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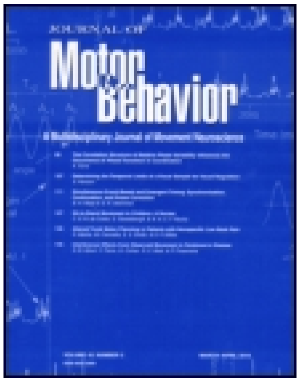

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RESEARCH ARTICLE

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ABSTRACT. Augmented feedback, provided by coaches or displays, is a well-established strategy to accelerate motor learning. Frequent terminal feedback and concurrent feedback have been shown to be detrimental for simple motor task learning but supportive for complex motor task learning. However, conclusions on optimal feedback strategies have been mainly drawn from studies on artificial laboratory tasks with visual feedback only. Therefore, the authors compared the effectiveness of learning a complex, 3-dimensional rowing-type task with either concurrent visual, auditory, or haptic feedback to self-controlled terminal visual feedback. Results revealed that terminal visual feedback was most effective because it emphasized the internalization of task-relevant aspects. In contrast, concurrent feedback fostered the correction of task-irrelevant errors, which hindered learning. The concurrent visual and haptic feedback group performed much better during training with the feedback than in nonfeedback trials. Auditory feedback based on sonification of the movement error was not practical for training the 3-dimensional movement for most participants. Concurrent multimodal feedback in combination with terminal feedback may be most effective, especially if the feedback strategy is adapted to individual preferences and skill level.

Keywords: augmented feedback, haptic guidance, movement sonification, self-controlled feedback, skill learning

Augmented feedback is a well-accepted strategy to accelerate motor skill learning. Augmented feedback provides information about motor performance or result, presented by an external source, such as a trainer, therapist, or display (Schmidt & Wrisberg, 2008). To be successfully applied, research has aimed to determine optimal feedback principles with respect to frequency, delay, focus of attention, and content, among others (Schmidt & Wrisberg, 2008; Wulf & Shea, 2002). In the past, simple or artificial tasks rather than real-life complex tasks have been investigated, mainly because the related paradigms are more straightforward to test, to set up, and to analyze. However, Wulf and Shea stated that feedback principles derived from simple tasks cannot be transferred to complex motor tasks. In particular, it seems that the guidance hypothesis proposing that concurrent or frequent feedback is detrimental for motor learning due to emerging dependency on the feedback (Salmoni, 1984; Schmidt, 1991; Schmidt, Young, Swinnen, & Shapiro, 1989), holds true for simple tasks (Schmidt & Wulf, 1997; Van der Linden, Cauraugh, & Greene, 1993; Winstein et al., 1996), but not for complex tasks (Marschall, Bund, & Wiemeyer, 2007; Swinnen, Lee, Verschueren, Serrien, & Bogaerds, 1997; Wulf, Shea, & Matschiner, 1998). In an early stage of complex task learning, concurrent feedback may accelerate learning by mediating a general idea of the movement (Huegel & O'Malley, 2010; Liebermann et al., 2002) and by preventing cognitive overload (Wulf & Shea, 2002). Indeed, concurrent visual feedback has facilitated learning of different complex tasks (Kovacs & Shea, 2011; Snodgrass, Rivett, Robertson, & Stojanovski, 2010; Swinnen et al., 1997; Todorov, Shadmehr, & Bizzi, 1997; Wishart, Lee, Cunningham, & Murdoch, 2002; Wulf, Hörger, & Shea, 1999). Research on feedback principles such as the guidance hypothesis has predominantly addressed the visual modality, thereby neglecting a comparison with feedback in other modalities such as auditory and haptic feedback (Sigrist, Rauter, Riener, & Wolf, 2013).

Concurrent augmented visual feedback may interfere with motor tasks that depend on visually perceived information. In such tasks, the attention on the environment and the augmented feedback compete and may overload the learner. Auditory feedback might be less interfering and distracting as, in contrast to visual information, neither a specific focus on the display nor a specific orientation of the head in space is required (Eldridge, 2006; Grond, Hermann, Verfaille, & Wanderley, 2010; Secoli, Milot, Rosati, & Reinkensmeyer, 2011). Auditory feedback such as movement sonification (i.e., the mapping of a movement variable to a parameter of sound such as pitch or volume) enhanced learning of time-dependent dynamic coordination in rowing (Effenberg & Mechling, 1998) and swimming (Chollet, Madani, & Micallef, 1992; Chollet, Micallef, & Rabischong, 1988). In a task on the German Wheel, which is a large wheel for gymnastics, movement sonification was only effective for experts, but not for novices (Hummel, Hermann, Frauenberger, & Stockman, 2010). This supports the assumption that the effectiveness of movement sonification is limited to athletes who already have a high skill level and thus can interpret the sonification and relate it to an optimal movement (Sigrist et al., 2013). Novices may not benefit, as they cannot estimate how the optimal movement should sound. To support also novices, error sonification may be effective (i.e., the auditory representation of the current deviation from a target movement to a parameter of sound, instead of directly mapping the movement variable to a parameter of sound as done in movement sonification). In a study on pistol shooting, mapping of the deviation from the aiming point to changes in pitch was more effective than feedback about the score only, i.e., knowledge of results (Konttinen, Mononen, Viitasalo, & Mets, 2004; Mononen, 2007). Although multidimensional error sonification is very challenging to design, it has already

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been shown to be interpretable for a rowing-type movement (Sigrist, Schellenberg, et al., 2011). However, its effectiveness in enhancing complex motor learning has not yet been evaluated.

Haptic guidance is another possibility for providing concurrent augmented feedback. Haptic guidance leads a person through or toward a target movement by addressing kinesthetic and sometimes also tactile perception. In contrast to visual or auditory feedback, haptic guidance can completely restrict the movement to the desired one (e.g., by a robot in position control; Bluteau, Coquillart, Payan, & Gentaz, 2008; Liu, Cramer, & Reinkensmeyer, 2006). However, it is believed that some freedom in performing the movement is needed. First, because errors drive motor learning (Emken, Benitez, & Reinkensmeyer, 2007; Patton, Stoykov, Kovic, & Mussa-Ivaldi, 2006; van Beers, 2009) and, second, to prevent passivity (Israel, Campbell, Kahn, & Hornby, 2006) and slackness (Reinkensmeyer, Akoner, Ferris, & Gordon, 2009) of the user that may hinder motor learning (Shadmehr & Mussa-Ivaldi, 1994). According concepts have often been based on a path controller (Khatib, 1986; Rauter et al., 2010; Rauter, Sigrist, Marchal-Crespo, et al., 2011; Vallery, Guidali, Duschau-Wicke, & Riener, 2009). A path controller is a controller that provides spatial guidance using, for example, conservative force fields to generate a virtual tunnel/path with elastic walls (Duschau-Wicke, von Zitzewitz, Caprez, Lunenburger, & Riener, 2010; Marchal-Crespo, Rauter, Wyss, von Zitzewitz, & Riener, 2012). Such a haptic guidance concept outperformed a control group without haptic guidance in terms of driving accuracy in a steering task (Marchal-Crespo & Reinkensmeyer, 2008) and in a wheelchair driving task (Marchal-Crespo, Furumasu, & Reinkensmeyer, 2010). However, complex tasks or even sportive tasks have not been investigated to date.

In summary, studies on concurrent augmented feedback in complex motor learning have rarely considered the auditory or haptic modality. Furthermore, training with one feedback strategy has usually been compared to training without feedback or to another feedback strategy of the same modality. However, in order to optimize motor learning in general, the effects of feedback strategies provided in different modalities should be systematically exploited (Sigrist et al., 2013). Thereby, it is important to consider the interaction of the feedback presentation with the stage of learning (Magill & Anderson, 2012). Consequently, in this study, we compared and contrasted learning of groups that trained a complex, multidimensional rowing-type task in several sessions with either concurrent visual, auditory, or haptic feedback.

