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Influence of Feedback Modality on Motor Sequence Learning

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Abstract

Throughout our lifespan we obtain and refine our motor skills with the use of sensory feedback, such as learning how to play a piano. Research has suggested visual feedback is more advantageous to improve motor learning compared to other types of feedback. However, it is unclear if these advantages stem from the feedback being more relevant to the task. We developed an experimental design that tests the influence of visual, auditory and haptic feedback when acquiring a sequence learning task. The study uses a piano-like task, and therefore we propose that learning is enhanced by auditory and haptic feedback, rather than visual feedback. Participants practiced four 11-digit sequences using a keyboard-like device over the course of five days. Participants were assigned to one of the three feedback groups (i.e., visual, auditory or haptic). Through measuring the participants' execution speed, the results displayed that the auditory group demonstrated greater learning compared to the visual group. During the last session, participants' sensory feedback was removed to measure whether performance improvement was reliant on the modality that was present during learning. Performance was hindered to a greater extent in the haptic group in comparison to the auditory group. This suggests that auditory feedback is most helpful in learning a finger-sequencing task, however, once learning is acquired the auditory feedback is no longer needed. Interestingly, this demonstrates that feedback most relevant to the task may enhance performance but performance does not become reliant on the feedback that is associated to the task's success.

Influence of Feedback Modality on Motor Sequence Learning

In our everyday lives we are highly reliant on sensory feedback, for instance, the slight vibration we feel coming from our phones when it notifies us about an incoming call and text or the sound you hear when you lock your car door. Beyond these commonly experienced influences of sensory feedback in our daily lives, feedback is also suggested to be a crucial asset to learning, acquiring and carrying out motor skills (Banton, 1995).

Playing the piano is an example of a motor skill where the learner receives several kinds of sensory feedback such as visual, auditory, and haptic feedback (Sigrist, Rauter, Riener & Wolf, 2012). The ability to see their finger placement on the keyboard is an example of visual feedback. An example of auditory feedback is hearing the sound after pressing a key, which in turn allows the learner to denote whether they pressed the correct key. The resistance and slight vibration that is felt when the key is pressed down completely is a source of haptic feedback. Feedback facilitates the acquisition of motor skill by providing a measure of performance accuracy which can be used by the learner to improve their skills. In our piano example, an individual learns the different notes, tones and finger placements on the keyboard and through feedback integration improves their execution. Adams (1971) “closed loop theory” asserts that during a motor task various decisions are formed in the brain and information is then sent to the muscles to execute the movements; at the same time, feedback is constantly present and is crucial to correcting and making adjustments to movement patterns. Overall, sensory feedback aids in improving motor skill by providing a direct measure of performance that can be used to adjust performance accordingly.

There is a lot of controversy around the idea that certain sensory feedback sources aid motor skill acquisition to a greater extent than other sensory feedback sources (Sigrist et al.,2012). When we are confronted with inputs from various sensory feedback modalities we may use information from one modality more than another to execute the task at hand (Sinnett, Spence & Soto-Faraco, 2007; Hetch & Reiner, 2009).

Motor learning using visual, auditory and haptic feedback

Humans are said to be visually dominant species where we depend on our visual system to achieve everyday tasks. Some studies suggest that visual feedback may have a greater influence on motor learning in comparison to haptic or auditory feedback (Morris, Tan, Barbagli, Chang, & Salisbury, 2007; Marchal-Crespo, Raai, Rauter, Wolf & Riener, 2013; Colavita, Tomko, & Weisberg, 1976; Colavita & Weisberg, 1979), while other studies suggest otherwise (Sigrist et al., 2012; Ronsse et al., 2011; Sigrist, 2011). Visual dominance has been thoroughly explored by Colavita (1974) using a switch task. Participants were asked to respond via button press whether they heard a tone or saw a light flash. When concurrent visual and auditory stimuli were presented, participants were more likely to report that a light flash was presented than reporting that either both were presented simultaneously or only a tone was presented. This finding supports the visual dominance theory which proposes that visual information is superior to auditory feedback when both kinds of feedback are present (Colavita et al., 1976; Colavita et al.,1979). This phenomenon was later described as the Colavita visual dominance effect. However, the studies conducted by Colavita and colleagues (1979) that assessed the Colavita effect used less complex motor tasks where participants waited for the stimuli (i.e.,

auditory tone and visual light) and simply responded. Hence, it is unclear whether the Colavita effect would be present in more complex motor tasks that require learning.

In more complex motor tasks empirical evidence has suggested that vision may also be the more superior sensory modality in enhancing motor learning (Morris et al., 2007; Hetch et al., 2009; Marchal-Crespo et al.,2013). Morris and colleagues (2007) investigated the influence of feedback modalities on motor learning. Participants within their study were assigned to either the haptic or visual feedback group where both groups learned a sequence of applied forces that they were later asked to recall using a spatial trajectory. During the recall phase, the visual feedback group made fewer errors compared to the haptic group. However, the spatial trajectory was presented visually throughout the course of the study and consequently, participants may have relied more on this feature of the task to encode the forces and hence benefited more from visual than haptic feedback.

Examining this and other studies that showed facilitated motor learning when using visual feedback compared to feedback from other modalities (Sigrist et al., 2012), the question arose whether these findings could be related to the particular tasks used in the study rather than a general superiority of visual feedback. If we were to use a task that requires difficult kinematics would a participant be more reliant on haptic feedback than visual or auditory feedback? In favor of this reasoning surgeons who practice dissecting to improve their cutting skills benefited more from haptic feedback than other types of feedback (Coles, Meglan & John, 2011). In line with this idea the “specificity-of-learning hypothesis” indicates that the brain utilizes the more optimal and appropriate sensory information source to develop and improve a new skill (Sigrist et al., 2012; Hetch et al.,2009).

