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Music-induced mood improves retention in visuomotor adaptation

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MUSIC-INDUCED MOOD IMPROVES RETENTION IN VISUOMOTOR

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Abstract

Learning to adapt motor outputs in response to changes in sensory feedback, or sensorimotor adaptation, is crucial to rehabilitation following injury or disease. Adapted movements are often forgotten when the sensory distortion is removed, creating a barrier to long-term rehabilitation. Binary success-error feedback and pictorial reinforcement have been shown to improve retention of adapted motor outputs. In one previous study, positively valenced music improved adaptation rate but had no effects on retention. Pleasurable music has been found to improve performance on spatial intelligence and cognitive tasks, possibly because of its mood- and arousal-enhancing qualities, and has been found to have similar neural properties as reward. In Experiment 1, participants who listened to music that induced a positive or negative mood increased retention of movements adapted to a visual feedback distortion in comparison to silence. In Experiment 2, the combination of reward feedback in adaptation and music that induced a positive mood decreased retention, possibly because the rewarding properties of the music which were present during training (no visuomotor distortion) overrode the rewarding properties of the reinforcement when it were no longer present. These experiments provide evidence for a novel method of improving retention in sensorimotor adaptation.

Keywords: sensorimotor adaptation, music, reinforcement, retention

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Firstly I would like to thank my advisor Dr. Li-Ann Leow who has devoted so much to this project over the past several months and whose advice has always been much appreciated; thanks for helping to make this one of the most valuable learning experiences of my undergraduate career. Thanks also to Dr. Christine Tsang, the second reader of this thesis, for valuable feedback and comments. I would also like to thank Dr. Jessica Grahn and the other members of her lab, especially the volunteers who assisted with some of the data collection.

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Introduction

Sensorimotor adaptation

Sensorimotor adaptation tasks involve learning to adapt movements in response to changes in sensory feedback, as a result of visual distortion (Kagerer, Contreras-Vidal, & Stelmach, 1997) or perturbations in limb dynamics (Shadmehr & Mussa-Ivaldi, 1994). Immediately following such a distortion, ability to achieve the goal of the movement is impaired, but with practice, people are able to adapt their movements to the distortion (Kagerer et al., 1997). When the perturbed feedback is removed, the adapted movement persists for a certain period of time before a return to regular movements (Shmuelof, Huang, Haith, Delnicki, Mazzoni & Krakauer, 2012). Sensorimotor adaptation can be used in the laboratory to examine various principles of motor learning, but it also occurs on a regular basis in everyday circumstances, and is highly relevant to rehabilitation in brain-injured patients (Shmuelof et al., 2012). A typical example of sensorimotor adaptation would be adjusting to a computer mouse that moves the cursor faster than expected (Bastian, 2008). At first a person in this situation would make many errors, but eventually they would adapt their movements to take into account the unexpected cursor feedback (Bastian, 2008). After adaptation has occurred and the person tries to use their old computer with slower mouse-cursor feedback again, they will initially make large errors again because of the persistence of the adapted movement (Bastian, 2008). Eventually, however, they will return to the original movements that they used for the slower feedback (Bastian, 2008). Some clinical applications of sensorimotor adaptation include the use of prism goggles to promote attention to the neglected side in hemineglect patients (Rossetti, Rode, Pisella, Farne, Li, Boisson, & Perenin, 1998), the use of split-

belt treadmills with different walking speeds to normalize locomotor asymmetry in stroke survivors (Reisman, Wityk, Silver, & Bastian, 2007), and the use of limb perturbation via a robot to normalize reaching movements, also in stroke survivors (Patton, Stoykov, Kovic, & Mussa-Ivaldi, 2006). A typical laboratory task examining sensorimotor adaptation might involve participants making movements from a start point to a target with their arm obscured from sight and a perturbation present, such as a distortion in the visual representation of the movement or a deflecting force on the arm (Huang, Haith, Mazzoni & Krakauer, 2011).

Sensorimotor adaptation is thought to occur through two mechanisms: a fast learning mechanism based on error feedback, and a slower, reinforcement-based mechanism (Shmuelof et al., 2012). The fast mechanism is influenced by discrepancies in predicted and observed sensory consequences of motor output (Tseng, Diedrichson, Krakauer, Shadmehr & Bastian, 2007) and is largely implicit; participants unintentionally adapt even when they are also using an explicit strategy to aim at a neighbouring target that will, as a result of the rotation, result in successfully hitting the goal target (Mazzoni & Krakauer, 2006). Reinforcement promotes adaptation through operant reinforcement of adapted movements (Huang et al., 2011) and may involve a direct reward such as a pictorial "explosion" of the target (Izawa & Shadmehr, 2011) or information about accuracy of movement based on visual feedback (Huang et al., 2011). Reinforcement-based learning can contribute to adaptation in the absence of error feedback. For example, when visual feedback of movement is removed and binary feedback regarding success at reaching the target is provided, adaptation occurs at a comparable rate as when online movement feedback is given (Izawa & Shadmehr, 2010). When error feedback is

present, information about success based on the feedback can act as a reward (Huang, Shadmehr, & Diedrichsenn, 2008). When participants learned several targets associated with different rotations and self-selected the amount of time spent practising each location, they repeated successful movements more frequently than would be beneficial if learning all rotations was the only goal of the task (Huang et al., 2008). This provides evidence for the proposition that successful movements in themselves can be rewarding, which is why participants repeated successful movements consistently rather than attempting new movements which would, initially, be unsuccessful and therefore unrewarding (Huang et al., 2008). Although the error-driven mechanism contributes to initial adaptation, it has been proposed that the reinforcement-driven mechanism promotes long-term retention (Shmuelof et al., 2012). When binary success-failure feedback was provided in the absence of error feedback, movements in the deadaptation stage – in which visual feedback resembled successful movements regardless of participants' actual movements – resembled the adapted movements for longer than when error feedback alone was provided (Shmuelof et al., 2012). Another factor that has been implicated in the increase of savings of an adapted movement is the repetition of the adapted movement (Huang et al., 2011). When the same hand movement was associated with successful adaptation of all targets, as opposed to slightly different hand movements, increased savings were demonstrated in relearning of the adaptation after a washout period (Huang et al., 2011). Initial adaptation occurs by fast, error-driven learning, while retention of the adapted movements appears to be influenced by reinforcement learning and repetition.

