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Abstract

In sport visual feedback is often used to enhance performance, mostly neglecting the auditory modality. However, athletes produce natural sounds when they move (acoustic reafferences) which they perceive and use to control their movements. We examined the short- and long-term effects of a training intervention on a complex movement by using acoustic reafferences. Natural step sounds produced during hurdling were recorded and played back to the participants immediately before each trial, with an increase (fast group), decrease (slow group), or no manipulation (control group) in the tempo. All groups increased their hurdling performance regarding overall running time, with the slow group showing the best performance development. After a 10-week retention, the fast and slow group further increased performance, whereas the control group declined. The repeated experience with acoustic information associated with the rhythmic pattern of hurdling may have helped developing a cognitive representation of that movement, especially regarding long-term effects.

Keywords: auditory, intrinsic, feedback, hurdling, perception

Training with acoustic reafferences

“Did you hear that? That was a good take-off”, the coach says to his athlete after yet another long jump attempt during training. Statements such as this are quite regularly heard on the field or in the gym during training. Providing feedback is considered one of the most important aspects for learning and optimizing motor skills (Schmidt & Lee, 2011). However, feedback typically focuses on the visual sense and is provided by an external source. This extrinsic or augmented feedback (for an overview on studies in this area, see Sigrist, Rauter, Riener, & Wolf, 2013) provides information in addition to the sensory-perceptual information which in turn is based on exteroceptors and interoceptors of the human body, also called intrinsic feedback (Schmidt & Lee, 2011). For movement calibration, the actual sensory feedback as a consequence of motor action is compared to predicted feedback through internal models simulating the consequences of an action. This process is also referred to as the reafference principle (Blakemore, Wolpert, & Frith, 2000; Desmurget & Grafton, 2000; Wolpert & Flanagan, 2001). Although such intrinsic feedback including visual, acoustic, and tactile information accompanies every movement, the focus of performers and of coaches is usually on the visual sense using augmented feedback. Much less is known about the acoustic sense and what role it plays in linking perception and motor performance as part of internal feedback. Considering that rhythm is a basic principle of many actions and this can be optimally represented via acoustic information, the aim of the current study was to examine whether acoustic reafferences can be used to optimize movements on a short- and long-term basis.

Mostly research has addressed the link between motor perception and motor execution by focusing on augmented feedback, specifically with respect to the visual sense. However, just recently, a review by Sors, Murgia, Santoro, and Agostini (2015) provided an overview of audio-based interventions, concluding that future studies should focus on the type of intervention and the auditory stimuli used as well as the implementation of such interventions into applied sporting contexts. Taking into account auditory information of complex sporting movements, Pizzera and Hohmann (2015) provide an overview of the current literature on this topic. The authors distinguish three dimensions regarding the use of auditory information. First, authorship describes the discrimination between one's own and other movement sounds. Second, timing refers to action-perception processes running either concurrently (online) or temporally separated (offline). Taking the example from above, the athlete may hear the take-off sounds while performing the take-off itself (online) or receive feedback on the take-off sounds after his or her performance from the coach (offline). Third, the type of feedback characterizes whether athletes use their own internal feedback system or external sources of information for optimizing performance. With respect to external acoustic information, athletes can receive help by the sonification technique. Physical and/or kinematic parameters of the movement are conversed into a synthetic sound, supplying meaningful information of parameter variation (Dubus & Bresin, 2013). Studies have revealed a positive effect of the use of sonification during the motor learning process on motor performance (for an overview, see Effenberg, 2005). However, Pizzera and Hohmann concluded that only a few studies addressed how natural as opposed to artificial sounds occurring as a byproduct of movement contribute to the control and learning of complex whole-body movements.

One study with golfers addressed the tight link between action and auditory perception of complex whole-body movements. The results revealed that athletes were able to discriminate sound recordings of their self-generated movement from recordings of another's movements (Murgia, Hohmann, Galmonte, Raab, & Agostini, 2012). In a study using basketball movements, athletes were even able to predict the final running direction of opponents from their natural sounds alone (Camponogara, Rodger, Craig, & Cesari, P. (2017). The authors suggested that the athletes picked up and used the relevant kinematic features of deceptive movements to guide their own movements for successful interception. And not only movement sounds of the opponent can be used, but also the sounds of balls while hitting them, to gain valuable information for the own appropriate motor response. For instance, volleyball athletes showed to be quite accurate in discriminating shot power of smashes based on auditory information (Sors et al., 2017). Accuracy was also higher compared to the use of visual information. This difference was not found for the estimation of shot power of penalty kicks. In an attempt to compare discrimination performance between own and other sounds, hurdlers showed to be able to discriminate identical and different sound pairs, independent of the agent, and identified their own movement sounds significantly better than strangers' sounds (Kennel, Hohmann, & Raab, 2014; Kennel et al., 2014). The results suggest that athletes are experts for their own movements and seem to perceive them somehow during movement execution. Therefore, athletes should also be able to discriminate expert from novice sounds with the aim to use expert sounds for movement enhancement. Referring to the above-described timing of action-perception processes, auditory perception can influence action momentarily (online) but can also exert long-term effects (offline) expressed through the development of controlling motor skills, also known as motor learning.