There are also tasks such as dancing where auditory feedback might be more important for learning than other feedback sources. Sigrist and colleagues (2012) explored how auditory feedback improves learning on a motor task such as playing volleyball. During a serve, the sound made from the server's hand hitting the volleyball denotes how hard the serve is; the louder the sound, the harder the hit and the stronger the serve. Additionally, auditory feedback has also been found to aid in other sports such as dance (Sigrist, 2011). Overall, auditory feedback may be superior in developing these motor skills, one may argue however that comparisons with other sensory feedback were not made in these studies and thus it cannot be concluded that haptic or visual feedback are not similarly important.

In sum, during the past decade scientists within in the field of motor learning have explored the relationship between feedback from diverse sensory modalities and motor skill and have placed an emphasis on visual feedback. However, it is also possible that the feedback that is more task relevant may enhance motor learning to a greater extent, in comparison to sensory feedback that is not as crucial to the task. Such a finding would provide evidence that visual feedback would only be superior in enhancing motor learning compared to other modalities when task success is predominantly related to the visual domain.

As such the current study investigates how auditory, visual and haptic feedback influence sequence learning. This is important to investigate as it would display whether performance is or is not enhanced by the modality most relevant to the task's success.

It is thus hypothesized by the current study that during a piano-like task, where auditory and haptic feedback are more crucial to motor learning than visual feedback (Baumann, Koeneke,

Meyer, Lutz & Jancke, 2005; Conde, Altenmuller, Villringer & Ragert, 2012) motor learning is facilitated to a greater degree with auditory or haptic feedback compared to visual feedback.

Reliance on sensory feedback

While information provided from feedback modalities enhances motor learning, the removal of feedback can be detrimental to performance (Adams, Gopher & Lintern, 1977; Proteau et al., 1987). This phenomenon is known as the “guidance hypothesis of information feedback”, which conveys that if you train a participant on a motor task using sensory feedback their performance may increase, however, once the feedback is removed the participant’s performance should decrease (Ronsse et al., 2011). This would suggest that the participant is reliant on the feedback modality for accurate performance.

The idea that humans are visually dominant and thus that we rely more on our visual system implies that removal of visual feedback should impair performance to a greater extent than removing auditory or haptic feedback (Adams et al., 1972). Ronsse and colleagues (2011) demonstrated this phenomenon during a complex bimanual coordination task where performance was hindered when they removed sensory feedback. Participants in their study were placed in either a visual or auditory feedback group. While the amount of learning in the task was similar across the groups, when feedback was removed, the visual group made more errors than the auditory group. However, it may be speculated that Ronsse and colleagues’ (2011) study may have benefited more from visual than auditory feedback. The task at hand required participants to control self-movement; past studies have displayed the reliance of visual feedback on a similar task (e.g., Carlton, 1981; Hay & Beaubaton, 1986).

For instance, Proteau and colleagues (1987) investigated how visual information is used to control and learn an aiming movement. Participants within their study received either visual feedback (the light was turned on) or no visual feedback. Participants' who were given visual feedback performed the task faster than those who did not receive any feedback. When all groups were tested in the "retention condition" in which visual feedback was removed, movement time significantly declined within the groups who initially received visual feedback in comparison to those who did not and thus, performance was shown to be highly reliant on visual information. This finding supports the results from Ronsse and colleagues (2011) study, suggesting that optimal performance on a motor control task was most reliant on visual feedback.

It is important to understand how sensory feedback contributes to performance since it is another measure of how feedback influences motor skill development. The previously discussed literature provides evidence that different kinds of feedback influence motor skill acquisition to differing degrees (e.g., Adams, Goetz & Marshall, 1972; Sigrist et al.,2012), but, it has not yet been clearly established whether the sensory feedback that results in the greatest amount of motor learning will also show the most performance detriment upon removal. As such, the current study investigates how performance may be influenced when the feedback most relevant to the task is removed.

The present study

In order to test whether learning in a piano-like task is enhanced to a greater extent by auditory or haptic feedback in comparison to visual feedback, a discrete sequence production (DSP) task was used. Participants were assigned to one of three sensory feedback groups (i.e.,

auditory, visual or haptic feedback group) and trained on four distinct sequences over the course of 5 days. To investigate the first hypothesis, that haptic and auditory feedback would aid motor learning to a greater extent than visual feedback, the difference in movement time (MT, the time between the first press to the release of the last press of each sequence) was examined at the end of learning. Then, in order to test the second hypothesis that motor performance after learning is more reliant on task relevant feedback, feedback was removed from each group on the last four blocks of the last training session. If a group's MT decreased upon removing their feedback, it indicated that they were reliant on their feedback. The present study also hypothesized that removing sensory feedback after training on a piano-like task would lead to greater performance decline when participants were trained with auditory or haptic feedback than when trained using visual feedback.

Methods

Participants

Sixty-four participants were recruited for the current study (female = 42; ages 18 to 38). Participants were recruited using fliers that were posted within the Western Interdisciplinary Research Building (WIRB). All participants were fluent in English and right-handed. No participants were excluded from the study. Informed consent was completed by all participants (See Appendix B).

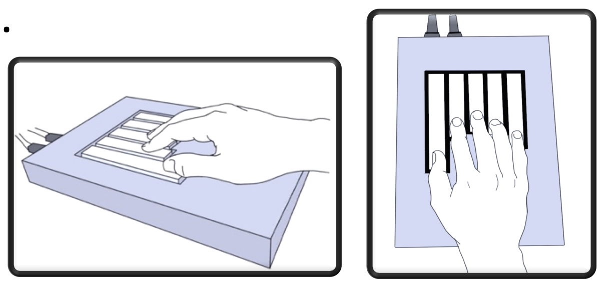
Materials

Handedness was measured using the Edinburg Handedness Inventory task (Oldfield, 1971). Participants were placed in front an LCD screen monitor that displayed the stimuli using Microsoft Visual C++ version 6.0. A non-depressible five-finger isometric keyboard was used during the study (see Figure 1a). A force transducer (FSG-15N1A, Sensing and Control,

Honeywell) was equipped underneath each key which enabled us to measure participants' isometric force threshold production.