Although there is a plethora of research on various factors influencing sensorimotor adaptation and the processes contributing to this skill, there is a paucity of research on the role of state variables, such as motivation, arousal and fatigue (Seidler, Benson, Boyden & Kwak, 2013). One study did investigate the role of emotional state on visuomotor adaptation using different types of music to influence affect (Bock, 2010). Participants used a digital pen on a tablet to make movements to a target that appeared on a computer monitor, with a shroud occluding their hand from view (Bock, 2010). Those who listened to serene music throughout the task produced smaller directional errors (the angular difference between an ideal movement from the start point to the target and the participants' actual movements) after a 60 ° counterclockwise rotation, than did participants listening to sad or neutral music (Bock, 2010). According to self-report measures, all music produced low and similar levels of arousal, and serene music elicited the highest mood and sad music the lowest (Bock, 2010). Bock (2010) found that the magnitude of directional errors depended on type of music listened to only for the adaptation phase of the task, and not for the aftereffect phase, concluding that music-induced affect influences learning but not retention.

The Mozart Effect and rewarding properties of music stimuli

The finding that music influences adaptive success in sensorimotor tasks is perhaps not surprising, considering that there is a large literature on the beneficial effects of music on cognitive tasks, also known as the "Mozart effect" (Hetland, 2000). This line of research began with the finding that listening to Mozart prior to testing resulted in an 8-9 point increase in spatial-reasoning IQ, in comparison to listening to a relaxation tape, a short story, or to nothing (Rauscher, Shaw and Ky, 1993). This initial study spurred a

plethora of subsequent replications involving different control conditions and types of cognitive tasks (Hetland, 2000). Taken together, the results indicate that listening to Mozart, as well as other classical or classical-sounding contemporary music, for 8-15 minutes prior to testing does appear to temporarily enhance performance on spatial reasoning tasks in comparison to a variety of control conditions: silence, relaxation instructions, artificial or natural noise, and other types of music (Chabris, 1999; Hetland, 2000).

Initial explanations for this effect from the original authors appeal to music's ability to organize cortical firing patterns, particularly in the right hemisphere where spatial-temporal processing occurs (Rauscher, Shaw, & Ky, 1995). However, others have suggested that the Mozart effect is an artifact of the mood- and arousal-enhancing effects of music, and of the neutral or negative effects on mood and/or arousal of the various control conditions (Chabris, 1999). Support for this hypothesis comes from previous research demonstrating that music can significantly change mood and arousal, and that mood and arousal, in turn, affect cognitive functioning. The ability of music to alter both mood and arousal, as evidenced by measures of skin conductance, heart rate, finger pulse, and breathing, has been demonstrated (Krumhansl, 1997). The beneficial effects of positive mood and moderate arousal have been well-documented in a variety of settings and samples and for a variety of cognitive tasks (Ashby, Isen, & Turken, 1999). Ashby et al. (1999) report that randomly assigned positive affect, using diverse induction techniques and measures of cognitive performance, has been demonstrated to improve performance in over 25 experiments. For example, performance on creative problem-solving tasks is improved when positive mood is induced in the laboratory, for example

by viewing a comedy video or receiving candy (Estrada, Young, & Isen, 1994; Isen,

Daubman, & Nowicki, 1987), and creative word association is enhanced when positive

affect is induced by using positively-valenced words (Isen, Johnson, Mertz, & Robinsin,

1985). Memory enhancements have also been demonstrated: when experimenters

manipulated a computer game to cause participants to win, presumably inducing positive

mood, word recall was enhanced (Isen, Shalker, Clark, & Karp, 1978). Word recall has

also been enhanced in children when positive mood was induced by reflection upon a

positive episodic memory (Nasby & Yando, 1982). On the other hand, negative mood

and low levels of arousal are associated with deficits in performance on a variety of

cognitive tasks (O'Hanlan, 1981). Furthermore, in an accurate replication of the original

experiment by Rauscher et al. (1993), the Mozart piece produced significantly higher

mood ratings than the repetitive piece of music (Steele, Bass, & Crook, 1999).

Therefore, it is possible that the improved performance on cognitive tasks is due to the

positive effects of Mozart on mood, in comparison to negative or neutral effects on mood

produced by the various control conditions. The reason for differences in performance in

experiments where different pieces of music were used as controls can be explained by

each piece's differential effects on arousal and mood. For example, performance on a

modified version of a spatial task from the Stanford-Binet Intelligence Test was enhanced

for participants who listened to a pleasant and energetic Mozart piece, but did not differ

from the silence condition for participants who listened to a slow, sad piece of music

(Thompson, Schellenberg & Husain, 2001). Participants who had listened to Mozart

reported higher mood and arousal than those who listened to the slow, sad piece of music,

further confirming the hypothesis that the differences in performance were due to

differences in affect and arousal (Thompson et al., 2001). Indeed, improvements on spatial reasoning tasks such as that used by Rauscher et al. (1993) are not modified exclusively by music. When a short story by Stephen King was compared with Mozart, there was no difference between the two conditions on performance on a spatial-temporal task, except when individual reports of which condition they found more interesting and enjoyable were considered (Nantais & Schellenberg, 1999). Therefore the Mozart effect may exist because any mood- and arousal-enhancing condition improves cognitive performance (Nantais & Schellenberg, 1999).