A control group trained with terminal self-controlled feedback (i.e., feedback provided after task execution) where the time point and frequency of feedback were selected by the learner. A self-controlled feedback strategy was applied because it has been shown to be more effective than an externally imposed feedback strategy (Chiviacowsky & Wulf, 2002, 2005; Huet, Camachon, Fernandez, Jacobs, & Montagne, 2009; Janelle, Barba, Frehlich, Tennant, & Cauraugh, 1997; Janelle, Kim, & Singer, 1995). Benefits of a self-controlled strategy are seen in the adaptation to the learner's needs, focus on the current aspect the learner wants to train, and involvement of the learner in the learning process resulting in an increased motivation (Wulf, 2007). In this study, terminal feedback was delayed for 10 s in order to enable self-estimation and information processing (Swinnen et al., 1990; Winstein, 1991).

We hypothesized, first, that the benefits of terminal feedback should be observable only after the initial learning stage (i.e., after a few training sessions) because the learners must first develop a general internal movement representation to which the terminal feedback could be compared to. Second, in contrast, concurrent visual and haptic feedback should accelerate learning in a very early stage because they should effectively mediate the general idea of the complex movement and, thus, the understanding of the movement pattern. Thereby, visual feedback should be most beneficial for learning spatial aspects of the trajectory (Feygin, Keehner, & Tendick 2002), due to the distinctive ability of humans to visually perceive spatial information (Freides, 1974; Nesbitt, 2003; Welch & Warren, 1980). Haptic feedback should contribute most to learning of temporal (Feygin et al., 2002) but also of spatiotemporal features (Marchal-Crespo et al., 2010; Marchal-Crespo & Reinkensmeyer, 2008) as haptic perception is well developed for both aspects (Nesbitt, 2003). One—dimensional error sonification was shown to reduce a spatial error (Konttinen et al., 2004; Mononen, 2007). Thus, third, we hypothesized that the three-dimensional error sonification would facilitate motor learning; however, a longer familiarization time to the auditory feedback is expected than to the visual, haptic, or terminal feedback.

Method

Participants

All 36 participants (8 women, 28 men; age range = 22–40 years; *M* age = 28 years, *SD* = 3.7 years) were healthy, nonrowers, without prior experience of the task, and had normal hearing and normal or corrected-to-normal vision. The participants signed an agreement following the guidelines of the local ethics commission, which had approved the study.

Apparatus and Task

During each experiment, the participant was seated in an actual (trimmed) rowing boat, set up in the middle of a CAVE (Cave Automated Virtual Environment; von Zitzewitz et al., 2008). Reflective markers were attached to a trimmed sweep rowing oar to track its movement with an optoelectrical motion tracking system (Qualisys, Gothenburg, Sweden). The kinematic data were used to virtually elongate the physical oar in real-time on a 4.44 m × 3.33 m screen as well as to provide input for the concurrent visual, auditory, and terminal feedback, and to analyze movement errors at 62.5 Hz. Standard headphones (Sennheiser HDR 170, GmbH & Co.

KG, Wedemark Wennebostel, Germany; frequency response: 18Hz to 21kHz) were used to display the auditory feedback. The haptic augmented feedback was realized via a rope-robot attached to the end of the trimmed oar (Rauter et al., 2010). The horizontal and vertical oar angles were thereby measured with the rope robot, while the blade rotation was computed from the data of two wire potentiometers at 1000 Hz. During the entire study, the rope robot was attached to the end effector (i.e., the outer end of the trimmed oar) for the participants of the haptic group only.

The task to be learned was very similar to body-arm rowing taught to beginners in their first rowing lessons and used by experienced rowers as a warm-up exercise. The participant moved the sweep rowing oar with both hands and both arms as well as the trunk, without moving the legs. The requested rowing-type oar movement required a horizontal range of the outer hand of about 25° (0.50 m) and a vertical range of about 13° (0.26 m). As in real rowing, the blade had to be turned to a vertical orientation (about 90°) before it was pulled (drive phase) and turned to a flat orientation (0°) when it was pushed (recovery phase). To increase task complexity, an angular velocity profile that is typical for rowing, was applied to the oar movement (i.e., the angular velocity was two times higher in the pulling phase than in the pushing phase). As water resistance was not simulated in this study, the participant only felt the inertia and the remaining friction of the oar throughout the whole movement. One cycle lasted 6 s, resulting in a stroke rate of 10 strokes/min.

Feedback Designs

Concurrent Visual Feedback

The visual feedback was created according to an evaluation of different designs performed in a prior study (Sigrist, Schellenberg, et al., 2011). The feedback consisted of a superposition of the virtual blade on the transparent virtual target blade, which was moving along the displayed target trajectory (Figure 1). The feedback was programmed in Lua (Ierusalimschy, 2013; http://www.lua.org).

Concurrent Auditory Feedback

Conclusions from earlier experiments revealed that unimodal auditory feedback for a three-dimensional rowing-type movement is unambiguous and practical if the current deviation from the target is sonified in each degree of freedom separately (Sigrist, Schellenberg, et al., 2011). Therefore, the auditory feedback applied in this study was based on the error sonification introduced in earlier experiments. The deviation from the target oar was mapped to a sound modulation. Changes in stereo balance represented changes in horizontal deviation, changes in pitch represented changes in vertical deviation, changes in volume represented the combined vertical and horizontal deviation, and a modulated timbre represented incorrect blade orientation (Figure 2).

Stereo balance (i.e., information from the left and right headphones) was correlated to the horizontal deviation. The deviation was minimal when a center-balanced signal (volume left channel = volume right channel) was heard. To facilitate the interpretation of stereo balance mapping, the participant was instructed to orient the head toward the outer end of the real oar.

Pitch is commonly described by terms such as high or low; therefore, vertical deviation was mapped to pitch. The frequency for a correct vertical angle was 370 Hz (f#0). Around this frequency, the pitch ranged within ±0.9 octaves

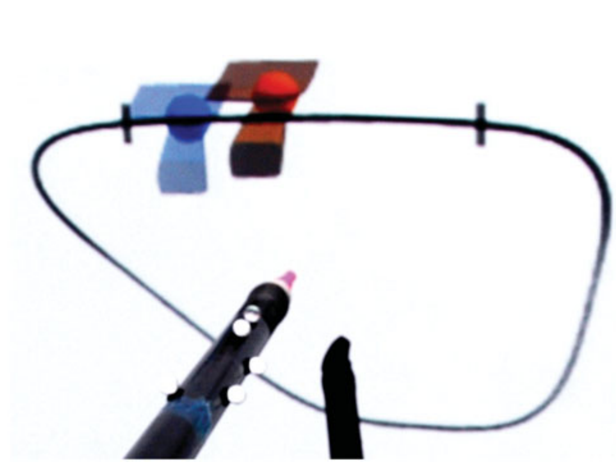

FIGURE 1. Superposition-based visual feedback. The virtual elongation of the oar in brown was superimposed on a transparent virtual target oar in blue, moving along the target trajectory. The brightness of the target trajectory indicated the target oar velocity (the brighter, the faster). Vertical bars on the target trajectory indicated the location of blade rotation. To enhance the perception of the relation of the oar blade positions in relation to the target trajectory, virtual spheres were attached to the blades. (Color figure available online).

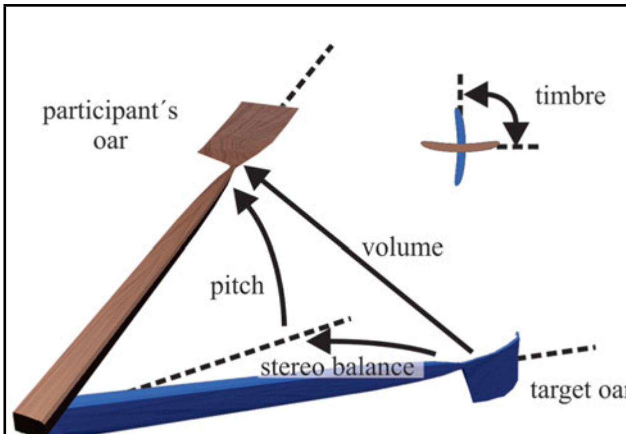

FIGURE 2. Auditory feedback mapping. The deviation from the participant's oar to the target oar was represented by modulations of stereo balance, pitch, volume, and timbre. (Color figure available online).

because an interval of 1.0 octave could be misinterpreted as being correct.

Additionally, the signal volume represented the combined deviation of the horizontal and vertical angles (with less volume indicating less deviation) to augment the perception of the total deviation. For no deviation, the signal was played at 10% of the maximal volume.