Additionally, each key was equipped with a linear resonant actuator (LRA, LVM061930B-L20, Jinlong Machinery & electronics Inc.) that provided haptic feedback during the experiment. The haptic stimulation was produced by a haptic motor controller (DRV2605L, Adafruit Industries LLC) that can produce a computer controlled click sensation.

a.



b.

Trained sequences
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41524312435
12452315314
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Figure 1. (a) Non-depressible five-finger isometric keyboard. (b) Trained sequences. Each participant was presented with all four 11-digit trained sequences throughout the five sessions.

Stimuli

A discrete sequence production task (DSP) was used in the current study where participants produced 11-digit keypresses. For each trial a set of 11-digit sequences were displayed on the screen (see Figure 1b). These sequences were chosen to allow for various finger press transitions without having the same number repeat back to back. The four 11-digit sequences were presented in random order. Each key corresponded to the number on the screen and ranged from one to five (e.g., thumb = 1, index = 2, etc.). A press was registered if

the force threshold surpassed 1N. Participants received one of 3 kinds of sensory feedback upon a correct keypress:

Visual feedback (N=25): Numbers presented on the screen changed from white to green when participants pressed the correct key.

Auditory feedback(N=23): Each key was paired with a tone that was played upon reaching the press threshold.

Haptic feedback(N=16): The haptic group felt a slight vibration under each individual key they pressed.

Participants were told that they could take their time before starting each trial as reaction time was not taken into consideration. Participants were told to press the keys in a serial manner, however, no pause was necessary between finger presses which led to some co-articulation between fingers. If an incorrect key was pressed, all three feedback groups received a visual cue (i.e., number on the screen turning red) indicating which press was incorrect. This aided in showing the participant where in the sequence they made the mistake. It should be noted that incorrect presses were excluded from the analysis. Nonetheless, participants were asked to finish the sequence as correctly as possible upon making a mistake. The auditory group additionally received a separate auditory tone when an error was made.

Procedure

All participants were asked about their musical experience where 73% (N = 47) of participants responded having at least a year of musical training with 43.8% (N= 28) of those participants having piano experience for an average of 2.4 years. The study protocol was approved by the ethics board of the University of Western Ontario (see Appendix A).

Prior to the start of the main 5-day experiment, participants were presented with a set of 4 practice blocks (20 trials each) which consisted of 4 sequences that were different from the sequences participants would later train on. At the end of the practice blocks, the results were plugged into a custom MATLAB script that was used to assign participants based on their average speed to one of three groups (i.e., auditory feedback, visual feedback or haptic feedback group). This insured that there was an even distribution of both fast and slow participants amongst the groups. Participants were given 13 blocks of trained sequences during each session (excluding the first session where participants were only given 7 blocks of trained sequences). Each block consisted of 32 trials (each sequence was presented 8 times). At the end of the 5^{th} training day all participants were given four additional blocks where the sensory feedback was removed. In these four blocks the visual group no longer saw the number cue turn green, the auditory group no longer heard the tones and the haptic group did not receive the slight key vibration. Participants still received a visual cue when making an incorrect press.

Throughout the experiment, participants were asked to perform the sequences as fast and as accurate as possible while maintaining an error rate under 15%. Overall execution speed was measured from the first keypress to the release (0.5N) of the last keypress of a sequence (i.e., their movement time (MT)). At the start of each session participants MT threshold was set at 10,000 milliseconds. Sequences performed within 95% to 110% of the current MT threshold received 1 point. MTs that were faster than 95% of the current threshold received 3 points. Sequences that were incorrect or slower than 110% of the current MT threshold were given 0 points. The point system was used to motivate the participants. Each block ended with a summary of that participant’s median MT for all correct trials, error rate, the amount of points

they accumulated throughout the block and the total amount of points obtained from the session. After each block the MT threshold was changed to the participant's new median MT if the participant had an error rate below 15% and a median faster than their current threshold. If either of these two criteria were not met the MT threshold stayed the same.

Statistical analysis

Participants' movement time (MT- time between the first press and last release) was examined for each block. A custom MATLAB script (The MathWorks) was used to analyze the data. Trials where the participants committed an error were excluded from the statistical analyses. An analysis of covariance (ANCOVA) of participant's movement time on the last day of training was used to compare the amount of learning between the feedback groups. Performance from day 1 was used as the covariate variable in the analyses to control for any confounding effects it may have on the results (e.g., varying starting MTs). Independent two-sample t-tests on the adjusted data were then used to calculate the differences between groups. To examine how much feedback removal hindered performance across the groups, an analysis of variance (ANOVA) with within factor of Feedback (present or absent) and between factor of Group (auditory, visual, haptic) was used. Independent-two-sample t-tests were then conducted to observe if performance detriment differed between groups when feedback was removed. For this analysis, the first two blocks of the last testing day (with feedback present) were removed from the analyses as we observed the greatest variability in performance across the days in the first two blocks; likely related to the fact that participants had a prolonged break between sessions. A probability threshold of $p < 0.05$ was used in all analyses to reject the null hypothesis.

Results

Throughout the course of 5 days a total of 64 participants produced sequences of 11 isometric keypresses on a keyboard-like device with sensory feedback. Points were rewarded to participants based on accuracy and speed. Participants were asked to perform the sequences as fast as possible while keeping the error rate below 15%. Participant's movement time (MT) threshold was decreased as a way to motivate participants to increase their speed.

