable so that it fitted a large range of participants' feet size. A pressure sensor was placed under the sole of each sandal at the level of the heel. The sensors detected feet pressure during contact with the ground; their analog signals were digitized by means of the Arduino UNO board and used to drive the footstep sound synthesis engine. The synthesized auditory feedback was then conveyed to the user by means of the headphones.

Although ideally this setup should be wireless, a wired setup allowed us to monitor continuously the time latency between the transmitter and the receiver, and checks for data loss. The total latency between the actual footstep fall and the heard synthesized sound was not noticeable (<5 ms).

While walking, participants were barely aware of the presence of the wires since the equipment was light, felt comfortable, and did not constitute any major constraint to their movements: The light box containing the Arduino UNO board was hung on the back of the user's trousers by means of a small hook; the wires coming out from the shoes and directed to the Arduino UNO board were attached to the user's trousers by means of a tape and secured to the external side of the lower limbs; the USB cable connecting the Arduino UNO board to the laptop was tied together with the wire of the headphones, which was also connected to the laptop. The wires were long enough to allow the participant to walk freely.

The footstep sounds were synthesized by means of a sound synthesis engine proposed in previous research and able to simulate the footstep sounds on aggregate (e.g., snow) and solid (e.g., concrete) surfaces (Turchet et al. 2010a) (see "Appendix").

Stimuli

Three types of stimuli were utilized in the experiment. Two consisted of interactively generated footstep sounds simulating an aggregate surface material (deep snow) and a solid one (concrete), while the third type, considered as a control, consisted of no additional auditory feedback. During the latter condition, participants could hear their own footstep sounds.

The selection of the two surface material stimuli was made to check whether the aftereffect would present diverse percentages of drift. It was inspired mainly by our previous work showing that these simulated ground materials were among those most easily recognizable (Nordahl et al. 2010) and, more importantly, because concrete and snow present two different levels of material compliance. The compliance of concrete is similar to the one of the surface material actually walked upon by participants during the experiment, while the compliance of snow differs greatly from it. These two materials were also chosen because the signals corresponding to their simulation had different features in terms of duration, amplitude, temporal evolution, and spectrum (see Fig. 1). The amplitudes of the sounds were set at 55.4 and 54.2 dB (A) for snow and concrete, respectively. Such values were chosen according to the results of a previous experiment whose goal was

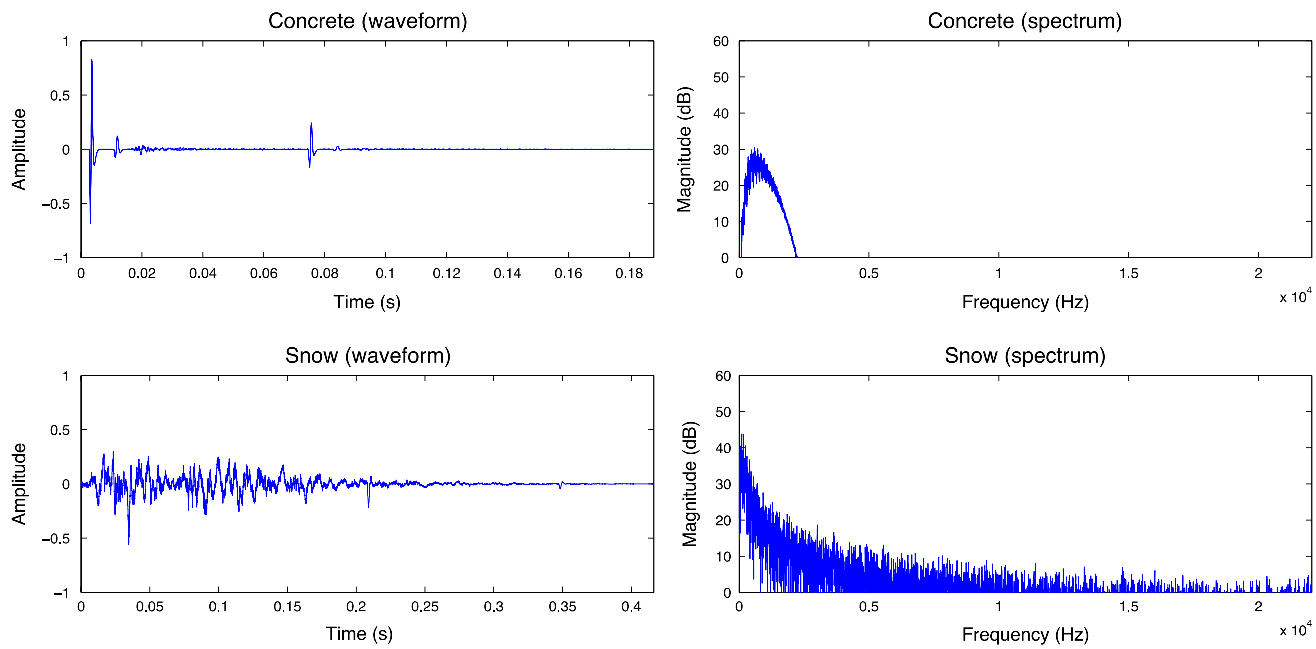

Fig. 1 Typical waveforms (*left*) and spectra (*right*) of the two simulated materials: concrete and snow