Deviations greater than 5° were displayed with the maximal signals of stereo balance (the signal only played on the left or right headphone), pitch (±0.9 octaves), or volume. Deviation values below 0.5° were neglected and displayed as being correct in order to make the signal steady within this interval. The participant was thus able to hear a correct signal within the specified dead zone. A direction-indicative polarity was applied for the stereo balance and pitch mapping (i.e., the signal indicated in which direction the participant should move the blade to decrease the deviation). For example, sound on the right headphone indicated the need to move the blade to the right and a high pitch signaled to lift the oar blade. A direction-indicative polarity was found to be more practical than an inverted one (Sigrist, Schellenberg, et al., 2011).

Finally, correct blade orientation was mapped to a euphonic and pleasant acoustic sine wave. Incorrect orientation was mapped to a raspy acoustic saw tooth wave. Orientation angles between 0° and 90° were assigned to the closer angle of these two states so that the mapping of timbre to blade orientation was binary. Note that this mapping as well as pitch, stereo balance, and volume mapping worked independently; for details on the mapping functions see Experiment 2 of Sigrist, Schellnberg, et al. (2011). The auditory feedback was programmed in C++ (Microsoft Corporation, Redmond, WA).

Concurrent Haptic Feedback

The haptic feedback of the rope-robot was based on a proportional derivative position controller (i.e., a position and velocity dependent controller with a dead-zone of 1° radius around the desired position; Figure 3). As soon as the participant deviated more than 1° from the desired end-effector position, the haptic feedback was faded in exponentially as described in the following equations:

$$G_{Window} = \begin{cases} 0, & ||\Delta\alpha|| < 1^\circ \\ \left|\left| \left(1 - \frac{1^\circ}{||\Delta\alpha||}\right) \right|\right|, & ||\Delta\alpha|| \geq 1^\circ \end{cases}$$

$$\Delta x_{EE} = x_{EE_{des}} - x_{EE_{meas}}$$

$$\Delta \dot{x}_{EE} = \dot{x}_{EE_{des}} - \dot{x}_{EE_{meas}}$$

$$F_{cont} = G_{Window} \min(P\Delta x_{EE} - D\Delta\dot{x}_{EE}, 400N)$$

with

$$P = 500\frac{N}{m}$$

$$D = 30\frac{Ns}{m},$$

using the gain of the window G_{Window}, the angular deviation from the target $\Delta\alpha$, the desired and measured end-effector positions, their derivatives, the resulting feedback force F_{cont}, and the proportional and derivative gains P and D, respectively. Feedback on incorrect blade orientation was delivered by a vibration motor (Pico Vibe 300-100, Precision Microdrives Ltd, London, England; 8.8 mm × 25 mm, voltage: 3V; amplitude: 6G) placed on top of the forearm, fixed with a sock. Orientation angles between 0° and 90° were assigned to the closer angle of these two states so that the mapping of vibration to blade orientation was binary, corresponding to the auditory feedback about blade orientation. Discrete vibrotactile feedback has been shown to be effective to mediate timing cues in the field of sports (Rosenthal et al., 2011; van Erp, Saturday, & Jansen, 2006).

FIGURE 3. Haptic feedback. The rope-robot pulled the participant's blade toward the target blade more strongly with increasing deviation. A vibrator placed on the left forearm indicated error in blade orientation. (Color figure available online).

Terminal Visual Self-Controlled Feedback

During the training sessions, participants of the terminal visual feedback group could request feedback whenever they had completed at least three cycles, but not during nonfeedback trials at the end of the training runs. The feedback provided a replay of the last 18 s of the movement, displayed with a delay of 10 s after the request. The position and velocity of the replay corresponded exactly to the movement performed (Figure 4). Following the replay, the participants could watch the trace of their performed trajectory superimposed to the target trajectory for up to 10 s. The feedback visualization was programmed in Matlab (The MathWorks, Natick, MA).

Experimental Design

The participants were randomly allocated to four groups of nine participants that trained exclusively with one feedback

FIGURE 4. The terminal feedback showed the target trajectory together with the participant's performed trajectory of the last 18 s, which is the period of three target cycles. Blade rotations were indicated by the symbols ⧫ (rotated to steep blade) and ▼ (rotated to flat blade). To provide feedback about the desired velocities, a synchronized replay of the actual and target movements was shown. The actual and target blade were represented by abstract symbols, moving along the trajectories at the velocities as performed. The symbols changed each time the blades were rotated (⧫ ↔ ▼). The start position of the target was set to the closest position of the participant's oar at the beginning of the replay. (Color figure available online).

design: visual feedback group (V), auditory feedback group (A), haptic feedback group (H), or terminal visual feedback group (T). Each participant was invited on three consecutive training days (Days 1–3), on Day 4 for a one-day retention test, and on Day 11 for a one-week retention test.

Familiarization

On Day 1, after general instruction, participants familiarized themselves with the simulator and the feedback design. First, for V and H, the virtual target oar was fixed at a central position. The participants moved the oar in order to experience the feedback. Thereafter, for 120 s, they were asked to match the virtual target blade moving in 8 s along a circle with constant velocity (15 cycles). The blade rotated at two positions from flat to steep and vice versa. The movement was different in terms of velocity and shape compared to the rowing-type target movement. Participants were thus introduced to the feedback and setup but not to the target movement. Some additional familiarization time was given to A in advance. While the target oar was fixed, they became familiarized with the sonification of the horizontal error (stereo balance) only, and with the vertical error (pitch) only. Thereafter, participants were asked to match a sinusoidal horizontal and a sinusoidal vertical movement for 80 s (10 cycles) each. Finally, the total deviation (volume) and blade orientation (timbre) feedback was added, and was performed with the fixed target oar first, and thereafter with a circular movement of the target oar including two blade rotations of 120 s (15 cycles), similar to V and H. The terminal visual feedback group was asked to match the circle movement with visual feedback in order to familiarize the participants with the setup. Participants of the terminal feedback group were introduced to the terminal feedback when they requested it for the first time.

Demonstration of the Target Movement and Baseline Test

After the familiarization, participants were asked to watch and memorize the visually displayed target movement (i.e., a blue oar moved on the target trajectory) for 60 s (10 cycles). Thereafter, they had to perform the movement with their own oar in a baseline test lasting 180 s without augmented feedback. All participants were instructed to maintain their focus on the oar blade and not on the hand at the beginning of the study.

Training Sessions and Retention Tests

After the baseline test on Day 1, three training sessions were conducted, each including an average of 180 s (30 cycles) of feedback training, immediately followed by 30 s (five cycles) of nonfeedback trials. The number of cycles during the training with concurrent augmented feedback was determined by the concurrently moving target. The number of cycles of T during the feedback training could vary, as a concurrently moving target and thus an external, online pace maker was missing. However, the training time was the same for all participants. The duration of the three training sessions with feedback varied (150 s, 180 s, or 210 s) so as to avoid an estimation of the point in time at which feedback was withdrawn (i.e., when the nonfeedback trials started). Participants were informed about the nonfeedback trials prior to the training sessions and were instructed to continue the movement without interruption when the feedback was withdrawn. The participants of T were verbally informed about the start of the nonfeedback trials immediately before their start. From then on, T was no longer allowed to request feedback. Day 2 and Day 3 started with a retention test of 180 s, equivalent to the baseline test on Day 1. After the retention test, three training sessions followed, as on Day 1. On Day 4 and on Day 11, a 180 s retention test was performed.