Participants were assigned to one of the three sensory feedback groups (i.e., visual, auditory or haptic). The objective of the study was to observe which sensory feedback enhanced sequence learning the most. Each group received a different kind of feedback: the visual group observed the numbers on the screen turn green for each correct press, the auditory group heard a different sound for each correct key and the haptic group felt a slight vibration for each press. During the last session, feedback was removed on the last 4 blocks to test if performance would be hindered. All participants were given the same set of 4 sequences (Methods, Fig. 1b) but differing in the kind of sensory feedback they received (based on their group assignment).

Enhanced performance in all groups

All groups showed enhanced performance with learning over the 5 days of training (Fig. 2: Main effect of day: $F_{(4,244)} = 450.4$, $p < 0.001$).

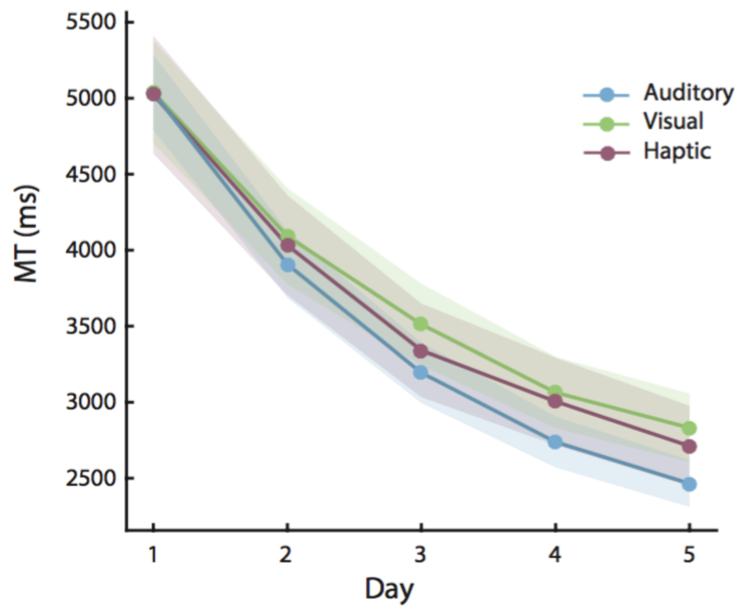

Figure 2. Changes in performance across days. Average movement time (MT) in ms of each group throughout the course of 5 days. Shaded areas represent the standard error of the mean.

Auditory feedback enhances performance to a greater extent than visual feedback

Performance differences on the last day of training were measured to understand the influence of sensory feedback on sequence learning. Differences in MT at the end of learning would suggest that the learning was differently enhanced by the distinct feedback types. An ANCOVA with participants' performance on day 5 as dependent variable and their performance on day 1 as covariate, showed a significant group effect. Post-hoc independent t-tests on the adjusted data displayed a significant difference between the auditory group and visual group where learning was greater in the auditory group (Fig.3: $t_{(44)} = -2.075$, $p = 0.044$). The significant difference between the auditory and visual groups suggests that auditory feedback enhanced

sequence learning to a greater degree in comparison to visual feedback. However, haptic feedback did not significantly enhance motor sequence learning when compared to either auditory feedback ($t_{(35)}$ = -0.897, p = 0.376) or visual feedback ($t_{(37)}$ = 0.879, p = 0.385).

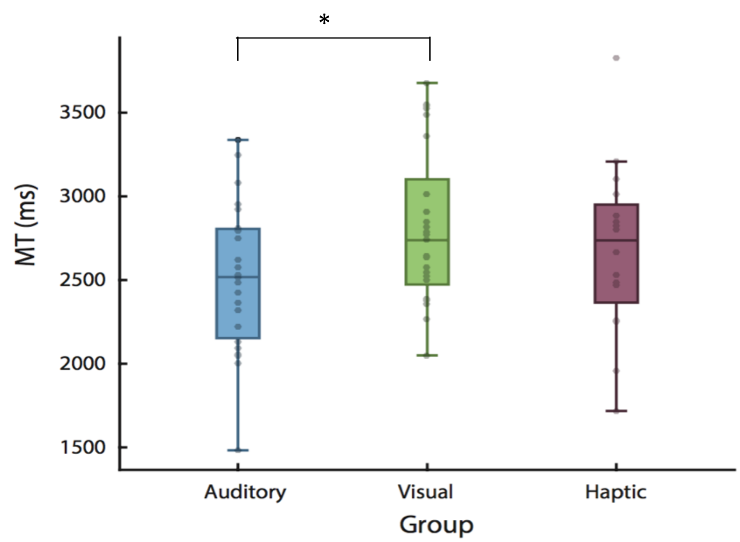

Figure 3. Difference in sequence learning on day 5. Difference in MT on day 5 adjusted for participants' performance of day. The asterisk indicates a significant difference in performance.

Feedback reliance

To show whether performance was hindered upon removing sensory feedback, participants executed the sequences with no feedback (i.e., auditory group no longer heard a tone, visual group did not see digits turn green, and haptic group did not feel the slight vibration). To analyze whether performance decreased when feedback was removed, participants' MT on the last six testing blocks with feedback was compared to the last four blocks without feedback during the last session. To assess whether the groups differed in how

much detriment the removal of feedback caused, we examined the difference in MT before feedback was removed to after and compared this difference across the feedback groups. The haptic group displayed a greater decline in performance compared to the auditory group when feedback was removed (Fig. 4: $t_{(37)} = 3.124$, $p = 0.003$). As such, the haptic group displayed a greater reliance on feedback compared to the auditory group. In contrast, there was no significant difference in performance detriment between the haptic and visual group ($t_{(39)} = -1.360$, $p = 0.182$) or the auditory and visual group ($t_{(46)} = 1.952$, $p = 0.057$) when feedback was removed.