to find the appropriate level of amplitude for those synthesized sounds (Turchet and Serafin 2013). These sound amplitudes were effective in completely masking the actual footstep sounds produced by participants. The choice of the two sonically simulated surface materials was also to check the presence of expected pseudo-haptic illusions capable of altering the foot-haptic perception of hardness of both the treadmill platform and the carpeted laboratory floor (the two floors' hardness was similar).

Since both males and females were involved in the experiment, footstep sounds were synthesized in order to simulate a sound that could generally be accepted as genderless (Li et al. 1991). These authors showed that sounds having spectra with a predominant high-frequency component was associated with females, while maleness was related to spectral dominancy of the low frequencies. This was achieved by modeling the contribution of a type of shoe that fitted both males and females, as ascertained in a previous gender recognition experiment (Turchet and Serafin 2013).

The experiment was conducted in a silent laboratory [background noise 46.7 dB (A)]. The headphones' noise canceling system further stopped participants hearing any background noise from the room and drastically reduced that created by the treadmill during its use.

Procedure

Participants were first asked to put on the sandals and the headphones. Subsequently, the experimenter placed 18 reflective markers on the body joints for motion tracking. Specifically, the body was modeled as a series of linked, rigid segments: The 18 markers were placed bilaterally on the anatomical landmark points (immediately anterior to ear tragus, shoulder, elbow, wrist, greater trochanter, lateral epicondyle of femur, lateral malleolus, calcaneus, and fifth metatarsal head). In this way, 12 body segments were defined (Seminati et al. 2013).

Each participant underwent three experimental conditions, each represented by a sound stimulus (Snow, Concrete, No Sound). Each condition consisted of five phases: the control (C), the exercise (E), the post-exercise (PE), the recovery (R), and the post-recovery (PR) trial. This protocol was inspired by the one applied in Zanetti and Schieppati (2007). In the control (C) phase, participants were asked to close their eyes and walk in place for 1 min. The exercise phase (E) consisted of walking for 3 min with open eyes on the treadmill at a speed of 4.5 km/h. After the cessation of treadmill walking in the (PE), the subjects were asked to step down from the treadmill and with their eyes closed to walk in place for 1 min. Subsequently, they were asked to rest for 5 min (R). Thereafter, they performed the (PR) phase that consisted of walking in place for 1 min with closed eyes. During phases C, E, PE, and PR, the same sound stimulus was present. For all the phases, two beeping sounds were provided through the headphones: one at the beginning and one at the end of each phase to inform participants when to start and stop the performance. Individuals were let free to select their own step frequency and step height, and none indication was given about how to step in place.

Each sound condition was performed once, and across participants, the conditions were presented in a randomized order.

Vision was included during the adaptation phase in order to assess whether a sound-motor recalibration could occur also in the presence of a concurrent visuo-motor recalibration. The treadmill speed was selected in order to achieve the maximum velocity allowed by the auditory feedback system for optimal and credible human–machine interaction, especially during the simulation of walking on deep snow. A pilot test was run to assess that both the selected treadmill speed and duration of the period of adaptation were effective in inducing the aftereffect.

Before data collection, participants had the opportunity to get used to wearing the shoes and to experience the sounds. They were not provided with information about the type of material that was simulated by the synthesis model.

Participants took, on average, about 45 min to complete the experiment. Fatigue was not an issue.

Questionnaire

At the end of the experimental data collection, subjects were asked to fill in a questionnaire and to answer by means of a visual analog score (VAS). The questionnaire was inspired by those already utilized in Turchet et al. (2013a, b). For each sound condition, six questions were asked:

- [Effort] Evaluate the sense of effort you experienced while walking [0 = no effort, 10 = high effort]
- [Easiness] Evaluate the degree of easiness with which you walked while listening to the sounds [0 = very hard, 10 = very easy]
- [Sinking] Evaluate to what extent you had the impression that your feet were sinking into the ground [0 = not at all, 10 = very much]
- [Influence] Evaluate to what extent the sound influenced your way of walking [0 = not at all, 10 = very much]
- [Softness] Evaluate the impression of softness of the floor you walked upon [0 = not soft at all, 10 = very soft]
- [Hardness] Evaluate the impression of hardness of the floor you walked on [0 = not hard at all, 10 = very hard]

The order of presentation of the questions was randomized using a 6 × 6 Latin square. At the end of the questionnaire, participants were asked to name the two simulated surface materials.