Analysis

Kinematic Data

Custom written programs in Matlab were used for data analysis. Data from the rope robot (1000 Hz) and tracking system (62.5 Hz) were downsampled to 50 Hz using a cubic spline interpolation. The first 12 s of each baseline test, retention test, and training session, i.e., the starting phase, were excluded. The first 3 s of each nonfeedback trial were not considered in the data analysis to exclude artifacts arising from abrupt withdrawal of the feedback. For concurrent augmented feedback conditions, the point in time corresponding to the minimal horizontal angle of the target oar was used to partition data into cycles. In contrast, for baseline and retention tests, for nonfeedback trials, and for terminal feedback

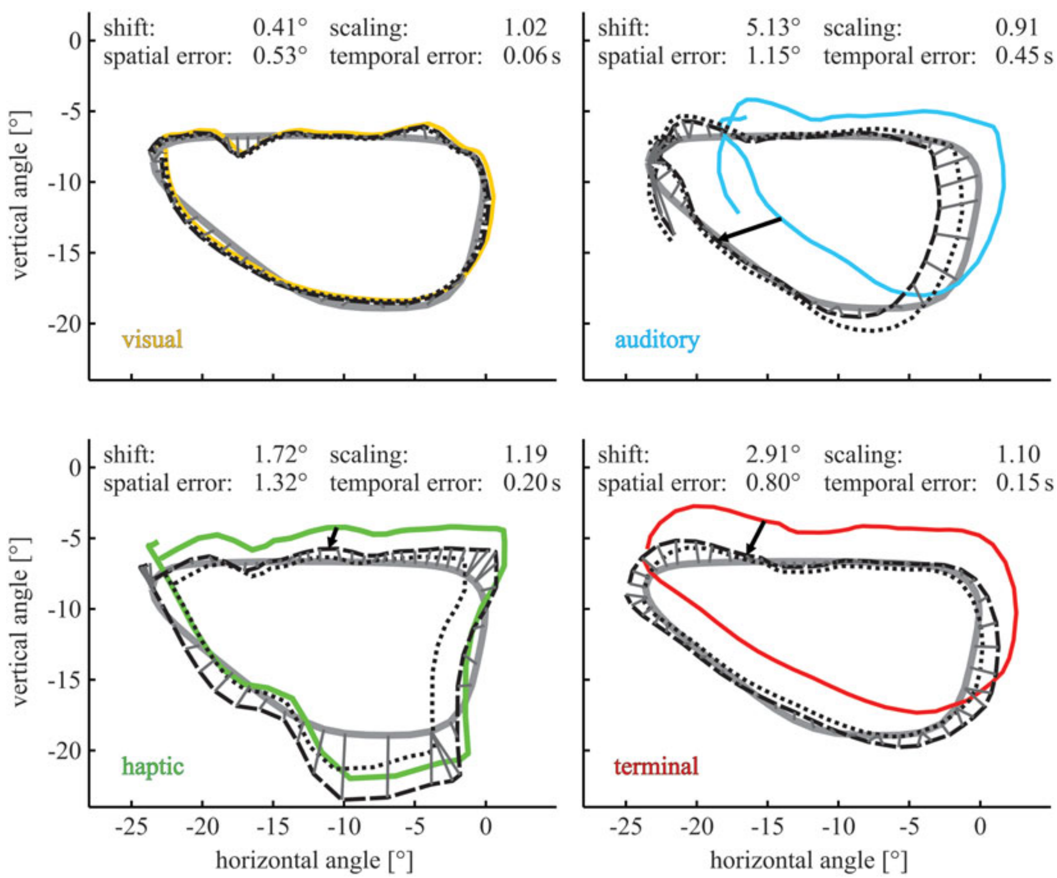

FIGURE 5. Illustration of spatiotemporal analysis. Example cycles of one participant of each group during feedback training on Day 2 are shown: target trajectory (gray solid fat); participant's original cycle (colored solid); shifted trajectory (dashed); spatial shift (arrow); shifted and scaled trajectory (dotted); and correspondences of data points of the spatiotemporal analysis (grey solid). The temporal error is 0 s and the spatial error is 0° if each data point of the target trajectory only corresponds to one point of the participant's shifted trajectory and if the points match spatially. (Color figure available online).

training, the point in time of the minimal horizontal angle of the participant was used to partition data into cycles as an online target movement was missing. The cycles were then resampled to 300 data points. The comparison to the target movement, which had also 300 data points, was matched to the time point of the minimal horizontal angle. Cycles were ignored when the marker cluster on the oar was corrupt due to the loss of too many individual markers or if they were shorter than 3 s or longer than 9 s. 9.4% of the cycles were ignored in V, 6.4% in A, 0% in H, and 4.8% in T. One participant of the auditory feedback group was excluded from the analysis as she was not able to use the feedback at all and did arbitrary movements with almost double the reference velocity in all conditions.

To evaluate the participants' performance, different variables were extracted from the recorded oar angles. To determine the absolute angular deviation (i.e., the combined horizontal and vertical deviation from target), the root mean square error (RMSE) was calculated. The RMSE represents the performance during training with the concurrent feedback perfectly, as the feedback designs displayed the deviation from the participant's oar to the virtual target oar. In addition to the RMSE, in order to evaluate the spatial and temporal errors in the baseline and retention tests, the horizontal and vertical oar angles of the participants were compared to the target oar angles using a spatiotemporal analysis (Giese & Poggio, 2000). By using time warping, spatiotemporal analysis takes the movement phase into account (Figure 5). In contrast to RMSE, time warping avoids overestimation of errors originating from small phase errors (Vlachos, Hadjieleftheriou, Gunopulos, & Keogh, 2003). The participant's trajectory of each cycle was spatially shifted toward the target trajectory until the mean spatial error (calculated from spatiotemporal analysis) of the cycle reached a minimum. Thereafter, the participant's trajectory was scaled until the spatial error was minimal to extract the scaling (Figure 5). To assess temporal aspects of the movement, besides the temporal error calculated by the spatiotemporal analysis, the error in timing of blade rotation, and the error in velocity ratio (between the fast pulling phase to the slow pushing phase) were extracted. Movement variability was assessed at key points of the cycle (i.e., the maximal and minimal horizontal angle, the minimal vertical angle, and the vertical angle at the center of the pushing phase). At each key point, the standard deviation of all cycles of a participant within each testing condition was calculated. To more robustly represent the variability at the center of the pushing phase, standard deviations of the samples ±5% around the center were averaged. The movement variability was defined as the mean of the standard deviations at the key points.

Questionnaire

After the last training session, a questionnaire was given to the participants to assess comprehensibility, practicability, and comfort of the feedback design as well as their focus (either on blade or on hand). It was further assessed if they had their eyes open or closed during the training. Additionally, participants in H were asked if they were rather active or passive during training. After the retention tests on Day 4 and Day 11, the participants were requested to report what information they had recalled in order to perform the trained movement on these two days. Responses were rated on a 7-point Likert-type scale ranging from 1 (*not at all*) to 7 (*very much*).

Statistical Analysis

Statistical analysis was done in IBM PASW Statistics 20 (IBM Corp., New York, NY). Two-sided p-values lower than .05 indicated significant differences. To compare kinematic data, firstly, one value describing an extracted variable was calculated for each cycle (e.g., the spatial error or error in timing of blade rotation). A mean value was then calculated for each condition (baseline, retention, feedback training, or nonfeedback trial) for each participant. The participants' mean values were used as an input for the statistical analysis. Consequently, the input data for the statistical analysis of each test condition (baseline, retention, feedback training, nonfeedback trial) contained 36 mean values (four groups of nine participants each).

To compare groups in terms of practicability of the feedback designs (i.e., during feedback training) and to compare the performance without feedback during the training sessions (i.e., during the nonfeedback trials), a univariate analysis of variance (ANOVA) with a mixed-model design was used. Group was set as fixed factor and the three training days and the three repetitions on each day as random factors. Tukey HSD post hoc tests were used for multiple comparisons between groups. A mixed-model univariate ANOVA was also used to compare performance during feedback training with nonfeedback trials within each group during the training sessions. Feedback availability (feedback training or nonfeedback trials) was used as the fixed factor and the three training days and the three repetitions on each day as random factors.

To assess learning within each of the four feedback groups from baseline to each retention test, a repeated measures ANOVA was used. Post hoc Bonferroni test were applied for multiple comparisons between the tests. Violations of sphericity were corrected using Greenhouse-Geisser correction. To compare learning between groups in early and late stages, the development of a variable from the baseline test to each retention test was compared by running a one-way ANOVA. The Tukey HSD post hoc test was used for multiple comparisons between groups.

To assess group effects in the questionnaire answers, a Kruskal-Wallis test with pairwise comparison was applied.

Results

Group Differences in Feedback Training

During training with the feedback, RMSE differed significantly between all groups, except between H and T (Table 1, Figure 6). H and T performed significantly better than A, but worse than V. H performed significantly larger movements than the other groups. V and A had the smallest scaling error. All groups differed significantly in timing in blade rotation, except V and T, which both timed the rotation more precisely than H and A (A had the highest error of all groups). H had significantly smaller and A significantly higher error in velocity ratio than the other groups. V showed the least and A the most variable movements (Table 1).