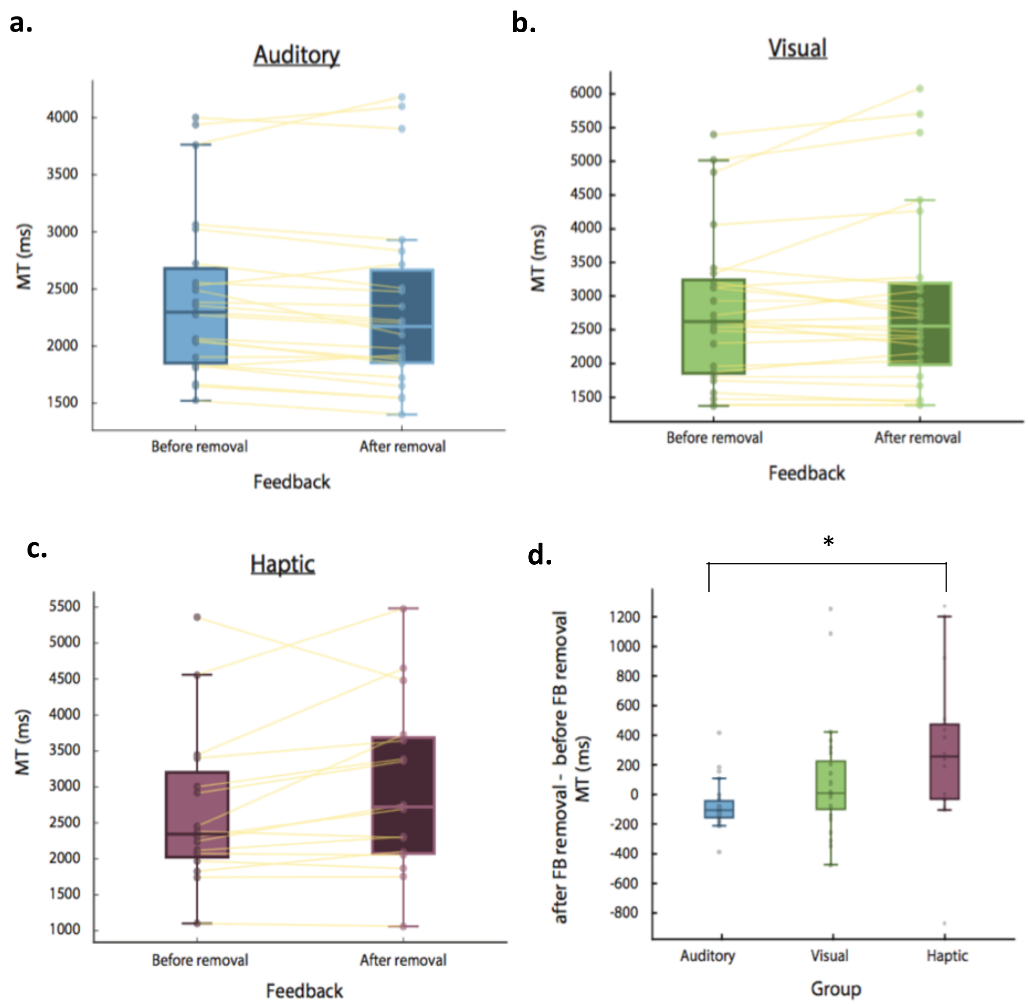

Figure 4. Performance before and after feedback removal. A, b & c: Dots represent each participant's measured MT before or after feedback removal and each participant is represented by a yellow line. D: The y-axis displays the MT difference (after-before feedback removal) for each group. A MT difference above zero implies a decline in performance upon feedback removal.

Discussion

The current study used a sequence learning task to analyze how auditory, visual and haptic feedback influence motor learning. Specifically, the study was carried out to answer two questions: do auditory and haptic feedback aid more in sequence learning compared to visual

feedback in a task that relies more on auditory and haptic feedback? Is performance hindered to a greater extent when removing the feedback that aids the most in motor learning compared to removing other types of feedback? Participants were assigned to one of the three feedback groups and were given training sequences that they were asked to execute as fast and as accurate as possible. By manipulating the type of sensory feedback each group received, movement time could then be used to analyze how fast learning progressed throughout the five training sessions. Feedback was removed during the last four blocks on day 5 to observe if performance was hindered.

The findings in this study displayed that all three groups showed enhanced performance with learning over the course of the five days. In contrast to previous findings (Colavita et al., 1976; Colavita et al.,1979; Morris, 1976) that proposed visual feedback facilitated greater motor learning in comparison to other types of feedback, the current study found that auditory feedback enhanced participants' performance to a greater extent when compared to visual feedback. The haptic group showed no significant differences in learning when compared to the auditory or visual group. The findings of our study are important as they propose that performance on a motor learning task may be enhanced by the feedback that is most relevant to the task's success. This idea is supported by previous research conducted by Walker and Scott (1981) whose study observed the influence of auditory and visual feedback on an auditory-visual task in which they concluded that performance was markedly influenced by auditory feedback as it was more relevant to the task's success.

As the current sequence learning task may be compared to a piano playing task, it may be suggested that auditory feedback plays a greater role in increasing performance on tasks

that resemble a piano-like task, in contrast to visual feedback. This may be supported by evidence from piano players who tend to close their eyes during their performance, as well as piano players who are blind or visually impaired. For instance, John William Boone (“Blind Boone”) was known as a great pianist and performer who was blind (Harrah, 2004). This asserts the prediction that that visual feedback is less significant to different forms of piano-like tasks (Wöllner& Williamon, 2007). As such, it may be concluded that auditory cues are more important for the current task than visual cues.