Data handling

Motion capture signals were examined by means of Matlab R_2012a software. For each condition and phase, subjects' drift, step lengths, times of foot contact, and knee joint angles were considered for data analysis. The amount of forward drift was calculated by considering the displacement of the median point between the hip markers on the transversal plane. A moving average among points taken every 200 instants was considered. Angle joint was calculated by considering the thigh and shank as Euclidean vectors. The vectors' magnitude and the dot product were calculated by using ankle, knee, and hip in the three Cartesian coordinates. The relative angle was obtained by calculating the inverse of the ratio between the magnitudes and the vectors' dot product (i.e., the inverse of the cosine). After that, by using O'Connor et al.'s algorithm (2007), consecutive heel strikes were detected and the maximum angle for each gait cycle was derived. The angle average in 1 min of walking was then computed.

The same algorithm was employed for calculating step length and the time of foot contact, considering respectively the distance covered by the left foot on the traversal plane and the time of the left foot "stance" phase. The mean of the step length and the time of foot contact in 1 min of walking were computed.

Statistics

A two-way repeated measures ANOVA 3 × 3 was performed, by considering the three sound conditions (Snow, Concrete, No Sound) and the three selected experimental phases (C, PE, and PR) where the aftereffect was calculated for each of the five dependent variables (forward drift, number of steps, step length, step duration, and knee angle flexion) separately. A further one-way repeated measures ANOVA was performed on the questionnaire data by considering the three sound conditions (3 levels) for each of the six dependent variables (Effort, Easiness, Sinking, Influence, Softness, and Hardness). All post hoc were performed using a Bonferroni post hoc test (critical p value = 0.05).

Moreover, a linear mixed-effects model analysis was performed considering the possible correlations between the walking parameters and the VAS evaluations.

Results

As far as forward drift is concerned, the ANOVA showed a significant main effect for the experimental phase, $F_{(2,22)} = 32.789$, $p < 0.001$. The post hoc comparisons indicated a significantly greater drift for the PE phase compared to both the C and PR phases ($p < 0.001$ and $p = 0.001$, respectively). No significant main effect was found either for the sound condition ($F_{(2,22)} = 0.022$, $p = 0.978$) or for the interaction effect ($F_{(4,44)} = 0.613$,

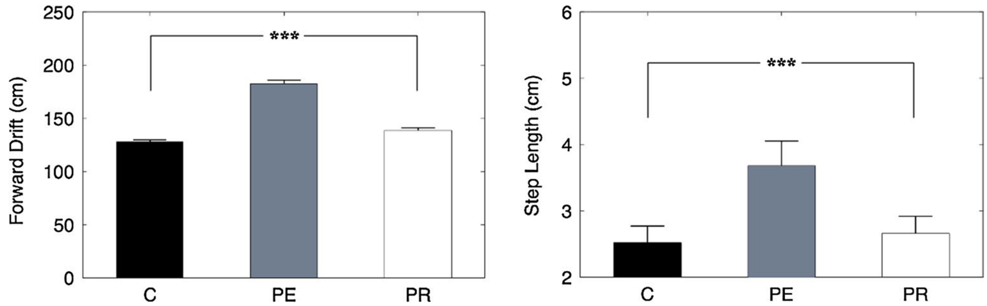

Fig. 2 Graphical representation of the mean and the standard error for participants' forward drift (*left*) and step length (*right*) as a function of the three experimental phases control (*C*), post-exercise (*PE*), and post-recovery (*PR*). ***$p \le 0.001$

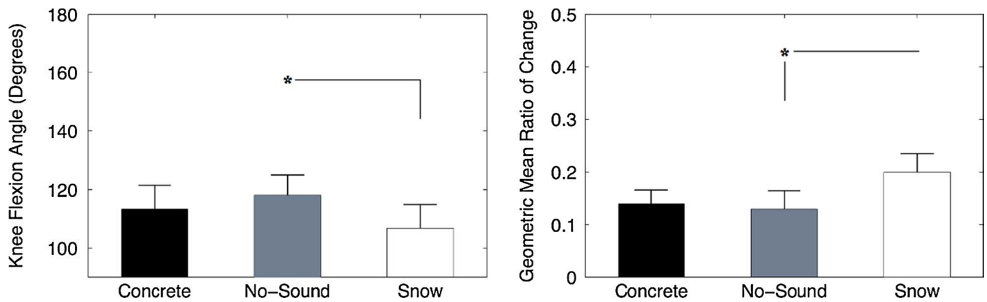

Fig. 3 Graphical representation of the mean and the standard error for participants' knee flexion angle (*left*) and geometric mean ratio of change (*right*) as a function of the sound conditions. *$p < 0.05$