Group Differences in the Nonfeedback Trials

In the nonfeedback trials, V and T had significantly lower RMSE than A and H (Table 1). H showed the worst scaling whereby H performed significantly larger movements than the other groups. T timed the blade rotation significantly more precisely than the other groups. V showed significantly smaller error in velocity ratio than the other groups. T had significantly smaller error in velocity ratio than A and H. In the nonfeedback trials, H moved significantly more variable than the other groups.

Differences Between Feedback Training and Nonfeedback Trials Within Each Group

V and H performed significantly better in the training sessions with feedback than in the nonfeedback trials regarding RMSE, scaling, error in timing of blade rotation, error in velocity ratio, and movement variability (Table 1). For A, error in timing of blade rotation and error in velocity ratio was significantly higher with feedback than without. The movement variability of A was significantly higher with the feedback than without.

Learning From Baseline Test to the Retention Tests Within Each Group

H significantly decreased RMSE, temporal error and error in velocity ratio from baseline to retention tests. T

TABLE 1. Statistical Results ($p < .05$) of the Training Sessions From Univariate Analysis of Variance With a Mixed-Model Design and Tukey HSD Corrected Post Hoc Tests

	Between-group differences						Within group differences		
	Feedback training			Nonfeedback trials			Feedback to nonfeedback trials		
Variable	Main effect post hoc	p	η^2_p	Main effect post hoc	p	η^2_p	Main effect	p	η^2_p
Root mean square error	$F(3, 303) = 162.83$	<.001	.62	$F(3, 300) = 38.49$	<.001	.28	lower with feedback:	<.001	.60
	V lower A, H, T	<.001		V, T lower A, H	<.001		V: $F(1, 151) = 225.19$	<.001	.38
	H, T lower A	<.001					H: $F(1, 151) = 89.89$		
Scaling	$F(3, 303) = 36.60$	<.001	.27	$F(3, 300) = 29.42$	<.001	.23	smaller with feedback:	<.001	.17
	H larger V, A, T	<.001		H larger V, A, T	<.001		V: $F(1, 151) = 31.69$	<.001	.13
	V larger T	.034					H: $F(1, 150) = 22.93$		
Error in timing of blade rotation	$F(3, 302) = 102.01$	<.001	.50	$F(3,298) = 14.69$	<.001	.13	lower with feedback:		
	V, T lower A, H	<.001		T lower V, A, H	<.010		V: $F(1, 151) = 21.71$	<.001	.13
	H lower A	.010		V lower H	.043		H: $F(1, 150) = 15.05$	<.001	.09
							higher with feedback:	<.001	
							A: $F(1, 134) = 44.39$		.25
Error in velocity ratio	$F(3, 303) = 225.64$	<.001	.69	$F(3, 300) = 36.63$	<.001	.27	lower with feedback:		
	V, H lower A, T	<.001		V lower A, H, T	<.001		V: $F(1, 151) = 18.59$	<.001	.11
	T lower A	<.001		T lower A, H	<.010		H: $F(1, 150) = 197.92$	<.001	.57
							higher with feedback:		.05
							A: $F(1, 134) = 7.24$	.008	
Movement variability	$F(3, 303) = 163.28$	<.001	.62	$F(3, 300) = 70.32$	<.001	.41	lower with feedback:		
	V, H, T lower A	<.001		V, A, T lower H	<.001		V: $F(1, 151) = 5.67$	.018	.04
	V lower A, T	<.050		V lower A	.005		H: $F(1, 150) = 151.13$	<.001	.50
							higher with feedback:	<.001	.50
							A: $F(1, 134) = 133.93$		

Note. V = visual feedback group; A = auditory feedback group; H = haptic feedback group; T = terminal feedback group.

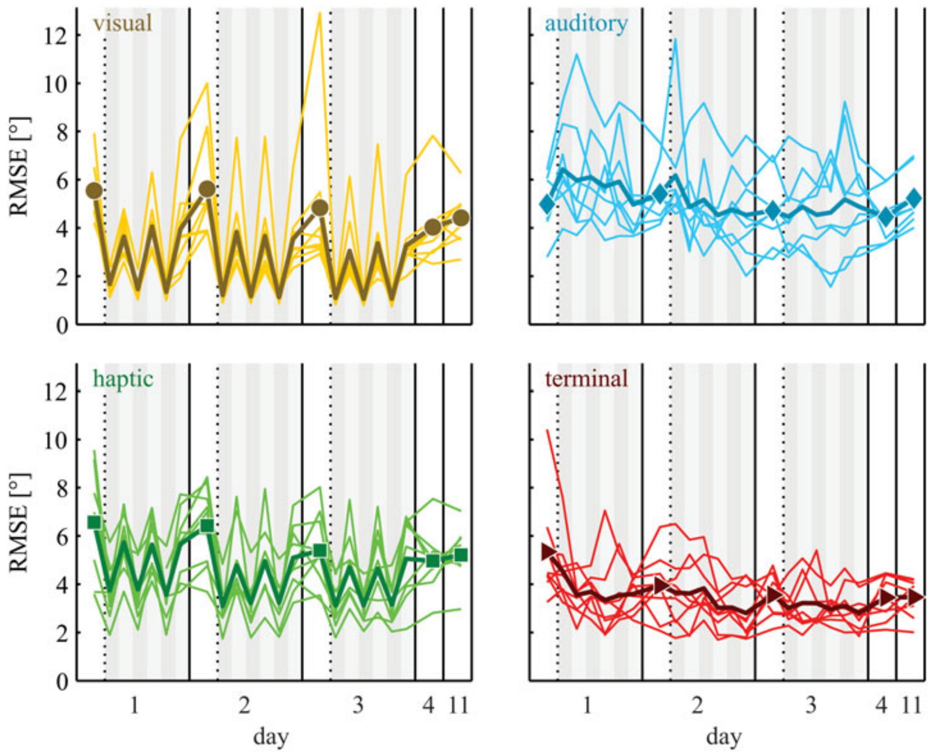

FIGURE 6. Development of the root mean square error (absolute angular deviation from the target) in the different groups. Group mean values are connected with dark, thick lines, whereby baseline and retention mean values are emphasized with symbols. Thin fair lines represent individual developments. Background colors indicate different conditions (white: baseline or retention; dark gray: feedback training; fair grey: nonfeedback trials). (Color figure available online).

significantly decreased RMSE, spatial error as well as for timing in blade rotation. In A, temporal error significantly increased from baseline to retention on Day 2. In all groups, movement variability significantly decreased over the days (Figure 7, Table 2).

Group Differences in Terms of Learning

T reduced the RMSE significantly more than H from baseline on Day 1 to the retention test on Day 11. T and H significantly differed in the development of the spatial error from Day 1 to Day 2. T significantly differed from the other groups in the reduction of the error in timing of blade rotation from baseline to the retention tests after Day 2. In A, the temporal error significantly increased compared to the other groups (Figure 7, Table 3).

Subjective Evaluation of the Feedback Designs

In general, V rated their feedback better than the other groups (Figure 8, left). In general, the auditory feedback was rated worst. The Kruskal-Wallis test revealed a significant group effect for comprehensibility ($H(3) = 12.57$, $p = .006$). The ratings were significantly worse by A than by V ($p = .011$) and T ($p = .015$). During training, the foci of the participants of all groups were, in general, more on the blade than on the hand (V: 85%; A: 87%; H: 68%; T: 81%). Participants had their eyes generally open (V: 100%; A: 90%; H: 88%; T: 100%). H reported to be, on average, 91% active during the training with the robotic guidance.

Resources Exploited at Retention

The participants applied different strategies in order to recall the desired movement in the retention tests on Day 4 and Day 11 (Figure 8, right). Kruskal-Wallis test showed that some groups relied more on the demonstration of Day 1 than other groups (Day 4, $H(3) = 25.21$, $p < .001$; Day 11, $H(3) = 19.67$, $p < .001$). Significantly more reliance on the demonstration was reported by A compared to V (Day 4: $p = .002$, Day 11: $p = .001$), compared to H (Day 4: $p = .022$), and compared T (Day 4: $p < .001$, Day 11: $p = .002$). Four participants of A, one of H, and one of T remembered the rhythmic sound of the blade rotation in the oarlock to perform the movement; in contrast, no participants of V did so. To perform the movement, one participant of A and three of H took advantage of the optical landmarks of the setup (e.g., the shadows of the physical oar on the screen; Figure 1).