In addition to observing the enhancing effects of sensory feedback on sequence learning, feedback removal was tested to explore how performance may be hindered when the feedback that participants trained with is no longer accessible. In contrast to our prediction that the type of feedback that increases sequence learning to a greater extent would also lead to more dependence, the auditory group’s performance did not decline to the same extent as the haptic group’s performance when feedback was removed. In fact, the haptic group showed a greater decline in performance after feedback removal compared to the auditory group but not compared to the visual group. This suggests that participants were more reliant on haptic information at the end of learning to achieve a given performance level compared to the group that were trained with auditory feedback. These results thus propose, that performance may be increased by the sensory modality that is most related to the task’s success, however, the feedback that enhanced sequence learning to a greater extent (when compared to other sensory feedback) may not decrease performance once it is removed. The auditory group’s less affected performance, upon removing their feedback, advocates that the auditory group gained

a motor control strategy that gradually became less dependent on the given sensory feedback as training progressed (Ronsse et al., 2010).

Interestingly, whereas the auditory group and haptic group did not show significant differences in the amount of sequence learning at the end of training, the haptic group showed a greater performance decline upon feedback removal compared to the auditory group. This finding is supported by Wöllner and Williamon (2007) whose results displayed that during a piano-like task although auditory feedback initially displayed to be the most relevant to the task's performance, the removal of haptic feedback hindered performance to greater extent in comparison to the removal of auditory feedback. Wöllner and Williamon (2007) suggest that the auditory group's unaffected performance when feedback was removed may be attributed to strong mental images that were formed using the sensory information that was given during the study. This phenomenon may also correspond to the current study and suggest that during a sequence learning task stronger mental images are formed by auditory feedback in comparison to haptic feedback.

Limitations & future directions

While each group received their individual feedback (i.e., the auditory group heard a tone, the visual group saw the digits change from white to green and the haptic group felt a slight vibration), it may be argued that all participants still received visual feedback by seeing their finger placement on the isometric key-board like device. Thus, participants had a second input of sensory feedback (i.e., seeing their finger presses) to coordinate a response; the task uses visuomotor control, which suggests that the introduction of the auditory feedback may enable parallel processing. In other words, auditory feedback augments visuomotor control

instead of being a confounding variable and thus enhancing performance on the given task (Rosati, Oscari, Spagnol, Avanzini & Masiero, 2012). Consequently, the visual cues (i.e., finger presses) may have led to the auditory group to display faster MTs when compared to the visual group on the last day (Rosati et al., 2012). In contrast, the visual group were only exposed to visual cues (i.e., given visual feedback and seeing their finger placements). Past literature suggests that performance may not be augmented when participants receive the same type of information cues (Rosati et al., 2012). However, the haptic group also saw their finger placement on the keyboard but their performance was not significantly different from the visual group. As such, it may be concluded that the additional visual information participants received during the task (i.e., seeing their finger placements on the keyboard) most likely did not play a key role in the result. However, it is still important for future studies to develop a similar sequence learning paradigm but control for the participant's ability to see their finger placement on the keyboard to control for the confounding visual cues.

Furthermore, all participants were given visual feedback that displayed when they made incorrect presses (i.e., the numbers turned red) and thus, it may be argued that participants received more than one feedback during the task. The visual stimuli for incorrect presses allowed the participants to note where in the sequence they made a mistake and to continue finishing the sequence. However, incorrect presses were excluded from the analyses and therefore did not influence the performance results.

An important future step will be to investigate whether we observe similar reliance results when participants receive all 3 types of feedback during learning and feedback is removed for one feedback type at a time. Based on our current results, it is expected that the

removal of haptic feedback would lead to the greatest performance detriment. This would strengthen the idea that motor sequence performance does not rely similarly on all feedback types.

Additionally, another future direction would be to develop a study where either visual or haptic feedback would be predicted to enhance performance to a greater extent in comparison to auditory feedback. This would then affirm our findings that performance is greatly influenced by the feedback most relevant to task's success in comparison to other types of feedback.

Conclusion

The current study illustrates how different feedback types can have distinct influences on the acquisition of a new motor skill (i.e., sequence learning). The experiment demonstrates that learning can be adopted through sensory feedback, however, motor learning may be enhanced to a greater degree by the modality most relevant to the task. The study also establishes, that performance does not become reliant on the feedback that is greatly associated to the tasks' success. The task design allows for future experiments to better understand the influence of sensory feedback on sequence learning.

References

Adams, J. A. (1971). A Closed-Loop Theory of Motor Learning. *Journal of Motor Behavior*, *3*(2), 111–150. doi: 10.1080/00222895.1971.10734898

Adams, J. A., Goetz, E. T., & Marshall, P. H. (1972). Response feedback and motor learning. *Journal of Experimental Psychology*, *92*(3), 391–397. doi: 10.1037/h0032358

Adams, J. A., Gopher, D., & Lintern, G. (1977). The effects of visual and proprioceptive feedback on motor learning. *PsycEXTRA Dataset*. doi: 10.1037/e573672012-004

Baumann, S., Koeneke, S., Meyer , M., Lutz, K., & Jancke, L. (2005). A Network for Sensory-Motor Integration: What Happens in the Auditory Cortex during Piano Playing without Acoustic Feedback? *Annals of the New York Academy of Sciences*, *1060*(1), 186–188. doi: 10.1196/annals.1360.038

Carlton, L. G. (1981). Processing visual feedback information for movement control. *Journal of Experimental Psychology: Human Perception and Performance*, *7*(5), 1019–1030. doi: 10.1037//0096-1523.7.5.1019

Colavita, F. B. (1974). Human sensory dominance. *Perception & Psychophysics*, *16*(2), 409–412. doi: 10.3758/bf03203962