On a behavioral level, auditory perception was shown to influence the control of bodily movements. Specifically, the walking speed and gait period of participants changed systematically when auditory feedback was delayed (Menzer et al., 2010). Similarly, in a study with hurdlers, participants were instructed to clear four hurdles with a three-step rhythm between the hurdles (Kennel et al., 2015). The authors invented a feedback apparatus that participants wore as a belt around the waist; the device recorded the participants' step sounds and immediately gave auditory feedback. The delayed feedback condition (180-ms delay) significantly reduced overall running time and changed kinematic parameters, whereas white noise showed no effects. To sum up, auditory information appears to have an effect on an internal level and to disrupt performance on an external level, if this information does not match the expected feedback.

Regarding long-term effects, researchers have also examined whether acoustic information might even support motor learning. The only study so far conducted with natural movement sounds showed that hammer throwers optimized their performance via training with auditory feedback (Agostini, Righi, Galmonte, & Bruno, 2004). The sounds were generated by recording the movement of the hammer flying through the air. These natural movement sounds were then played back as auditory feedback to the participants while training. Training consisted of a single training session of 10 trials, during which participants listened to their best personal throw five times before each throw. As a result, all athletes improved and standardized their performance. A limitation of the study is the small size of five expert athletes and the fact that athletes performed only one training session. However, this is, to the best to our knowledge, the only study conducted with complex natural movement sounds for training purposes, providing a good basis for further investigations in this area.

Our study aimed at overcoming these limitations and extending investigations on training with acoustic reafferences, specifically examining offline effects of acoustic perception on action, to achieve long-term effects. Using the reafference principle as a basis for understanding the contribution of natural acoustic feedback for training and optimizing complex movements, we chose the task of hurdling, as it represents a typical rhythmic structure that can be nicely depicted through sound (MacPherson, Collins, & Obhi, 2009). Considering that the technique of top-level hurdlers is characterized by a stable and structured running pattern based on temporal structure, whereas that of unpracticed hurdlers shows problems of spatiotemporal adaptation and regulation on approaching hurdles (Hay & Schöbel, 1990), we assumed that a focus on audition during skill acquisition should be beneficial.

On the basis of the law of practice, we predicted that all athletes would increase their short-term hurdling performance independent of experimental group, due to training or practice (Guadagnoli & Lee, 2004; Schmidt & Lee, 2011). In addition, referring to the study by Agostini et al. (2004), we hypothesized that optimized acoustic feedback (own best practice, because humans are experts of their own movement sounds) would lead to greater hurdling performance increases and positive long-term effects (retention after break). Since the ultimate goal in hurdling is to decrease overall running time, a faster tempo of the same rhythmic structure displayed through acoustic feedback was predicted to lead to better performance (as shown by a decrease in overall running time). We hypothesized that the faster tempo would lead to a more expert-like representation and therefore enhance overall performance. In addition, shorter overall running time can only be achieved by improving movement technique, as depicted by spatiotemporal parameters (Hay & Schoebel, 1990). Specifically, to reduce overall time, both ground and air times should be as short as possible, which can be achieved by proper body-segment positioning before and after the hurdle (Mann & Herman, 1985). Due to the relation between distance and time, a shorter flight time over the hurdle is the result of shorter flight distance and flight height. Taking into account the link between spatiotemporal parameters and rhythm, we predicted an improvement in movement technique due to optimized acoustic feedback, as depicted by different kinematic parameters.

On the basis of the hurdles study by Kennel et al. (2015), in which a delayed online feedback condition significantly increased overall running time and changed kinematic parameters, we further sought to test whether such effects also account for offline acoustic perception and action links.