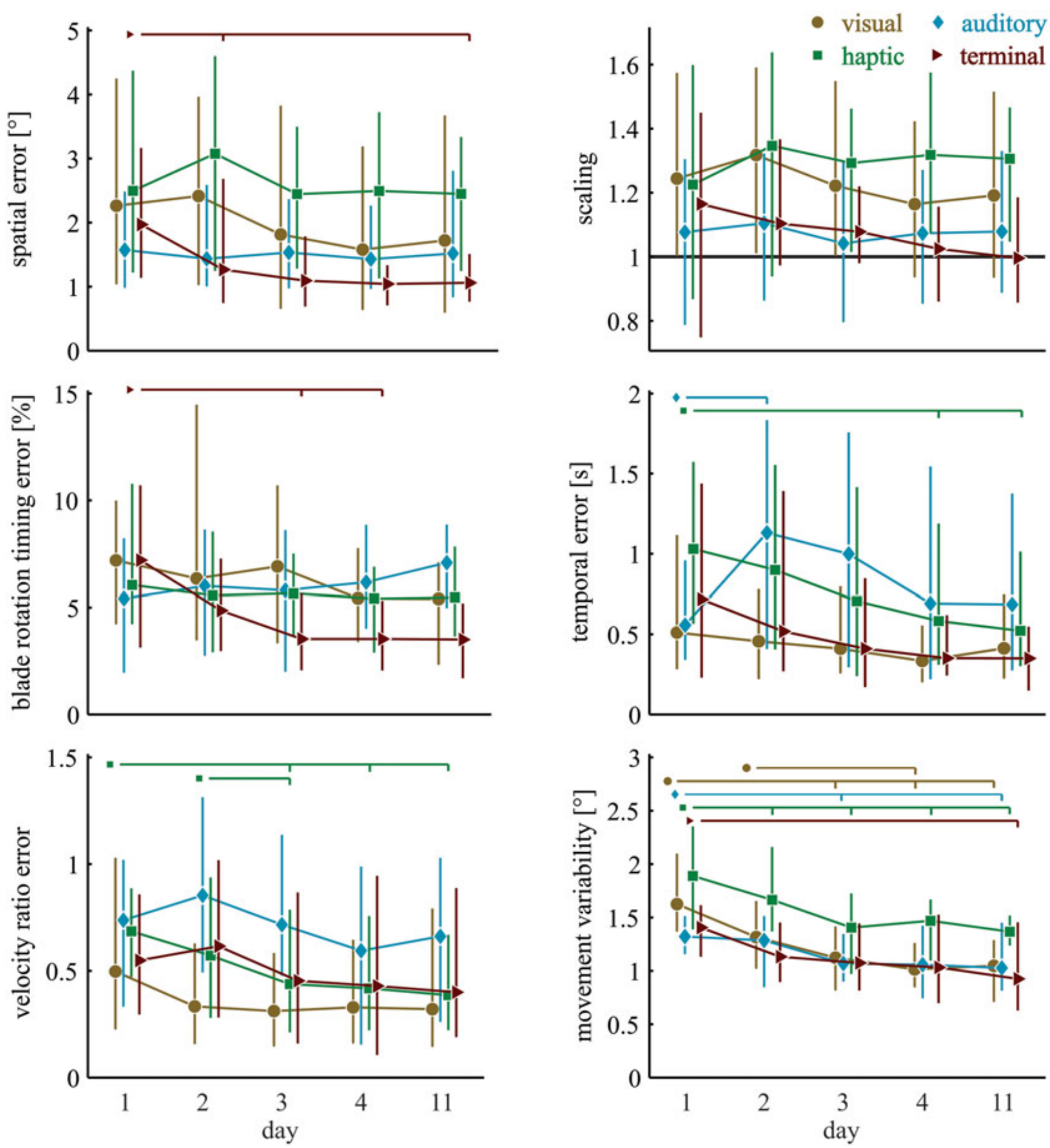

FIGURE 7. Learning curves of different variables. Group mean values at baseline (Day 1) and all retention tests (Days 2–11) are connected with lines. Vertical bars connect the minimal and maximal values of participants within each group on each day. Bonferroni-corrected significant differences within the groups between baseline and retention tests are indicated with horizontal lines and group symbols ($p < .05$). For scaling, the target value is indicated with a horizontal line at 1. (Color figure available online).

Discussion

In sports and rehabilitation, simulator training and virtual reality-based motor learning have become very popular, taking advantage of an adjustable training environment, kinematic and kinetic data recording, and manifold augmented feedback. These training facilities are designed to optimize feedback for complex motor tasks (Holden, 2005). However, there is a lack of studies that compare different feedback strategies, and in particular, of designs addressing different modalities (Sigrist et al., 2013). Here we investigated the learning of a complex, sports-related task enhanced through feedback strategies either displayed concurrently in one of three modalities (visual, auditory, haptic) or displayed visually after the task (i.e., terminal visual feedback).

Performance During Training Sessions With the Feedback and in Nonfeedback Trials

In order to profit from an augmented feedback design, the design must be comprehensive, easy to interpret and practical to use during training. As hypothesized, group V interpreted

TABLE 2. Statistically Significant Differences ($p < .05$) Between the Baseline and the Retention Tests Within Each Group Gained by Repeated Measures Analysis of Variance (With Bonferroni Corrected Post Hoc Tests)

	Visual group			Auditory group			Haptic group			Terminal group		
Variable	Main effect post hoc	p	η^2_p	Main effect post hoc	p	η^2_p	Main effect post hoc	p	η^2_p	Main effect post hoc	p	η^2_p
Root mean square error							$F(4, 32) = 5.52$ Day 1 to 2	.002 .032	.41	$F(4, 32) = 4.91$	.003	.38
Spatial error										$F(1.69, 13.55) = 8.17$ Day 1 to 2, 5	.006 <.050	.51
Error in timing of blade rotation										$F(1.65, 13.19) = 9.87$ Day 1 to 2, 4	.003 <.050	.55
Temporal error				$F(4, 28) = 6.25$ Day 1 to 2[a]	.001 .029	.47	$F(1.77, 14.17) = 9.82$ Day 1 to 4, 5	9.82 <.050	.55			
Error in velocity ratio							$F(1.70, 13.61) = 13.75$ Day 1 to 3, 4, 5 Day 2 to 3	.001 <.050 .019	.63			
Movement variability	$F(1.91, 15.31) = 20.49$ Day 1 to 3, 4, 5 Day 2 to 4	<.001 <.05 .029	.72	$F(4, 28) = 6.97$ Day 1 to 3, 5	.001 <.050	.50	$F(4, 32) = 12.45$ Day 1 to 3, 4, 5	.001 <.050	.61	$F(4, 32) = 9.77$ Day 1 to 5	<.001 .038	.55

Note. No significant differences found for scaling. [a]Increase of the error.

TABLE 3. Statistically Significant Results ($p < .05$) on the Group Differences in the Developments From Baseline to Each Retention Tests Gained by One-Way Analysis of Variance

	Day 1 to Day 2			Day 1 to Day 3			Day 1 to Day 4			Day 1 to Day 11		
Variable	Main effect post hoc	p	η^2	Main effect post hoc	p	η^2	Main effect post hoc	p	η^2	Main effect post hoc	p	η^2
Root mean square error										$F(3, 31) = 2.90$ T to A	.051 .037	.22
Spatial error	$F(3, 31) = 4.24$ T to H	.013 .008	.29									
Error in timing of blade rotation				$F(3, 31) = 5.60$ T to V, A, H	.003 <.050	.35	$F(3, 31) = 5.69$ T to A, H	.003 <.050	.36	$F(3, 31) = 6.56$ V, T to A	.001 <.050	.39
Temporal error	$F(3, 31) = 7.44$ V, H,T to A	.001 <.010	.42	$F(3, 31) = 7.73$ V, H,T to A	.001 <.050	.43	$F(3, 31) = 4.14$ H, T to A	.014 <.050	.29	$F(3, 31) = 4.49$ H to A	.010 .011	.30
Movement variability							$F(3, 31) = 2.93$ V to A	.049 .035	.22			

Note. Tukey HSD corrected post hoc tests: first mentioned group(s) show a decrease in the variable compared to the second mentioned group(s). No significant results found for scaling and error in velocity ratio. T = terminal feedback group; H = haptic feedback group; A = auditory feedback group; V = visual feedback group.