$p = 0.656$). Step length was significant for the experimental phase, $F_{(2,22)} = 27.79$, $p < 0.001$. The post hoc comparisons indicated a greater step length for the PE phase compared to both the C and PR phases ($p < 0.001$ and $p = 0.001$, respectively). No significant main effect was found either for the sound condition ($F_{(2,22)} = 1.882$, $p = 0.176$) or for the interaction effect ($F_{(4,44)} = 1.320$, $p = 0.278$). Taken together, these results show that the aftereffect was clearly present independently of the sound condition. Forward drift and step length were enhanced when, after treadmill adaptation, individuals were asked to walk in place with closed eyes, while the effect disappeared after 5 min of resting. Figure 2 illustrates the results for forward drift and step length in the three phases.

Regarding time of foot contact, the ANOVA yielded a significant main effect for sound condition, $F_{(2,22)} = 4.987$, $p < 0.05$. However, none of the pairwise comparisons was significant. No significant main effect was found either for the trial phase ($F_{(2,22)} = 1.317$, $p = 0.288$) or for the interaction effect ($F_{(4,44)} = 0.377$, $p = 0.824$). For the knee angle, the ANOVA yielded a significant main effect for the sound condition, $F_{(2,22)} = 6.104$, $p < 0.01$. The pairwise comparison showed that the knee angle was significantly smaller for the Snow condition compared to the No Sound condition ($p < 0.01$). Figure 3 (left) illustrates the results for the knee flexion angle in the three sound conditions.

In order to evaluate whether different sound feedback affected the aftereffect, a subsequent analysis was performed by considering the logarithm of the ratio between the forward drift in the posttest (PE) and pretest (C) (Durgin and Pelah 1999; Brennan et al. 2012). The ANOVA yielded a significant main effect, $F_{(2,22)} = 3.750$, $p < 0.05$. The pairwise comparison showed that the ratio was significantly greater for the Snow condition compared to the No Sound condition ($p < 0.05$). Such result is illustrated in Fig. 3 (right).

In order to define whether the subjects perceived the surfaces differently, the VAS results for each questionnaire item were compared with the sound conditions. The ANOVA revealed a significant effect for Effort, $F_{(2,22)} = 3.219$, $p < 0.05$; for Sinking, $F(2,22) = 31.34$, $p < 0.001$; for Influence, $F_{(2,22)} = 11.1$, $p < 0.001$; for Softness, $F_{(2,22)} = 13.29$, $p < 0.001$; and for Hardness, $F_{(2,22)} = 7.74$, $p < 0.01$. The post hoc analyses revealed significant differences for the combination Snow–No Sound in questions Effort ($p < 0.05$), Sinking ($p < 0.001$), Influence ($p < 0.001$), Softness ($p < 0.01$), and Hardness ($p < 0.05$), for the combination Snow–Concrete for questions Sinking ($p < 0.001$), Softness ($p < 0.001$), and Hardness ($p < 0.001$), and for the combination Concrete–No Sound for questions Influence ($p < 0.01$), Softness ($p < 0.001$), and Hardness ($p < 0.001$). The results of this analysis are illustrated in Fig. 4.

The analyses using a linear mixed-effects model revealed that the knee flexion angle was linearly related to perceived effort [$\beta = -2.546$, $t(23) = -2.817$, $p < 0.01$], sinking [$\beta = -1.076$, $t(23) = -2.409$, $p < 0.05$], and sound influence [$\beta = -1.125$, $t(23) = -2.167$, $p < 0.05$].