Colavita, F. B., Tomko, R., & Weisberg, D. (1976). Visual prepotency and eye orientation. *Bulletin of the Psychonomic Society*, *8*(1), 25–26. doi: 10.3758/bf03337062

Colavita, F. B., & Weisberg, D. (1979). A further investigation of visual dominance. *Perception & Psychophysics*, *25*(4), 345–347. doi: 10.3758/bf03198814

Coles, T. R., Meglan, D., & John, N. W. (2011). The Role of Haptics in Medical Training Simulators: A Survey of the State of the Art. *IEEE Transactions on Haptics*, *4*(1), 51–66. doi: 10.1109/toh.2010.19

Conde, V., Altenmüller, E., Villringer, A., & Ragert, P. (2012). Task-Irrelevant Auditory Feedback Facilitates Motor Performance in Musicians. *Frontiers in Psychology*, *3*. doi: 10.3389/fpsyg.2012.00146

Harrah, M. (2004). *Blind Boone piano prodigy*. Minneapolis: Carolrhoda Books.

Hay, L., & Beaubaton, D. (1986). Visual Correction of a Rapid Goal-Directed Response. *Perceptual and Motor Skills*, *62*(1), 51–57. doi: 10.2466/pms.1986.62.1.51

Hecht, D., & Reiner, M. (2008). Sensory dominance in combinations of audio, visual and haptic stimuli. *Experimental Brain Research*, *193*(2), 307–314. doi: 10.1007/s00221-008-1626-z

Marchal-Crespo, L., Raai, M. V., Rauter, G., Wolf, P., & Riener, R. (2013). The effect of haptic guidance and visual feedback on learning a complex tennis task. *Experimental Brain Research*, *231*(3), 277–291. doi: 10.1007/s00221-013-3690-2

Morris, D., Tan, H., Barbagli, F., Chang, T., & Salisbury, K. (2007). Haptic Feedback Enhances Force Skill Learning. *Second Joint EuroHaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems (WHC07)*. doi: 10.1109/whc.2007.65

Oldfield, R.c. “The Assessment and Analysis of Handedness: The Edinburgh Inventory.” *Neuropsychologia*, vol. 9, no. 1, 1971, pp. 97–113., doi:10.1016/0028-3932(71)90067-4.

Proteau, L., Marteniuk, R. G., Girouard, Y., & Dugas, C. (1987). On the type of information used to control and learn an aiming movement after moderate and extensive training. *Human Movement Science*, *6*(2), 181–199. doi: 10.1016/0167-9457(87)90011-x

Ronsse, R., Puttemans, V., Coxon, J. P., Goble, D. J., Wagemans, J., Wenderoth, N., & Swinnen, S. P. (2010). Motor Learning with Augmented Feedback: Modality-Dependent Behavioral and Neural Consequences. *Cerebral Cortex*, *21*(6), 1283–1294. doi: 10.1093/cercor/bhq209

Rosati, G., Oscari, F., Spagnol, S., Avanzini, F., & Masiero, S. (2012). Effect of task-related continuous auditory feedback during learning of tracking motion exercises. *Journal of NeuroEngineering and Rehabilitation*, *9*(1), 79. doi: 10.1186/1743-0003-9-79

Sigrist, R. (2011). Visual and Auditory Augmented Concurrent Feedback in a Complex Motor Task. *Presence: Teleoperators and Virtual Environments*, *20*(1), 15–32. doi: 10.1162/pres_a_00032

Sigrist, R., Rauter, G., Riener, R., & Wolf, P. (2012). Augmented visual, auditory, haptic, and multimodal feedback in motor learning: A review. *Psychonomic Bulletin & Review*, *20*(1), 21–53. doi: 10.3758/s13423-012-0333-8

Sinnett, S., Spence, C., & Soto-Faraco, S. (2007). Visual dominance and attention: The Colavita effect revisited. *Perception & Psychophysics*, *69*(5), 673–686. doi: 10.3758/bf03193770

Walker, J. T., & Scott, K. J. (1981). Auditory–visual conflicts in the perceived duration of lights, tones, and gaps. *Journal of Experimental Psychology: Human Perception and Performance*, *7*(6), 1327–1339. doi: 10.1037/0096-1523.7.6.1327

Wöllner, C., & Williamon, A. (2007). An exploratory study of the role of performance feedback and musical imagery in piano playing. *Research Studies in Music Education*, *29*(1), 39–54. doi: 10.1177/1321103x07087567

Zhu, B., Kaber, D., Zahabi, M., & Ma, W. (2019). Effects of feedback type and modality on motor skill learning and retention. *Behaviour & Information Technology*, *39*(4), 431–442. doi: 10.1080/0144929x.2019.1599068

Appendix A

Western Research

Date: 29 April 2019

To: Prof. Joern Diedrichsen

Project ID: 108479

Study Title: Studies of the acquisition and control of skilled finger movements.

Application Type: Continuing Ethics Review (CER) Form

Review Type: Delegated

Meeting Date: 07/Jun/2019

Date Approval Issued: 29/Apr/2019

REB Approval Expiry Date: 15/May/2020

Dear Prof. Joern Diedrichsen,

The Western University Non-Medical Research Ethics Board has reviewed this application. This study, including all currently approved documents, has been re-approved until the expiry date noted above.

REB members involved in the research project do not participate in the review, discussion or decision.

The Western University NMREB operates in compliance with the Tri-Council Policy Statement Ethical Conduct for Research Involving Humans (TCPS2), the Ontario Personal Health Information Protection Act (PHIPA, 2004), and the applicable laws and regulations of Ontario. Members of the NMREB who are named as Investigators in research studies do not participate in discussions related to, nor vote on such studies when they are presented to the REB. The NMREB is registered with the U.S. Department of Health & Human Services under the IRB registration number IRB 00000941.

Please do not hesitate to contact us if you have any questions.