The Mozart effect is therefore not exclusive to Mozart or to music in general, but is an artifact of the improvements in cognitive performance seen in individuals experiencing positive affect, a state that can be induced by many stimuli (Chabris, 1999). The ability of music to elicit specific emotions has been demonstrated by the finding that music reported to elicit a particular emotion is associated with patterns of autonomic nervous activity, such as skin conductance, heart rate, finger pulse, and breathing, that are similar to those found in participants in which the same emotion is induced with a non-musical stimulus (Krumhansl, 1997). Furthermore, these effects are not due to differences in tempo or rhythm in musical pieces that elicit different emotions (Khalfa, Roy, Rainville, Dalla Bella, & Peretz, 2008). When rhythm and tempo variations from happy and sad musical pieces were removed, differences in skin conductance, blood pressure and facial muscles persisted (Khalfa et al., 2008).

Emotional responses to music are also associated with distinct patterns of brain activity. Interestingly, many of the neural regions associated with listening to music that evokes positive emotion are also activated in response to rewards (Blood & Zatorre,

2001; Mitterschiffthaler, Fu, Dalton, Andrew & Williams, 2007; Salimpoor, Benovoy, Larcher, Daghore & Zatorre, 2011). Intensely pleasurable emotional responses to music, sometimes called "chills", were found by PET scan to activate the brain regions typically thought to be involved in pleasure and reward, such as the ventral striatum and anterior cingulate, regions that are also activated by other euphoria-inducing stimuli such as food, sex, and drugs of abuse (Blood & Zatorre, 2001). Similar results have been found using fMRI; music rated as pleasant tends to evoke activation in various brain regions that have previously been associated with reward, such as the ventral and dorsal striatum and anterior cingulate, while sad music elicited more activation in the amygdala, which has been associated with negative emotions (Mitterschiffthaler et al., 2007). Dopamine, a neurotransmitter known to be involved in reward mechanisms, is released from the ventral striatum when high emotional pleasure is experienced in response to music (Salimpoor et al., 2011).

Dopamine release is not associated with hedonic experiences per se but with beneficial deviations between expected and actual occurrences of reward (Berridge & Kringelbach, 2008; Schultz, 2002). The tendency for music to have a similar effect on the brain as reward can be understood in light of the evidence that reward prediction errors associated with music are what causes dopamine release (Gold, Frank, Bogert, & Brattico, 2013). For example, previous research has demonstrated that peak emotional pleasure is experienced when a musical piece introduces new or unexpected harmonies (Sloboda, 1991). Although there are probably other factors contributing to the release of dopamine during pleasurable music, positive reward prediction errors appears to be an important and viable cause of music-induced positive emotion (Gold et al., 2013). One

study has examined the ability of music to acts as a reward in a learning task in which participants learned to choose the more frequently rewarded stimuli (Gold et al., 2013). This task has been shown to depend on dopamine transmission (Frank, Seeberger, & O'Reilly, 2004), and the finding that pleasurable music was associated with better learning than neutral music, as indicated by lower reaction times, suggests that music-mediated dopamine release facilitates reinforcement learning (Gold et al., 2013). The authors suggest that music acts as a non-pharmacological dopamine enhancer, increasing the effects of dopamine-based reinforcement learning (Gold et al., 2013). Previous literature has distinguished between phasic dopamine release in response to stimuli, and tonic "background" dopamine which regulates the intensity of phasic dopamine responses by influencing the level of dopamine receptor sensitivity (Grace, 1991).

Study aims and hypotheses

Neuroimaging data suggest that music that evokes positive emotions acts in a similar manner as rewards do (Blood & Zatorre, 2001; Mitterschiffthaler et al., 2007; Salimpoor et al., 2011), and one previous study has found that positive emotions evoked by music improves reinforcement learning (Gold et al., 2013). These findings of improved reinforcement learning with music appear somewhat inconsistent with the finding that music does not affect the retention of sensorimotor adaptation (Bock, 2010). If positively valenced music facilitates reinforcement learning (Gold et al., 2013), and retention of sensorimotor adaptation is partially mediated by reinforcement learning (Huang et al., 2011), it could be expected that positively valenced music would enhance the reinforcement aspect of sensorimotor adaptation. Given that the reinforcement process of adaptation is thought to increase retention (Huang et al., 2011), music-induced

facilitation of reinforcement learning during the task would be expected to result in increased retention of the adapted movement. However, results of the only previous study examining the effects of music on sensorimotor adaptation were not consistent with this hypothesis (Bock, 2010). To further examine the effects of music on sensorimotor adaptation and to examine the hypothesis that music acts as a reward, two experiments were conducted. The first assessed the reliability of Bock's (2010) finding that low arousal, positively valenced music improves adaptive success while low arousal, negatively valenced music does not (Bock, 2010). Interestingly, results from Experiment 1 contradicted Bock's (2010) finding: music did not alter adaptation, but increased retention in the deadaptation phase, suggesting that, consistent with the neuroimaging data (Blood & Zatorre, 2001; Mitterschiffthaler et al., 2007; Salimpoor et al., 2011), music acts as an abstract reward. This finding motivated Experiment 2, in which direct rewards were provided during adaptation in order to test the hypothesis that music facilitates reinforcement learning (Gold et al., 2013). Based on previous findings that positively valenced music facilitated reinforcement learning (Gold et al., 2013), it was predicted that the conditions that previously led to more persistent aftereffects in the deadaptation phase (positively valenced, and, to a lesser extent, negatively valenced music) would be improved even further by the direct reward.