Not all participants recognized the simulated material correctly: Six participants recognized correctly the snow aggregate, and two interpreted the snow as sand, one as gravel, one as polystyrene, whereas two could not name the

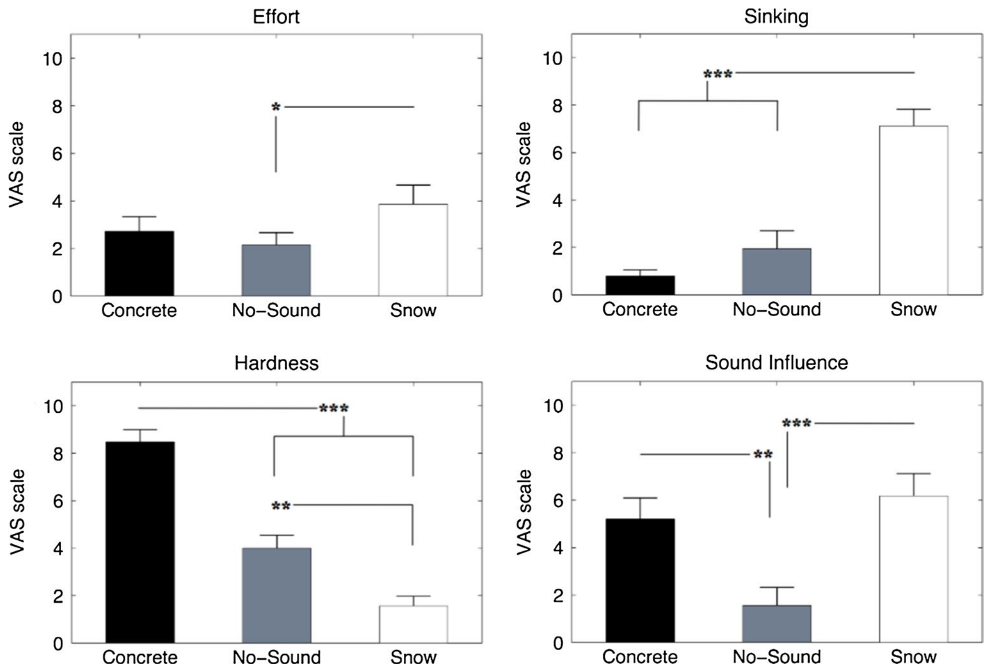

Fig. 4 Graphical representation of the mean and the standard error for participants' answers to questionnaire for the three sound conditions. Items presented are Effort (*top left*), Sinking (*top right*), Hardness (*bottom left*), and Influence (*bottom right*). $*p < 0.05$; $**p < 0.01$; $***p < 0.001$

material. Three participants recognized correctly the concrete material; seven participants interpreted concrete as wood, whereas two could not name the material. Therefore, considering both correct and incorrect answers, participants perceived clearly the difference between solid and aggregate surfaces, and this result is in accordance with the findings reported in our previous study using the same footstep sounds engine (Nordahl et al. 2010).

Discussion

In this experiment, we investigated whether interactive sounds, provided through headphones and simulating walking on different surfaces, could influence the perceptual-motor recalibration caused after treadmill walking. Here, we showed that when different sound-simulated surfaces were tested, the increase in forward drift (calculated as the ratio between the post-treadmill exercise/pre-treadmill exercise) was greater for the snow material compared with the concrete material or with the no additional sound condition. This result provides evidence that the walking-in-place aftereffect results from a recalibration of both visuo-motor and sound-motor control systems.

Firstly, it is important to mention that our results successfully replicate previous findings on the aftereffect in that we measured its presence in all the experimental conditions tested: Participants walking for 1 min in place with closed eyes after a period of adaptation inadvertently moved forward without exception, and this happened with, as well as without, the addition of interactive sounds. Interestingly here, we showed that in all the experimental conditions, the effect decayed toward the initial values after 5 min of rest. In addition, the velocity imposed by the treadmill and the consequent modulations of the gait parameters (Stolze et al. 1997; Alton et al. 1998; Dingwell et al. 2001) were effective in modifying also the length of the steps once the subject got off the treadmill. These results are all consistent with those of the previous studies on the aftereffect (Anstis 1995; Durgin et al. 2005; Brennan et al. 2012; Zanetti and Schieppati 2007).

In the same vein, our results also replicate previous findings on the kinematic changes observed after the addition of interactive footstep sounds while walking on a solid surface: We showed that by providing auditory feedback, the biomechanics of walking changed, particularly when the sound simulates an aggregate surface (Turchet et al. 2013a; Rodger et al. 2013). This is reasonable if we consider that when actually walking on snow and maintaining one's balance, a higher production of force under one's feet is necessary. Indeed, participants in the snow sound simulation flexed their knee joints with a wider amplitude compared with the concrete sound simulation and when no additional sound was added. The perceptual questionnaire was in line with what was observed in the knee joint angle. The sound resembling a footstep on snow induced an impression of sinking with one's feet into the ground and an impression of effort during walking, while no difference in sinking and effort evaluation was present for the concrete and the no addition of sound conditions, underlying the fact that concrete simulated a material highly similar to the one people who were actually walking on.