Methods

Participants

We recruited 39 sports students (18 women, 21 men; $M_{\text{age}} = 22.30$ years, $SD = 5.46$) with hurdling experience gained through university courses in track and field or training sessions as part of their sport. Participants were randomly assigned to three groups. Because all participants were active athletes, some suffered injuries and were not able to complete the study. This led to an uneven distribution of participants in the different groups. Hurdling experience and gender, however, were matched across groups. The fast group (*n* = 12; seven women, five men) received acoustic feedback during training that depicted a faster running velocity than that recorded at the pretest; the slow group (*n* = 12; five women, seven men) trained with slower running velocity sounds; and the control group (*n* = 15; six women, nine men) trained with their original sounds, recorded at pretest. All participants provided written informed consent prior to the study and they were not informed about the experimental hypotheses. After completion of the study they were debriefed about the experimental hypotheses and the group they had belonged to. Additionally they received €10 per participation hour. The study was approved by the local university's ethics committee.

Task

The participants were asked to clear four hurdles with the normal hurdle rhythm of four steps between hurdles and seven to nine steps to the first hurdle. The distance from the start (out of a starting block) was 11.50 m for women and 12.80 m for men, and the distance between hurdles was 7.60 m (women) and 8.30 m (men). The height of the hurdles (Erhard Sport, Geslau, Germany) was 84 cm for women and 91.4 cm for men. These dimensions (slightly lower than the official competition norms for 100/110-m hurdles of the International Association of Athletics Federations) turned out to be optimal for novice to intermediate hurdlers in a pilot study as well as in previous studies (Kennel, Hohmann, & Raab, 2014; Kennel et al., 2014, 2015). After one or two warm-up trials, we recorded five valid attempts (correct number of steps) of every participant with no acoustic start signal so that participants could start whenever they were ready.

Materials

Time and kinematic data served as performance measures of the movement task. Overall time was measured by double light barriers (SPORTRONIC Double Infrared

Photoelectric Barriers, DLS/F03) with the first light barrier placed at the starting point (5 m after the starting block to disregard individual reaction time) and the second at 40 m (directly after the fourth hurdle). Two-dimensional kinematic data were collected at the third hurdle, assuming peak velocity based on analysis of the 100-m and 110-m hurdling races at the track and field World Championship 2010 (Graubner & Nixdorf, 2011). A high-speed camera (Casio EX-FH100) was used with 120 frames/s recording speed, a resolution of 640 × 480 pixels, and a 2 × 2 calibration square. The camera was placed 5.50 m away and orthogonal to the movement plane.

The auditory data were collected on a Tartan track at the local university. Movement sounds were recorded binaurally with Soundman OKM classic in-ear microphones (sensitivity: 5 mV Pa^{-1} ± 3 dB). An A3 adapter (input impedance = 1 kΩ; output impedance = 47 kΩ) was plugged in between the microphones and the recording equipment (Zoom H1 Handy Recorder; 24 bit/96 kHz/320 kbps) to obtain a low noise floor. To protect the microphones against rustling noises while the athletes were running, we used an acrylic windshield.

To develop the acoustic feedback stimuli, we used the audio editor Audacity 2.0.3. (Audacity Team, 2014). We cut the movement sounds so that each stimulus contained the full run (first step from the starting block to the flight phase over the last hurdle). Depending on the group, we either kept the original sound (control group) or manipulated the tempo of the run while retaining the rhythm (intervention groups). For the fast group, we increased the tempo by 10%, 15%, and 20% by cutting 10%, 15%, and 20% off the flight phase for each individual step, respectively. For the slow group we added 10%, 15%, and 20%, respectively. Tempo was gradually increased or decreased after two training sessions, so that participants would not suspect any experimental manipulations. Participants therefore always trained with the new tempo for two training sessions. In addition, we added a short verbal instruction at the beginning of the audio file: “Following this instruction, you will hear two movement sounds.

Please listen carefully and concentrate well on the sound." As stated in the verbal instruction, the acoustic feedback stimulus was then played two times.

Procedure

Recording sessions. In total, participants had to complete a pretest, six training sessions, a posttest, and 10 weeks later, a retention test (see Figure 1). The trainings sessions were completed within two to three weeks, with two/three training sessions each week. We assessed the participants' time and kinematic data four times: At the beginning of the experiment (pretest), halfway through the training phase after three training sessions (midtest), at the end of the training phase (posttest), and after the posttest (retention test). During each test, participants performed five trials.

*** Figure 1 near here***

Training sessions. The participants completed 30 trials altogether during the training intervention, with six training sessions of five trials each. For organizational reasons and to keep a tight protocol, participants trained in groups of three. Groups were formed based on time availability of the participants, leading to a random distribution regarding their experimental condition. During each training session, participants first listened to their individual audio file via headphones and then immediately stepped into the starting block and ran the 40-m hurdles track as described in the task. One minute after Participant 1, the second participant started with listening to the audio file and again 1 min later, Participant 3. This procedure was repeated five times and ensured that participants each had a pause of 3 min between trials to reduce possible effects of different training protocols.