Experiment 1
Method

Participants

Forty-six undergraduate students at the University of Western Ontario (32 female; mean age = 18.88 years) were recruited for partial course credit. All participants had normal or corrected-to-normal vision, were right-handed, and had no hearing or

neurological deficits. The study was approved by the Research Ethics Board of the University of Western Ontario.

Apparatus

Participants sat on a chair in front of a desk, on which there was a digitizing tablet (Intuos 5 Touch Large Pen Tablet; width of 48.77 cm, length of 31.75 cm, height of 1.27 cm; 260.1 cm^2 of active area; resolution 0.05 mm) underneath a stand (width of 53.34 cm, length of 38.10 cm, height of 25.40 cm). Participants made movements on the tablet using a digitizing pen (length of 15.7 cm long, diameter of 1.5 cm, weight of 17 g). On top of the stand was a laptop which displayed the pen's position on the tablet with a radius of 5 pixels. A movement of 3.5 cm on the tablet produced a 7 cm movement on the screen. Also displayed on the top monitor were a start circle (8 pixels) and a target (23 pixels). The target alternated between three possible equidistant locations (7.5 cm from the start point): either directly above or 45° to the left or right of the start point. Custom software written in LabVIEW 12.0 recorded the data. Participants used headphones (Sennheiser HD 280 Pro) to listen to music throughout the task.

Stimulus Materials

The musical stimuli were selected from a database of music clips created in 2011-2013 that had been previously rated on arousal and mood. Of songs rated as low in arousal, 10 with the highest mood rating and 16 with the lowest mood rating were selected and placed into the low arousal positively valenced and low arousal negatively valenced conditions, respectively.

Procedure

Participants were randomly assigned to either the positive music condition, the negative music condition, or the silent condition. They were then given a music ratings task, in which they were asked to individually rate either all of the positive or negative songs, depending on the condition. Each song required a rating on familiarity, enjoyment, arousal level of the music, mood of the music, and the participant's mood after listening to the music, on a scale of 1-10. Participants were encouraged to use the full scale and to listen to as much of each song as they felt was necessary in order to accurately complete the scale. The experimenter then selected the song that was rated highest (for positive) or lowest (for negative) in induced mood to play for the rest of the experiment. Participants in the silent condition rated the positive and negative songs used in the original Bock (2010) study.

At the start of the sensorimotor adaptation task, a series of instructions appeared on-screen and were read to the participant by the experimenter. The instructions informed the participant that their task was to move the cursor from the start point to a target in a single straight movement, as quickly and accurately as possible, and to move with the elbow rather than the wrist. Finally, the participants were told that: "From time to time, the feedback of your movement will be altered. Your job is to alter your movement is response to this alteration in feedback".

The adaptation task consisted of 90 practice trials (30 per target location), followed by 300 adaptation trials (100 per target location) in which the visual feedback of the participants' movement was rotated by 60° counterclockwise. Finally, there were 60 deadaptation trials (20 per target location) in which normal visual feedback was restored.

The visual feedback was real-time, online feedback, and remained on-screen for 1 s after the trial had ended. After the adaptation task, participants (except those in the silence condition) once again completed the ratings scales for the song they had been listening to throughout the adaptation task. The entire procedure took approximately 50 minutes.

Data Analysis

Adaptation Phase

Two participants in the positive condition and three in the negative condition were excluded from the adaptation analysis because they were unable to complete the task in the allotted time period. Two participants each were removed from the positive and negative condition because their rating scales responses indicated that the music did not elicit the intended mood (a rating of induced mood between 4-6 was considered to be neutral). This resulted in a total of participants 14 positive participants, 13 negative participants, and 8 silent participants.

The XY coordinates of movements that were recorded by the computer program were used to calculate directional error (the distance between an accurate straight movement from the start point and the participants' actual movement). Directional error was scored at either 150 ms or at 25% of the movement trajectory, whichever came first. Directional errors greater than 120° were excluded from analysis because directional errors greater than twice the rotation suggest aberrations in the trials. This resulted in exclusion of 1.66% of all data. Directional errors were scored as negative when the error was counterclockwise to an ideal movement trajectory and positive when the error was clockwise to an ideal movement. Two repeated measures ANOVAs were conducted with directional error as the dependent variable: one using directional error in the first half of

trials (trials 2-151) and the second using directional error from the second half of trials (trials152-300), with bin (10 bins of 15 trials each) as a within-subjects factor and music condition (positive, negative or silence) as a between-subjects factor. In order to avoid averaging of negative and positive values, absolute values of directional errors were used in the directional error calculations.

Deadaptation Phase

In addition to the participants removed for the adaptation analysis, four participants were removed from the positive condition, three from the negative condition and two from the silent condition, due to an error in the computer program preventing recording of the deadaptation data, resulting in a total of 10 positive, 10 negative, and 6 silent participants. The deadaptation data was analyzed in the same manner as the adaptation data, except that there were only four bins of 15 trials each (trials 302-360) and one repeated measures ANOVA was conducted with all phases.