Interestingly, the provided sounds were effective in altering the tactile perception of both softness and hardness of the walked-upon floor, as shown in the reports of the questionnaire items Softness and Hardness. Such results confirm those reported in Turchet et al. (2013a, b), indicating that the auditory cues involved created haptic sensations that have no basis in the mechanical signals perceived by the feet and therefore indicate the presence of pseudo-haptic illusions (Lécuyer 2009).

The strength of data in replicating previous findings permits more confidence in answering our initial main question: Whether by applying different interactive sounds, the aftereffect would present diverse percentages of drift, proving that the aftereffect is also sound-dependent and not just vision- and proprioception-dependent. Here, we found that the ratio between the pre- and post-treadmill drift was greater under the influence of the snow sound compared with the other two experimental conditions, and this sheds new light on the multimodal nature of the aftereffect.

According to Durgin et al. (2005), the aftereffect would result from a conflict between self-motion prediction, based on previous locomotion experiences, and actual self-motion perception, such that the greater the discrepancy, the stronger the aftereffect. This is precisely what was found. During treadmill walking, the proprioceptive system encoded that the body was moving and, in particular under the influence of the snow sound, that the performance required a relevant amount of effort (as indicated by the greater evaluations of Effort and Sinking), yet the absence of optic flow was signaling zero self-motion. Therefore, if on the one hand, the absence of optic flow decreases the amount of self-motion that is actually perceived, on the other hand, the presence of the snow sound alters the foot-haptic perception on the treadmill surface along with the perceived sense of effort and sinking. This creates a discrepancy between predicted self-motion and the amount of actual self-motion perceived. Such a discrepancy is greater for the snow sound compared to the other two conditions and results in greater aftereffect strength. As a consequence, our results provide support to the theory of Durgin et al. (2005), according to which the aftereffect involves self-motion perception and that self-motion is multimodal in nature.

In this regard, one could argue that a more appropriate experimental protocol would have been that of providing auditory feedback only during the adaptation phase and then to test the amount of aftereffect without the auditory feedback. However, by means of our protocol, it was possible not only to study the aftereffect as such, but also the changes in the actual kinematics of locomotion under the influence of the inseparable combination of the perceptual-motor feedback: the sound produced while stepping in combination with the proprioceptive activation, importantly, though the similar amount of drift measured across sound conditions in both C and PR phases showed the relative strength of this motor-perceptual feedback.

It is important to mention that different walking/running speeds and durations have been used in previous researches, in particular, 1 min at 8.0 km/h in Anstis (1995); 20 min at 4.83 km/h in Brennan et al. (2012); ~6.6 min at 9.0 km/h in Durgin and Pelah (1999); and 6 min at 6 km/h in Zanetti and Schieppati (2007). Here, individuals were running for 3 min at 4.5 km/h (this was constrained by the fragility of the sensors located in the shoes), but nevertheless, the aftereffect was present.

It is worth noticing that individuals were able to discern the level of hardness between the three sounds, while for the sense of effort and sinking, they evaluated snow as different to the other two conditions, which in turn were perceived as the same. This may underline the strength of the evaluation for items that are highly specific for a particular action, such as sinking in the case of walking on snow. Interestingly, as the kinematics (the knee angle flexion) distinguished the snow from the other two conditions, the same was true for the evaluation of sinking and effort.

One could argue that the effect of auditory feedback on the aftereffect is simply mediated by its effect on gait kinematics and/or kinesthetic. However, if this was true, then it would result in differences in the amount of walked distance between the sound conditions during the Control (C) phase. This did not happen. In principle, it is possible to cover the same distance with different kinematics of walking. Therefore, it is safe to conclude that the effect of auditory feedback on the aftereffect was due to its influence on the self-motion perception.

On the other side, the absence in difference in percentage of drift between the Concrete and the No Sound conditions sheds some light on under which condition audition plays a role in the aftereffect. Here, we showed that the aftereffect is not influenced by auditory information in the presence of similar compliance of the material sonically simulated and that of the material actually walked upon.

The influence of the snow sound on walking-in-place kinematics parallels the findings of other studies, which showed that auditory feedback has an influence at a kinematic level (Castiello et al. 2010; Sedda et al. 2011; Rodger et al. 2013; Turchet et al. 2013a). Sound, as reviewed in Thaut and Abiru (2010), strongly influences motor responses, in particular during locomotion, and this is supported by neural pathways shared by the auditory and motor systems. Furthermore, various neurophysiological studies showed common neural pathways involved in sounds and actions coupling (for a review see Molnar-Szakacs and Overy 2006). Hearing the sound of an action evokes the motor plan that controls the limbs responsible for that sound production (Lahav et al. 2007; Cesari et al.