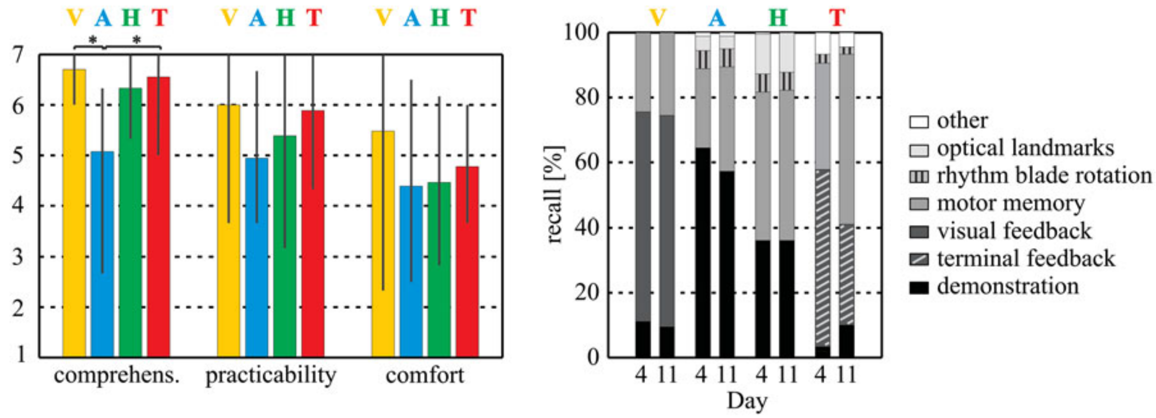

FIGURE 8. Questionnaire results. Left: group mean ratings of feedback comprehensibility, practicability, and comfort (1 = very bad; 7 = excellent). Vertical bars connect the minimal and maximal ratings of participants within a group. Right: illustration of what participants of each group recalled during the retention tests on Day 4 (left bars) and Day 11 (right bars) in order to perform the movement. $^{*}p < .05$. (Color figure available online).

the concurrent visual superposition of the actual and target oars excellently from the onset, leading to the best performance of all groups during the feedback training (Figure 6 and Table 1), and also to the best ratings in the questionnaire (Figure 8). These results are in agreement with those of a previous study with a rowing-type task, in which concurrent visual feedback led to a more precise tracking performance than auditory feedback (Sigrist, Schellenberg, et al., 2011). We found three main advantages of the concurrent visual feedback over the other designs. First, the participants could look ahead and prepare their movements since the target trajectory was permanently displayed. The other groups, on the other hand, reacted on the feedback, either instantly (A and H), or delayed (T). Second, vision is specialized to perceive spatial information (Freides, 1974; Nesbitt, 2003; Welch & Warren, 1980), and correcting a spatial error was the main component of the task as the movement was rather slow. Third, visual feedback designs are, in general, very common and can be interpreted immediately.

It seems that much more familiarization than initially expected is needed to benefit from the auditory feedback (i.e., the multidimensional error sonification). On average, group A was not able to use the feedback to track the movement sufficiently and rated the feedback worst. Throughout all the error variables, performance was significantly worse than in all the other groups during the training (Table 1). The high movement variability indicates that the participants were struggling with correcting the oar position. Some participants of group A were even not able to use the error sonification to perform the general movement, which has also been shown in pervious experiments (Sigrist, Schellenberg, et al., 2011). We assumed that the demonstration mediated the general idea of the movement, such as the rough movement range, shape, and velocity profile, and the auditory feedback was then used to fine-tune the movement execution. However, during feedback training, A seemed to ignore the information they received from the demonstration. In contrast, during the retention test, participants in group A attempted to recall the demonstration more than all the other groups (Figure 8). It seems that multidimensional error sonification overwhelmed naïve participants, whereas one error could be handled (Godbout & Boyd, 2010; Konttinen et al., 2004; Mononen, 2007). However, a few participants of group A could follow the target movement within an error range comparable to that of H, and also became more precise with more training time (Figure 6), and might even increase performance further following more training with the feedback design. Also for V, H, and T, individual differences in the ability to use the feedback arose, although were less pronounced than in A. Consequently, feedback modality and design preferences should be taken into account to optimize individual training (Sigrist et al., 2013).

Interestingly, participants in group A performed worse in timing of blade rotation than all other groups (Table 1), although the alarm-type signal indicating incorrect blade rotation was assumed to be easy to interpret. T and V timed the blade rotation at a similar level, and both were significantly better than A and H. It seems that the visual feedback designs were less cognitively demanding than the other feedback designs, i.e., V and T had the cognitive resources to concentrate not only on the horizontal and vertical oar movement but also on blade rotation. An explanation might be that timing of blade rotation was judged less important than the two-dimensional correction of horizontal and vertical oar angle.

As hypothesized, the haptic feedback could generally guide the participants through the movement. However, the movement of H was distinctively too large, significantly larger than that of the other groups (Table 1). This can be explained by the design of the feedback: the force that pushed the participant toward the target position increased with the deviation. Therefore, the participants tended to slide along the border zone of the window of the position controller. In contrast, the error in velocity ratio was smallest of all groups. It could thus be concluded that the movement with haptic feedback was mainly too large, but synchronized to the target movement. Interestingly, H moved significantly faster during nonfeedback trials than during feedback training, mainly due to faster pushing phases (decrease in the velocity ratio). This change in velocity is very likely caused by the transparency property of the robot: in very slow movements, the transparency was decreased, friction increased, and stick-slip effects occurred at some points. Consequently, to avoid increased friction, H increased velocity in nonfeedback trials in which they were no longer forced to also perform the slow movements by the haptic guidance during the pushing phase.

T improved performance very early in the training sessions, even on Day 1 (Figure 6). Therefore, an internal movement representation to which the feedback could be compared was developed earlier than expected. An exception was the error in velocity ratio, which was significantly higher than that of V and H during training. It is likely that the velocity profile was not well reflected by the applied design of the terminal visual feedback.

Effectiveness of Feedback Designs to Enhance Learning

As concurrent feedback can mediate the general pattern of the movement and prevent cognitive overload (Wulf & Shea, 2002), it was hypothesized that guidance in form of concurrent visual or haptic feedback can contribute to learning of the complex, real-life movement that was used in this study, at least in early learning stages. However, the results of this study clearly confirm the guidance hypothesis. V and H performed significantly better during feedback training than in nonfeedback trials, in contrast to T (Figure 6 and Table 1). Auditory feedback was hypothesized to be effective later in the training, after having familiarized with the uncommon multidimensional error sonification. However, the applied auditory feedback was not practical, at least for most participants.

According to the specificity of learning hypothesis, the optimal source of afferent information is processed for motor control, thereby blocking processing of other sources such as proprioception (Proteau, 1992). In this study, the concurrent visual feedback was the optimal source of afferent information to reach the highest instantaneous task performance. For H, the concurrent feedback was not an ideal source of information; instead, the haptic feedback peculiarities became part of the task, changing the original task (Schmidt & Wrisberg, 2008). Consequently, in nonfeedback trials, participants were asked to perform a task based on alternative afferent information. As this was not trained, performance dropped, which is in line with many studies examining the specificity of learning hypothesis (e.g., Blandin, Toussaint, & Shea, 2008; Proteau, 2005; Proteau & Isabelle, 2002; Ranganathan & Newell, 2009; Robin, Toussaint, Blandin, & Proteau, 2005; Schmidt & Wulf, 1997; Van der Linden et al., 1993). In contrast, the afferent information perceived by T was the same during feedback training and retention. Thus, T could use the feedback to calibrate proprioception, i.e., to fine-tune their movements. As proprioceptive information could also be recalled in nonfeedback conditions, performance gains could be retained.