Results

Adaptation Phase

For the analysis of the first ten bins, a main effect of phase was identified, $F(4.45, 142.31) = 59.61$, $p < 0.001$, Greenhouse-Geisser adjusted. As shown in Figure 1, directional errors decreased across bins. There was no main effect of music condition, $F(2, 32) = 0.08$, $p > 0.05$, and no interaction effect, $F(8.89, 142.31) = 0.98$, $p > 0.05$, Greenhouse-Geisser adjusted. For the analysis of the last ten bins, there was no main effect of bin, $F(4.64, 148.57) = 1.68$, $p > 0.05$, Greenhouse-Geisser adjusted. There was no main effect of music, $F(2, 32) = 0.05$, $p > 0.05$, and no interaction effect, $F(9.29, 148.58) = 0.81$, $p > 0.05$, Greenhouse-Geisser adjusted.
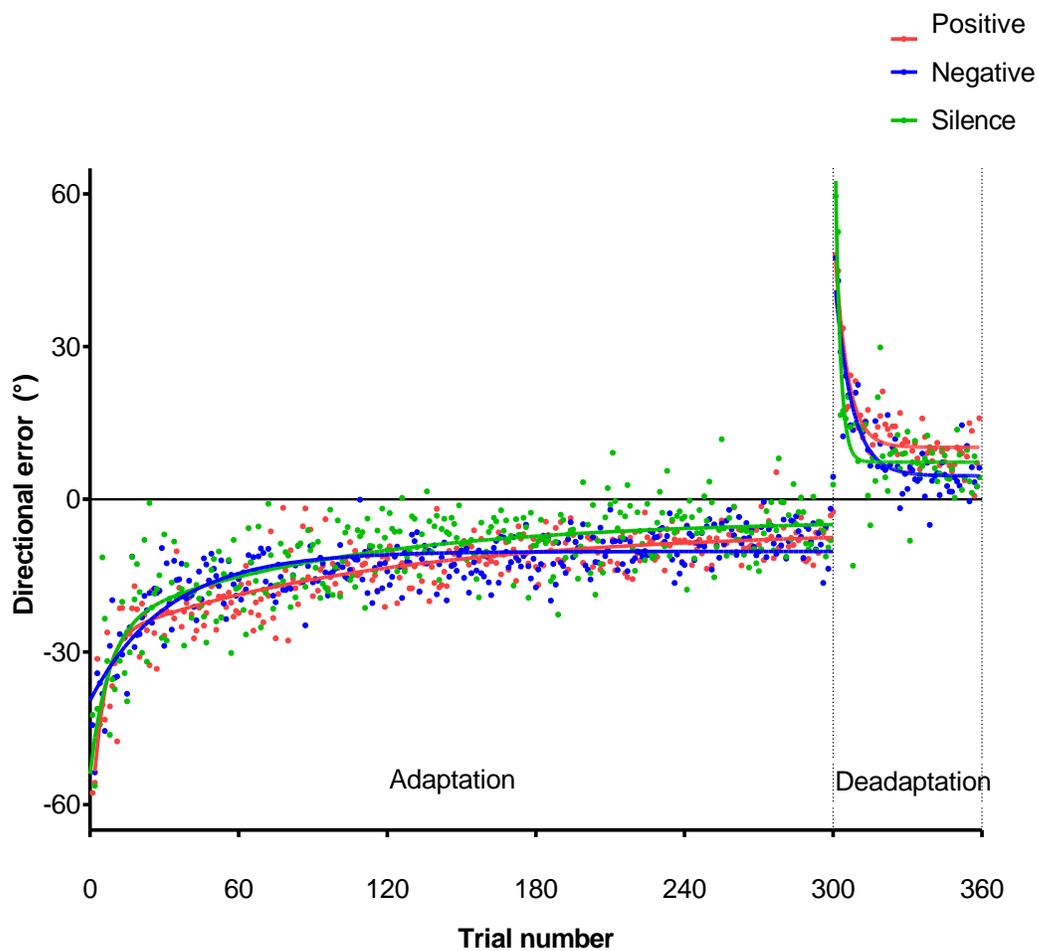
Figure 1. Average directional errors across trials for participants listening to positive music, negative music or silence. Directional errors decrease across trials.

Deadaptation Phase

A main effect of bin was identified, $F(1,23) = 22.34$, $p < 0.05$, Greenhouse-Geisser adjusted. As shown in Figure1, directional errors decreased across trials. There was no main effect of music condition, $F(2, 23) = 1.92$, $p > 0.05$, and no interaction effect, $F(2, 23) = 96.85$, $p > 0.05$, Greenhouse-Geisser adjusted. However, differences between the means of the three conditions in the first bin were of interest and therefore three independent t-tests were conducted to examine pairs of interest, the results of which are displayed in Figure 2. Mean directional errors did not differ significantly between positive music ($M = 22.98$, $SD = 10.35$) and negative music ($M = 19.75$, $SD = 7.41$), $t(18) = 0.81$, $p > 0.05$, $d = 0.36$. Mean directional errors were larger for positive music ($M = 22.98$, $SD = 10.35$) than silence ($M = 13.01$, $SD = 9.77$), and although this difference missed significance, $t(14) = 1.90$, $p = 0.08$, there was a large effect size, $d = 0.99$. Mean directional errors were larger for negative music than for silence, again missing significance, $t(14) = 1.57$, $p > 0.05$, but yielding a large effect size, $d = 0.78$.