Sincerely,

Daniel Wyzynski, Research Ethics Coordinator, on behalf of Prof. Randal Graham, NMREB Chair

Note: This correspondence includes an electronic signature (validation and approval via an online system that is compliant with all regulations).

Appendix B

Western

LETTER OF INFORMATION FOR PARTICIPANTS

Studies of the acquisition and control of skilled finger movements

Principal Investigator:
Jörn Diedrichsen, Ph.D.
Departments of Computer Science and Statistics
University of Western Ontario, London, Ontario
jdiedric@uwo.ca
Phone: 519-661-2111 x 86994

Introduction

We would like to invite you to take part in an observational study in motor control. The purpose of the research is to determine how complex movement skills are learned and controlled. You are being asked to participate in this research, because we recruit participants without neurological disorders, with two functional upper limbs and with normal or corrected-to-normal vision. You should participate in this study only if you want to; you are not required to in any way. Before you decide whether you wish to take part, please read the information below. Please ask us if anything is unclear or you would like more information.

Research Procedures

If you agree to participate in this study, you will undergo multiple training and testing sessions. We will schedule the sessions during days that are most convenient for you. These sessions will involve behavioral training in the laboratory in the Brain and Mind Institute located in the Western Interdisciplinary Research Building on Perth Drive.

In these sessions, you will be seated in front of a finger box, which resembles a piano keyboard, and a monitor. You will be asked to make a sequence of key presses in a pre-specified order as quickly as possible – sometimes you also have to press multiple fingers at once in a coordinated pattern. The finger box will record the movement and force of each finger.

In some experiments, we might attach a number of adhesive electrodes to the surface of your skin to record your muscle activity. These electrodes will only be used for recording and never for stimulation. In other experiments you may be asked to look at the screen through an eye tracker, so that we can record the movements of your eyes. This will simply be done by resting your chin on the eye-tracker's chin rest.

After each activity, you will receive visual and/or auditory feedback on speed and accuracy. The testing is organized into blocks of trials of 3-6min length. After each block you will have the opportunity to take a break. Each session may take up to 2 hours. You may be asked to come to the testing centre for a single session or multiple sessions depending on which experiment you are completing.

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We anticipate enrolling 400 participants in total, with approximately 20 versions of the experiment involving 6 - 20 participants each. The research staff will let you know which experiment you will be completing as well as the expected duration and number of sessions involved at the time of consent.

Risks

The study has basically the same level of risk as working at a computer keyboard or practicing a musical instrument. The main risk is fatigue in the hand from the repetitive movement. The experimenter will offer you opportunity to take breaks during the experiment as often as you wish.

Benefits and compensation

There is no direct benefit to you from participating in this study. The results from this study may help us to better understand the brain regions underlying human motor learning.

You will be compensated for each session you attend, and will receive $10 for every hour of participation. Additionally, you will receive bonuses based on your performance during the motor task. On average the additional reward will be $5 an hour. If the study has to be stopped for any reason, compensation will be adjusted according to the fraction of the study that was completed.

Voluntary Participation / Withdrawal from Study

You should only participate in the study if you really want to; choosing not to take part will not disadvantage you in any way. At any time during the study, the experimenter may ask you to stop the study. This usually occurs for technical reasons. You can withdraw from the study at any point in time if you feel uncomfortable or tired –you just have to tell the experimenter that you wish to stop. Withdrawal will have no negative consequence for you or your academic status, and you will be paid for your time that you have spent on the experiment up to that point. You can also withdraw your data from the study at any time, without negative consequence for yourself, your academic status, or your reimbursement.

At a future date, we may ask whether you would be willing to participate in an additional study from our lab or institute. If you are interested in participating, please check and initial the "Contact for Future Studies" section on the Consent Form. You may freely decline to participate in any future studies and to be contacted further.

Confidentiality

Any information obtained from this study will be kept confidential. Any data resulting from your participation will be identified only by a participant code, without any reference to your name or personal information. A sheet linking you name to the participant code will be stored in a securely locked filing cabinet in a room that will be accessible only to the experimenters. Seven years after completion of the study these records will be destroyed. Representatives of the University of Western Ontario Health Sciences Research Ethics Board may require access to the study-related records or may follow up with you to monitor the conduct of the study. De-identified data will be kept past these seven years for future usage.

Name of Sponsor / Conflict of Interest

The research is supported by a startup grant from Western University, and a Scholar award from the James S. McDonnell Foundation. Neither of the funders has played any role in study design or analysis. None of the **Investigators has a financial interest in the outcome of the study.**

Consent Form
You do not waive any legal rights by signing the consent form. If you wish, we can provide you with a copy of this letter of information and the consent form.

Contact Information
A more complete and detailed description of the study is available from the principal investigator, Professor Jörn Diedrichsen (email: jdiedric@uwo.ca). Professor Diedrichsen will try to answer any questions that you may have.

If you have any questions about your rights as a research participant or the conduct of the study you may contact:

The Office of Research Ethics
Western University
519-661-3036
E-mail: ethics@uwo.ca

CONSENT FOR RESEARCH STUDY

Studies of the acquisition and control skilled finger movements

I have read the letter of information, have had the nature of the study explained to me, and I agree to participate. All questions have been answered to my satisfaction.

Dated in London, this__________ day of________________,20___.

Name of Participant (Please print): _____________________________________

Signature of Participant: ____

My signature means that I have explained the study to the participant named above. I have answered all questions.

Signature of Person Responsible
for Obtaining Consent:____

Name of Person Responsible
for Obtaining Consent (Please print):____________________________________

Date for Obtaining Consent: ____________________________________

Contact for Future Studies

Please check the appropriate box below and initial:

☐ I agree to be contacted for future research studies

☐ I do NOT agree to be contacted for future research studies