2014) and can influence movement kinematic parameters (Castiello et al. 2010; Sedda et al. 2011). However, it is important to notice that in this experiment, individuals experienced, through sound, walking as if performed on different materials, while in fact, they were actually interacting with the same type of floor (the treadmill and the laboratory floor). This could create potential discrepancies (Turchet et al. 2013a): (1) a semantic discrepancy between the provided sound and the sensory feedback received from the soles of the feet on the actual hardness of the walked-upon surface; (2) an audio-haptic temporal discrepancy due to the differences between the duration of the snow sound and the haptic sensory feedback; (3) an adjustment to the perceived material so subjects changed their walking kinematics to be consistent with the sounds they were hearing. All three hypotheses are potentially valid for the present study, and further research is needed to investigate in more detail the exact origin of these discrepancies. But whatever the nature of the discrepancy, we showed that interactive sounds induce a sound-specific self-motion expectation that can be measured in terms of strength of aftereffect. Here, we showed that individuals, while walking in place, presented different amount of unintentional forward drift depending on the type of materials they were experiencing. This result clearly indicates that along with haptic and visuo-motor systems, the audio-motor system is also involved in self-perception.

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Appendix

The developed footstep engine uses a sound synthesis technique known as physical modeling, where the physics of sound production mechanism is simulated.

Specifically, we adopted the impact model described in Avanzini and Rocchesso (2001) and a physically informed sonic model (PhiSM) (Cook 1997). These models were used to simulate walking on solid and aggregate surfaces, respectively. The two approaches are briefly recalled below.

The interaction between solid surfaces can be expressed by the force between two bodies (Hunt and Crossley 1975):

$$f(x, \dot{x}) = -kx^{\alpha} - \lambda x^{\alpha}\dot{x} \quad \text{if } x > 0, 0 \text{ otherwise}$$

where x represents the contact interpenetration, k accounts for the material stiffness, λ represents the force dissipation due to internal friction during the impact, and α is a coefficient which depends on the local geometry around the contact surface. The model described has been discretized using the numerical method proposed in Avanzini and Rocchesso (2001).

In order to simulate particle interactions typical of aggregate surfaces, we adopted a PhiSM model. In this model, the interaction between the foot and the floor can be represented using a simple Poisson distribution, where the probability of sound production is constant at each time step, giving rise to an exponential probability weighting time between events.

In the experiment described in this paper, the footstep sounds synthesis is driven interactively by the user wearing the shoes. From the real acoustical signal of a footstep sound, the ground reaction force (GRF) is estimated, i.e., the reaction force supplied by the ground at every step. Such GRF is used to drive the described physical models, as explained in detail in Turchet et al. (2010a). A description of the control algorithms based on the analysis of the values of the pressure sensors embedded in the shoes can be found in Turchet et al. (2010b). The sound synthesis engine and the relative control algorithms were implemented using the Max/MSP sound synthesis and multimedia real-time platform.

References

Alton F, Baldey L, Caplan S, Morrissey MC (1998) A kinematic comparison of overground and treadmill walking. Clin Biomech 13(6):434–440

Anstis S (1995) Aftereffects from jogging. Exp Brain Res 103(3): 476–478

Avanzini F, Rocchesso D (2001) Modeling collision sounds: non-linear contact force. In: Proceedings of the digital audio effects conference, pp 61–66

Baram Y, Lenger R (2012) Gait improvement in patients with cerebral palsy by visual and auditory feedback. Neuromodulation 15(1):48–52

Baram Y, Miller A (2007) Auditory feedback control for improvement of gait in patients with multiple sclerosis. J Neurol Sci 254(1):90–94

Brennan AA, Bakdash JZ, Proffitt DR (2012) Treadmill experience mediates the perceptual-motor aftereffect of treadmill walking. Exp Brain Res 216(4):527–534

Castiello U, Giordano BL, Begliomini C, Ansuini C, Grassi M (2010) When ears drive hands: the influence of contact sound on reaching to grasp. PLoS ONE 5(8):e12240

Cesari P, Camponogara I, Papetti S, Rocchesso D, Fontana F (2014) Might as well jump: sound affects muscle activation in skateboarding. PLoS ONE 9(3):e90156

Cook P (1997) Physically informed sonic modeling (PhISM): synthesis of percussive sounds. Comput Music J 21(3):38–49

Dingwell JB, Cusumano JP, Cavanagh PR, Sternad D (2001) Local dynamic stability versus kinematic variability of continuous overground and treadmill walking. J Biomech Eng 123(1):27–32