Experiment 2

Experiment 2 used the same apparatus, musical stimuli, procedure and data analysis process as Experiment 1. The only difference was that, during the adaptation phase when the participants made a reaching movement which was at peak velocity within 10° of an ideal movement to the target, two colourful images containing the words "Well Done" and "Bang" were presented as a binary reward. The images were presented on either side of the screen, at about the same height as the start point.
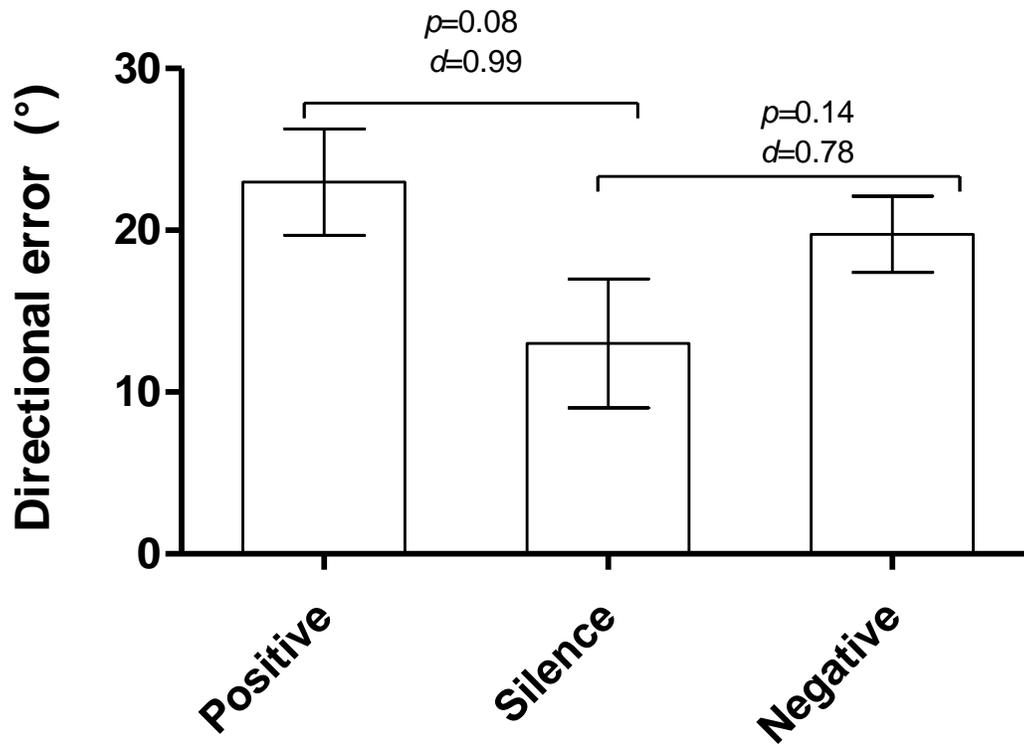
Figure 2. Mean directional errors for the first 15 trials of deadaptation (trials 302-316) for music inducing a positive mood, music inducing a negative mood, and silence. Error bars represent SEM.

Method

Participants

Thirty undergraduate students at the University of Western Ontario (16 females; mean age = 18.80 years) were recruited for partial course credit. All participants had normal or corrected-to-normal vision, were right-handed, and had no hearing or neurological deficits. The study was approved by the Research Ethics Board of the University of Western Ontario. For data analysis, two participants were removed from the negative condition and one from the positive condition due to neutral ratings on induced mood, resulting in 8 participants each in the negative and positive conditions, and 10 in the silent condition.

Results

Adaptation Phase

A significant main effect of bin was identified for the first ten bins, $F(2.77, 66.42) = 48.36$, $p < 0.05$, Greenhouse-Geisser adjusted. As shown in Figure 3, directional errors decreased across trials. There was no main effect of music condition, $F(2, 24) = 0.11$, $p > 0.05$, and no interaction effect, $F(5.54, 66.42) = 1.21$, $p > 0.05$, Greenhouse-Geisser adjusted. For the last ten bins, there was no main effect of bin, $F(5.19, 124.54) = 1.83$, $p > 0.05$, Greenhouse-Geisser adjusted, no main effect of music condition, $F(2, 24) = 0.26$, $p > 0.05$, and no interaction effect, $F(10.38, 124.54) = 1.61$, $p > 0.05$.