It was assumed that concurrent visual feedback can instruct the general idea of the complex movement very intuitively, and it was therefore hypothesized that the groups employing this feedback would learn faster than group T. However, already in the first nonfeedback trial, the performances of V and T were on a similar level (Figure 6). Considering findings on observational learning (Wulf & Shea, 2002; Wulf, Shea, & Lewthwaite, 2010), it seems that the observation of the demonstration already led to a development of an internal movement representations of our complex task. From Day 1 onward, T could profit from the feedback (Figures 6 and 7, Table 2). Thereafter, T further fine-tuned its motor behavior throughout the training sessions, but improvements were less distinct.

In general, T developed better from baseline to retention tests than the other groups (Figure 7 and Table 3). T improved blade rotation timing from Day 1 to Day 3 significantly more than all other groups. Moreover, T was the only group that significantly learned over the days regarding spatial error and blade rotation timing error (Figure 7 and Table 2). T was also able to focus on the timing of blade rotation very early in the training sessions, in contrast to A and H, who longer struggled with the correction of movement trajectory. V could not improve significantly more than any other group at an early or a later learning stage in any movement variable (except movement variability and temporal error: A was worst). However, V generally performed better in the nonfeedback trials (at a level comparable to T, see Table 1) than at baseline and during retention tests (Figure 6). Thus, it may be concluded that visual concurrent feedback evoked some immediate performance increases. However, performance could not be retained until the next day. A similar, but less pronounced effect was observed for H, only with generally higher errors probably caused by the limited transparency of the robot.

In this study, concurrent feedback could not contribute to the understanding of the task requirements beyond the demonstration. The relevant aspects were not improved significantly compared to T. We assume that, instead, concurrent feedback designs forced the correction of task-irrelevant errors as observed by others (Liu & Todorov, 2007; Todorov, 2004; Todorov & Jordan, 2002; Wei & Körding, 2009; Wolpert, Diedrichsen, & Flanagan, 2011). In terms of the different groups, V focused on irrelevant local detail corrections caused by sensory-motor noise (van Beers, 2009), A on the interpretation of the sonification, and H tried to avoid friction. The concurrent feedback about the rather slow movement used in this study forced the correction of local errors within a cycle, instead of systematic errors recurring in several cycles. Consequently, the precise execution of the global movement was not learned.

To foster motor learning by haptic guidance, a controller was chosen allowing active movements (Marchal-Crespo & Reinkensmeyer, 2009) while also enabling movement errors within a certain bandwidth (Emken et al., 2007; Patton et al., 2006, van Beers, 2009). H did not improve spatial error or scaling (Figures 6 and 7, Table 2). However, temporal error and error in velocity ratio were decreased significantly. These results support previous findings that indicate that haptic feedback is beneficial for teaching temporal aspects (Feygin et al., 2002; Marchal-Crespo et al., 2010; Marchal-Crespo & Reinkensmeyer, 2008). However, the impact of this result is weakened as H might have learned to cope with the friction of the rope robot instead of, or besides, having learned to perform the temporal aspect of the movement better. The question remains if learning of spatial and temporal aspects would be possible with an improved haptic feedback controller, or if an optimized terminal feedback design (e.g., in terms of mediating the temporal error) would have been even more successful.

Observations and Suggestions for Effective Application of Augmented Feedback

Concurrent feedback was believed to be beneficial because it can reduce cognitive load and mediate the task requirements such as the movement pattern in an undemanding way (Wulf & Shea, 2002). However, in our study, cognitive load and understanding the task requirements may not have been critical. It is more likely that the internalization of the precise task execution (i.e., the fine-tuning of the motor program) was challenging. Indeed, if we take the performance of V during feedback training as being nearly optimal, it becomes evident that retaining the precise task execution was difficult as the performance level reached with concurrent visual feedback was never reached by any group in nonfeedback conditions. Therefore, the effectiveness of concurrent feedback might not only depend on the complexity of the required motor skill per se, but also in the complexity of understanding the task requirements.

A self-controlled strategy was applied for T but not for the other groups. It remains unclear whether the concurrent feedback groups would have profited from a self-controlled strategy. However, the results strongly indicate that the detrimental effect of the concurrent feedback was caused by a forced focus on local, irrelevant corrections. It is assumed that the capability of the terminal feedback to indicate relevant errors, the enhanced information processing of proprioceptive information due to the feedback delay (Swinnen et al., 1990), and forced self-estimation (Sigrist, Rauter, et al., 2011) enabled T to outperform the concurrent feedback groups. A combination of terminal and concurrent feedback might be even more effective as shown in previous studies on simple task learning (Blandin et al., 2008; Park, Li, & O'Malley, 2000). Visual concurrent or haptic concurrent feedback could instruct the movement, whereby terminal feedback reduces the dependency on concurrent feedback (Blandin et al., 2008) and may contribute to internalization of the motor program.

Not only should the advantages of a combination of terminal and concurrent feedback be exploited, but also the combination of modalities (Sigrist et al., 2013). Thereby, modalities should be applied according to their specific advantages. Sonification might represent variables such as velocity, acceleration or force more effectively than a spatial error. A combination of visual and haptic feedback, together with a sonification of the movement dynamics, has great potential to enhance motor learning. Especially for faster movements, haptic and auditory feedback might be more effective than purely visual feedback.

The feedback designs used in this study are not fully equivalent (e.g., in terms of resolution of the movement error). However, each design was found to be the most practical of a modality based on a prior systematic evaluation. Therefore, an informative comparison between modalities could be done. At this point, the goal was to get fundamental insights in modality-specific effects on complex motor learning based on unimodal designs. The search of optimal feedback designs within each modality might take many more studies considering all the parameters to be tuned (e.g., the gains of the mapping function).

A general issue in motor learning research with augmented feedback is that tasks are created to investigate a certain theory, and that the feedback is adapted to that artificial task. Therefore, an evaluation of the feedback design itself is not in the focus. In other cases, it seems that, rather than finding a feedback design for a real-world task, a feedback idea is found first, and thereafter, a task is created to prove its effectiveness. Task simplifications or adaption allow a proper study design and evaluation, have a high value for basic motor learning and control research, but also involve some hazards. Also in our study, the task was indeed complex, but the target movement was adapted in terms of a reduction in movement velocity. This might have provoked a bias, since at baseline, participants performed generally too fast because they may have expected a rowing movement to be faster. It remains unclear whether the results of this study are also valid for faster rowing movements. The generalizability of conclusions made in studies on simple or artificial tasks to the broad variety of real-world tasks is yet unknown (Krakauer & Mazzoni, 2011; Wulf & Shea, 2002). In future, further studies on realistic movements should be conducted in order to facilitate the transfer of the results to real-life applications (Sigrist et al., 2013).

Conclusion

This study has shown that self-controlled terminal feedback in the form of a visual replay is more effective for teaching a complex, rowing-type target movement than the applied designs of concurrent visual, auditory, or haptic feedback. It seems that the internalization of the movement could only occur when participants were forced to actively process the previously performed global errors. No internalization was achieved if the participant had to cope with local, less relevant aspects. The guidance hypothesis and specificity of learning hypothesis were thereby clearly confirmed. However, concurrent visual feedback has shown its potential to instruct a complex movements, and haptic guidance to teach temporal aspects of a movement. Therefore, a combination of modalities (i.e., multimodal feedback) together with an intelligent alteration of concurrent and terminal feedback seems a promising approach to enhancing complex motor learning and should be further investigated, especially for application in real-life tasks.

Moreover, feedback should be adapted to the learning stage in order to prevent reliance on the feedback, e.g., with assist-as-needed or fading feedback strategies (Patoglu, Li, & O'Malley, 2009; Marchal-Crespo et al., 2010; Marchal-Crespo & Reinkensmeyer, 2009). A very sophisticated solution could be an intelligent virtual trainer, which provides individualized feedback based on the current skill level of the learner (Rauter, Sigrist, Baur, et al., 2011a). Therefore, an intelligent, user-cooperative feedback strategy is strongly recommended to account for individual learning rates, error patterns, preferences on feedback design and modality, and individual feedback susceptibility. Feedback may also be adapted to the user performance, not only in sports simulator training, but also in the field of virtual reality-based training with rehabilitation robots and medical and surgical training simulators.

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