Analyses

For both time and kinematic data, we took the best three trials (out of five) of each test and calculated the mean, since some participants did not successfully clear all four hurdles in all five trials. The kinematic data were analyzed using the movement analysis software utilius easyINSPECT (CCC Software, Markkleeberg, Germany). Selected parameters for movement quality include distances (meters = m) and time (seconds = s): distance of the last step to the hurdle (distance before hurdle), vertical distance between hurdle and trochanter (vertical distance), distance from the hurdle to the landing leg (distance after hurdle), distance between takeoff and landing (stride length), foot–ground contact time before and after the hurdle (takeoff step duration and landing step duration), and flight time (Čoh, 2002; Čoh & Iskra, 2012). Outlier correction was performed for 2.5% outliers in total, using the Winsorizing method, by replacing each outlier with the next highest score of the group in the respective condition (Field, 2013).

To examine the effect of the training intervention on hurdling performance, we performed separate 4 × 3 (Test × Group) repeated-measures analyses of variance (ANOVAs) for each of the individual dependent variables, with test (pre, mid, post, retention) as within-group variable and group (fast, slow, control) as between-group variable. Movement time and the above-described seven movement quality measures served as the dependent variables. This procedure was chosen because there was a mix of positively correlated and uncorrelated dependent variables, which is not recommended for applying a multivariate ANOVA and because our hypotheses were not strictly multivariate in nature (Tabachnik & Fidell, 2007). In addition, one-way ANOVAs for each variable confirmed that there was no significant difference between the groups in the pretest. To control for the family-wise Type I error, we applied the Holm’s correction (Knudson, 2009). When the sphericity assumption was violated, the Greenhouse–Geisser correction was used. Effect sizes were calculated as partial eta-squared values (η_p^2) and are reported only for $F > 1$. A significance criterion of $p = .05$ was established for all results reported.

Results

Time data

All participants decreased their overall running time from pretest to retention test (fast group: by 189 ms, slow group: by 383 ms, control group: by 55 ms), as shown by a significant main effect of Test, $F(2.49, 89.76) = 15.71$, $p < .01$, $\eta_p^2 = .30$. Figure 2 shows that this was mainly due to the two intervention groups, who also further increased their performance from posttest to retention test, whereas the performance of the control group declined, as indicated by an interaction effect, $F(4.99, 89.76) = 2.69$, $p = .026$, $\eta_p^2 = .13$. However, after applying Holm's correction, the p value stayed above the adjusted critical p value of .006. There was no main effect of group.

*** Figure 2 near here***

Kinematic data

For the kinematic data, all participants showed significant decreases with regard to vertical distance, $F(2.37, 85.16) = 28.51$, $p < .01$, $\eta_p^2 = .44$, distance after hurdle, $F(3, 108) = 6.39$, $p = .001$, $\eta_p^2 = .15$, and landing step duration, $F(3, 108) = 9.48$, $p < .01$, $\eta_p^2 = .21$, after applying the Holm's correction. In addition, there was a Test × Group interaction effect for distance after hurdle, $F(6, 108) = 2.22$, $p = .046$, $\eta_p^2 = .11$, and stride length, $F(4.85, 87.36) = 4.17$, $p = .002$, $\eta_p^2 = .19$, reflecting the different learning curves between the two intervention groups and the control group (Figure 2). However, after applying the Holm's correction, only the latter stayed under the adjusted critical p value. There was no significant main effect of group for any of the kinematic data. For an overview of the means and standard deviations of the time and kinematic data, see Table 1.

*** Table 1 near here***

Discussion

The aim of the current study was to examine the effect of a training intervention on a complex whole-body continuous movement by using acoustic reafferences. Natural movement sounds of the steps produced during hurdling were recorded and played back to the participants immediately before each trial, with an increase (fast group) or decrease (slow group) in the tempo. The effects of the intervention were examined using time and kinematic data.