Deadaptation Phase

A significant main effect of bin was identified, $F(2.06, 47.30) = 50.53$, $p < 0.05$, Greenhouse-Geisser adjusted. As shown in Figure 3, directional errors decreased
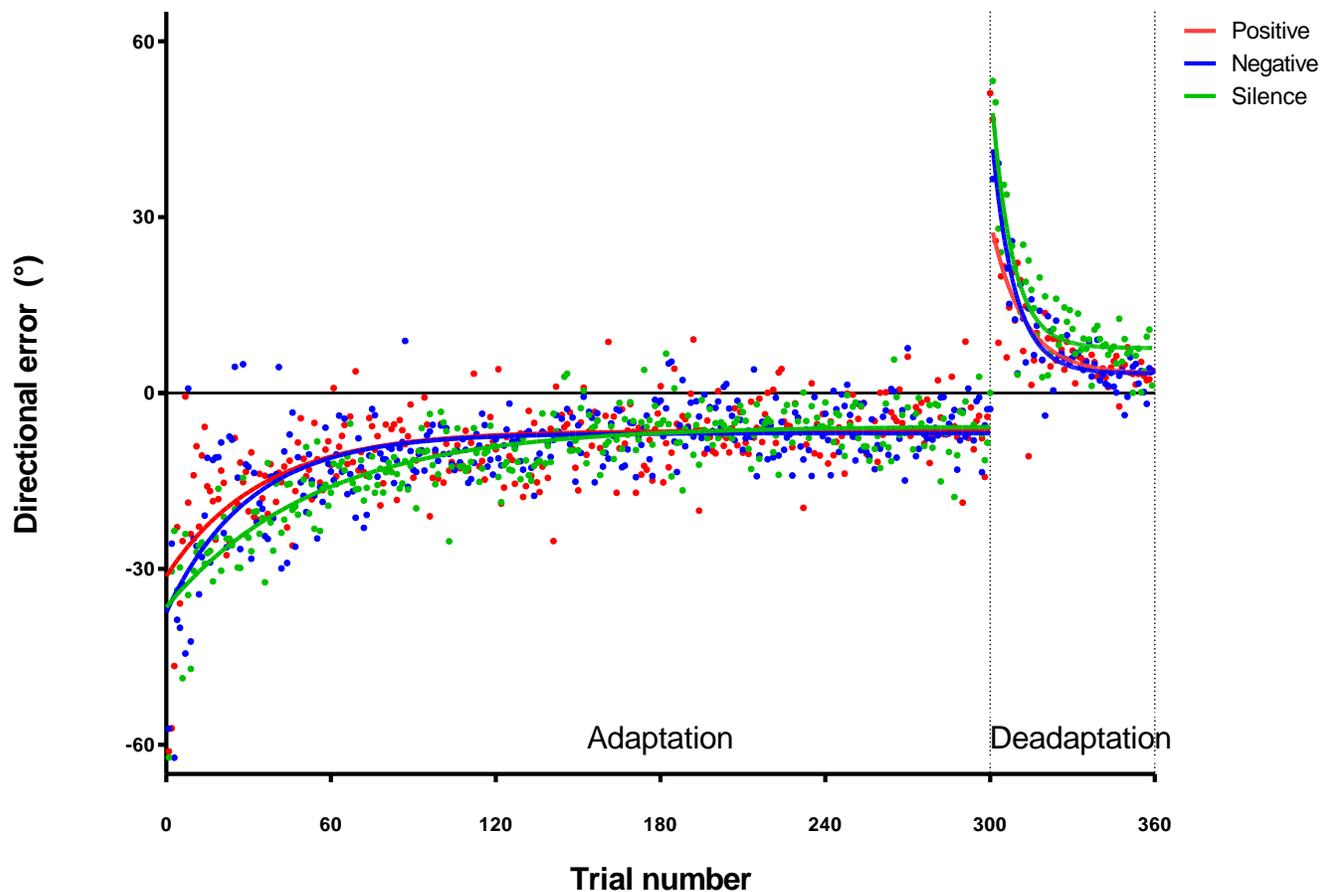
Figure 3. Average directional errors across trials for participants listening to positive music, negative music, or silence, with reward feedback given during the adaptation phase. Directional errors decrease across trials.

across trials. There was no interaction effect, $F(4.11, 47.30) = 1.78$, $p > 0.05$, Greenhouse-Geisser adjusted. A significant main effect of music condition was identified, $F(2, 23) = 3.51$, $p < 0.05$. Three independent t-tests were conducted to examine pairs of interest in the first bin, the results of which are displayed in Figure 4. The difference between the positive condition ($M = 13.11$, $SD = 1.96$) and the negative condition ($M = 20.48$, $SD = 8.86$) neared significance $t(14) = 1.99$, $p = 0.07$, and yielded a large effect size, $d = 1.02$. The means of the positive condition were significantly lower than those of silence ($M = 24.29$, $SD = 10.21$), $t(16) = 2.78$, $p = 0.01$, $d = 1.42$.

Comparison of Deadaptation Results of Experiment 1 and Experiment 2

A comparison of results of Experiments 1 and 2 was made to examine pairs of interest within the first bin (trials 302-316) of deadaptation. The silence condition without reward ($M = 13.01$, $SD = 9.77$) had significantly lower directional errors than the silence condition with reward, ($M = 24.29$, $SD = 10.21$), $t(14) = 2.17$, $p = 0.047$, $d = 1.13$. The positive condition without reward ($M = 22.98$, $SD = 10.35$) exhibited significantly higher directional errors than the positive reward condition ($M = 13.11$, $SD = 5.56$), $t(16)$ $= 2.42$, $p = 0.028$, $d = 1.24$. The mean directional errors in the first phase for each condition are displayed in Figure 5.