Durgin FH, Pelah A (1999) Visuomotor adaptation without vision? Exp Brain Res 127(1):12–18

Durgin FH, Pelah A, Fox LF, Lewis J, Kane R, Walley KA (2005) Self-motion perception during locomotor recalibration: more than meets the eye. J Exp Psychol Hum Percept Perform 31(3):398–419

Gaver W (1993a) How do we hear in the world? Explorations in ecological acoustics. Ecol Psychol 5(4):285–313

Gaver W (1993b) What in the world do we hear? An ecological approach to auditory event perception. Ecol Psychol 5(1):1–29

Hunt KH, Crossley FRE (1975) Coefficient of restitution interpreted as damping in vibroimpact. J Appl Mech 42(2):440–445
Lahav A, Saltzman E, Schlaug G (2007) Action representation of sound: audiomotor recognition network while listening to newly acquired actions. J Neurosci 27(2):308–314
Lécuyer A (2009) Simulating haptic feedback using vision: a survey of research and applications of pseudo-haptic feedback. Presence Tele Oper Virtual Environ 18(1):39–53
Lepers R, Brenière Y, Maton B (1999) Changes to the gait initiation programme following a running exercise in human subjects. Neurosci Lett 260(1):69–73
Li X, Logan RJ, Pastore RE (1991) Perception of acoustic source characteristics: walking sounds. J Acoust Soc Am 90(6):3036–3049
Molnar-Szakacs I, Overy K (2006) Music and mirror neurons: from motion to 'e'motion. Soc Cogn Affect Neurosci 1(3):235–241
Nordahl R, Serafin S, Turchet L (2010) Sound synthesis and evaluation of interactive footsteps for virtual reality applications. In: Proceedings of the IEEE virtual reality conference, pp 147–153
O'Connor CM, Thorpe SK, O'Malley MJ, Vaughan CL (2007) Automatic detection of gait events using kinematic data. Gait Posture 25(3):469–474
Philbeck JW, Woods AJ, Arthur J, Todd J (2008) Progressive locomotor recalibration during blind walking. Percept Psychophys 70(8):1459–1470
Rieser JJ, Pick HL, Ashmead DH, Garing AE (1995) Calibration of human locomotion and models of perceptual-motor organization. J Exp Psychol Hum Percept Perform 21(3):480
Rodger MW, Young WR, Craig CM (2013) Synthesis of walking sounds for alleviating gait disturbances in Parkinson's Disease. IEEE Trans Neural Syst Rehab Eng 22(3):543–548
Sedda A, Monaco S, Bottini G, Goodale MA (2011) Integration of visual and auditory information for hand actions: preliminary evidence for the contribution of natural sounds to grasping. Exp Brain Res 209(3):365–374
Seminati E, Nardello F, Zamparo P, Ardigò LP, Faccioli N, Minetti AE (2013) Anatomically asymmetrical runners move more asymmetrically at the same metabolic cost. PLoS ONE 8(9):e74134
Stolze H, Kuhtz-Buschbeck JP, Mondwurf C, Boczek-Funcke A, Jöhnk K, Deuschl G, Illert M (1997) Gait analysis during treadmill and overground locomotion in children and adults. Electroencephalogr Clin Neurophysiol 105(6):490–497
Thaut M, Abiru M (2010) Rhythmic auditory stimulation in rehabilitation of movement disorders: a review of current research. Music Percept 27(4):263–269
Turchet L, Serafin S (2013) Investigating the amplitude of interactive footstep sounds and soundscape reproduction. Appl Acoust 74(4):566–574
Turchet L, Serafin S, Dimitrov S, Nordahl R (2010a) Physically based sound synthesis and control of footsteps sounds. In: Proceedings of digital audio effects conference, pp 161–168
Turchet L, Nordahl R, Berrezag A, Dimitrov S, Hayward V, Serafin S (2010b) Audio–haptic physically based simulation of walking on different grounds. In: Proceedings of IEEE international workshop on multimedia signal processing. IEEE Press, pp 269–273
Turchet L, Serafin S, Cesari P (2013a) Walking pace affected by interactive sounds simulating stepping on different terrains. ACM Trans Appl Percet 10(4):1–14
Turchet L, Pugliese R, Takala T (2013b) Physically based sound synthesis and control of jumping sounds on an elastic trampoline. In: Proceedings of the 4th interactive sonification workshop, pp 87–94
Zanetti C, Schieppati M (2007) Quiet stance control is affected by prior treadmill but not overground locomotion. Eur J Appl Physiol 100(3):331–339