First, the results confirmed our hypothesis based on the law of practice (Schmidt & Lee, 2011), in that all groups increased their hurdling performance with respect to overall running time. These results replicate many studies that found a generalizability of the relationship between practice and skill, resulting even in a law on practice (Guidagnoli & Lee, 2004). Our hypothesis that the fast group would show a greater increase in performance than the control group was not confirmed. In addition, we predicted that the slow group would decrease performance. However, there was no clear prediction as to whether this manipulation would reduce the law of practice effect, with performance showing no change, or indeed overrule the law of practice effect and result in a decreased performance. Contrary to our general prediction of a decrease or no change in performance, the slow group also showed an increase in performance, which, on a descriptive level, was even higher than in the other two groups (overall running time reduction of 383 ms as opposed to189 and 55 ms of the fast and control group, respectively). On a long-term basis and as predicted, the fast group further increased performance after no training in the retention period of about 10 weeks. Interestingly and contrary to our prediction, so did the slow group, whereas the control group showed a significant performance decline. It seems that focusing on the rhythm of the run in general, which was displayed acoustically, may have triggered movement calibration. Specifically, the repeated experience with acoustic information associated with the rhythmic pattern of hurdling may have helped the participants develop a template or cognitive representation of that movement.

With regard to the reafference principle (Blakemore et al., 2000; Desmurget & Grafton, 2000; Wolpert & Flanagan, 2011), it is speculated that acoustic feedback is used together with internal models to predict action consequences and compare them to actual feedback while running. Hence, the fast group tried to adjust their tempo to the faster tempo they had heard immediately before running, while the slow group somehow subconsciously perceived the tempo to be slower and tried to be even faster. This was partly reflected in the comments of the participants during the debriefing in post-experimental interviews. When asked if they had noticed anything with regard to their individual audio file, most of the participants reported that they had not noticed anything. Some of the participants of the slow group reported that they had perceived the sound to be slower, which in turn motivated them to try to run even faster during the next trial. This motivational aspect was not examined in this study but could be added in a follow-up study. Another aspect might be that rhythm, which is quite important for this movement, may have become more apparent and clear to the participants, similar to effects found for using slow motion for visual feedback (Scully & Carnegie, 1998; Ste-Marie et al., 2012).

Second, our prediction that all participants would show an increase in movement technique was partly confirmed. In four of the seven kinematic parameters participants showed a significant decrease, representing enhanced performance. Again, this was independent of the group, except for stride length. However, Figure 2 nicely shows how the learning curves of the two intervention groups are mostly similar, while the control group differs. Therefore, it seems that the participants used the manipulated acoustic feedback for their movement execution/control, which confirms earlier studies that have revealed effects of natural acoustic feedback on movement control (Kennel et al., 2015; Menzer et al., 2010) and optimization through short-term training (Agostini et al., 2004). Still, although general effects were found, these are in contrast to the direction of the effect found in previous studies. Namely, delayed acoustic feedback during movement execution was shown to disturb the control of movements, as indicated by a decrease in walking speed (Menzer et al., 2010) and running time in hurdling (Kennel et al., 2015). In the current study, slower and faster acoustic feedback showed similar effects, which might be because an offline paradigm for training purposes was used, as opposed to manipulating acoustic feedback during movement execution.

One methodological limitation of the current study was the lack of a real control group that received no feedback. In our study the control group trained for the same length of time as the other two groups while also listening to their own movement sounds. The only difference was that they listened to their original sounds that were not manipulated. Although we believe that this kind of group is also necessary to rule out any general acoustic feedback effects, an additional training group without any feedback needs to be added as well in future studies to rule out increased motivation and attention due to new training methods. In addition, sample size was quite small and reliable effects need replications with larger power. However, with such a complex study design and injury dropouts due to the participants' main sports throughout the intervention phase, it was quite difficult to maintain equal and high numbers of participants per group.

From a practical point of view, this study poses some new implications. The participants, especially in the two intervention groups, were able to increase their hurdling performance after six weeks of training with acoustic feedback and only five trials per training session and maintain or even further improve their performance after a 10-week break. This improvement of up to 383 ms is quite astonishing especially when considering that this was achieved for a distance of only 35 m. In addition, most of the participants were low-level hurdlers and received no other feedback (visual or verbal) during the training intervention. The recording apparatus is also easily usable, consisting of an mp3 player, in-ear microphones, and an acrylic windshield. Overall, we would encourage practitioners, besides visually recording motor performance, to also acoustically record motor performance in order to use a multisensory approach for feedback and training purposes. This can be done in two ways, either by using artificial sound for variables of motor performance that do not make any noise (method of sonification, which is different from using acoustic reafferences; see Effenberg, 2004 or Schaffert, 2011) or to use natural movement sounds as we have done in the current study.

To the best of our knowledge, no study so far has examined the effects of natural acoustic feedback on a complex continuous movement, also taking into account long-term effects. The current study revealed that a manipulation of the tempo of the hurdling rhythm can lead to positive short-term as well as long-term effects with respect to overall running time and kinematic data. Training to optimize movement should therefore include more than the visual sense, in that the acoustic sense might help unravel hidden movement concepts or rhythmic information for such complex movement techniques as those used in hurdling.

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