Ratings

The ratings of the song played for each participant throughout the adaptation task taken prior to and after the testing were analyzed and are displayed in Figure 6. There were no expected differences between ratings of songs in Experiment 1 and Experiment 2 and therefore, ratings data were collapsed across the two experiments and divided only into positive ($N = 26$) and negative ($N = 26$). Ratings from participants whose data had
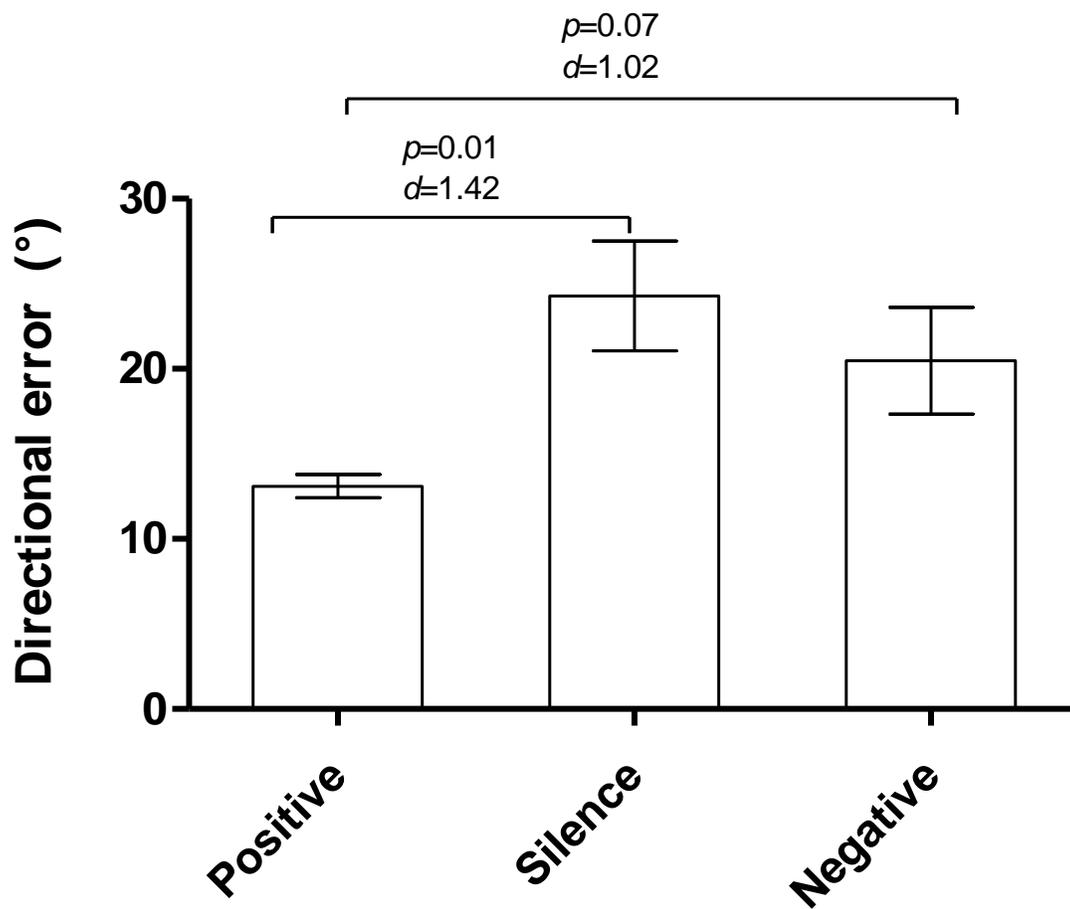
Figure 4. Mean directional errors for the first 15 trials of deadaptation (trials 302-316) for music inducing a positive mood, music inducing a negative mood, and silence for Experiment 2. Error bars represent SEM.
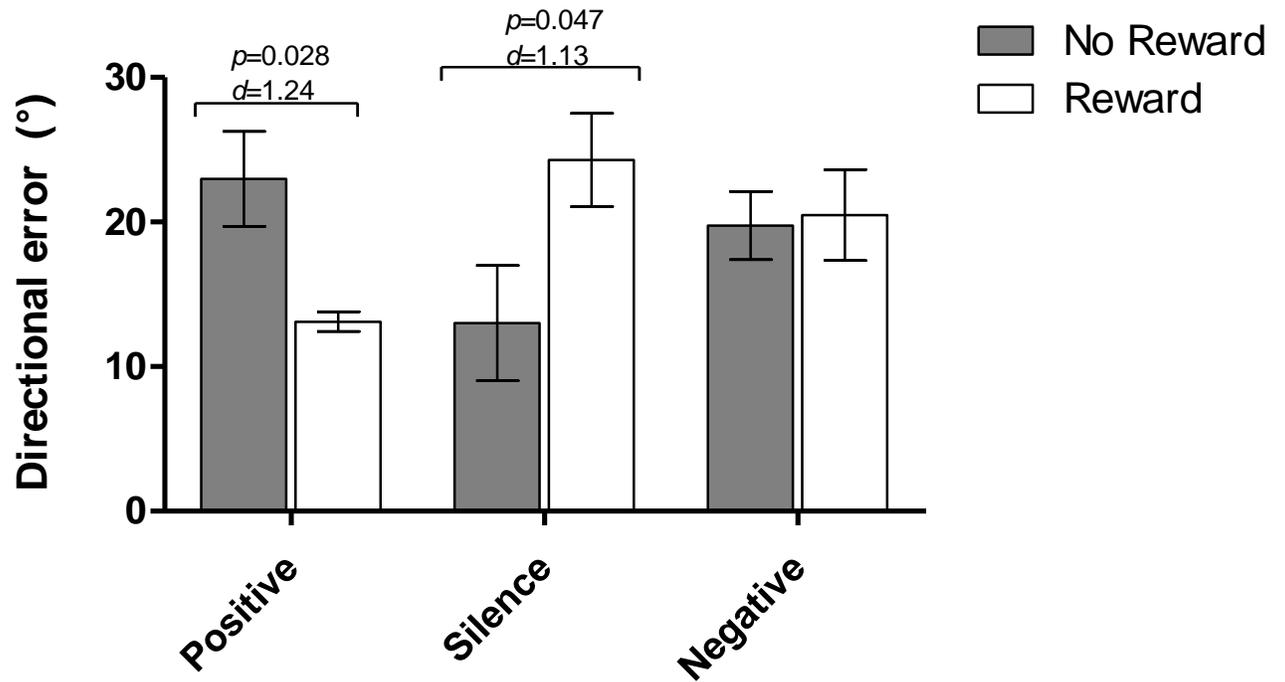
Figure 5.   Mean directional error for the first 15 trials of deadaptation (trials 302-316) music inducing a positive mood, music inducing a negative mood, and silence. Directional errors for positive no reward are significantly higher than those of positive reward and those of silence reward are significantly higher than those of silence no reward. Error bars represent SEM.
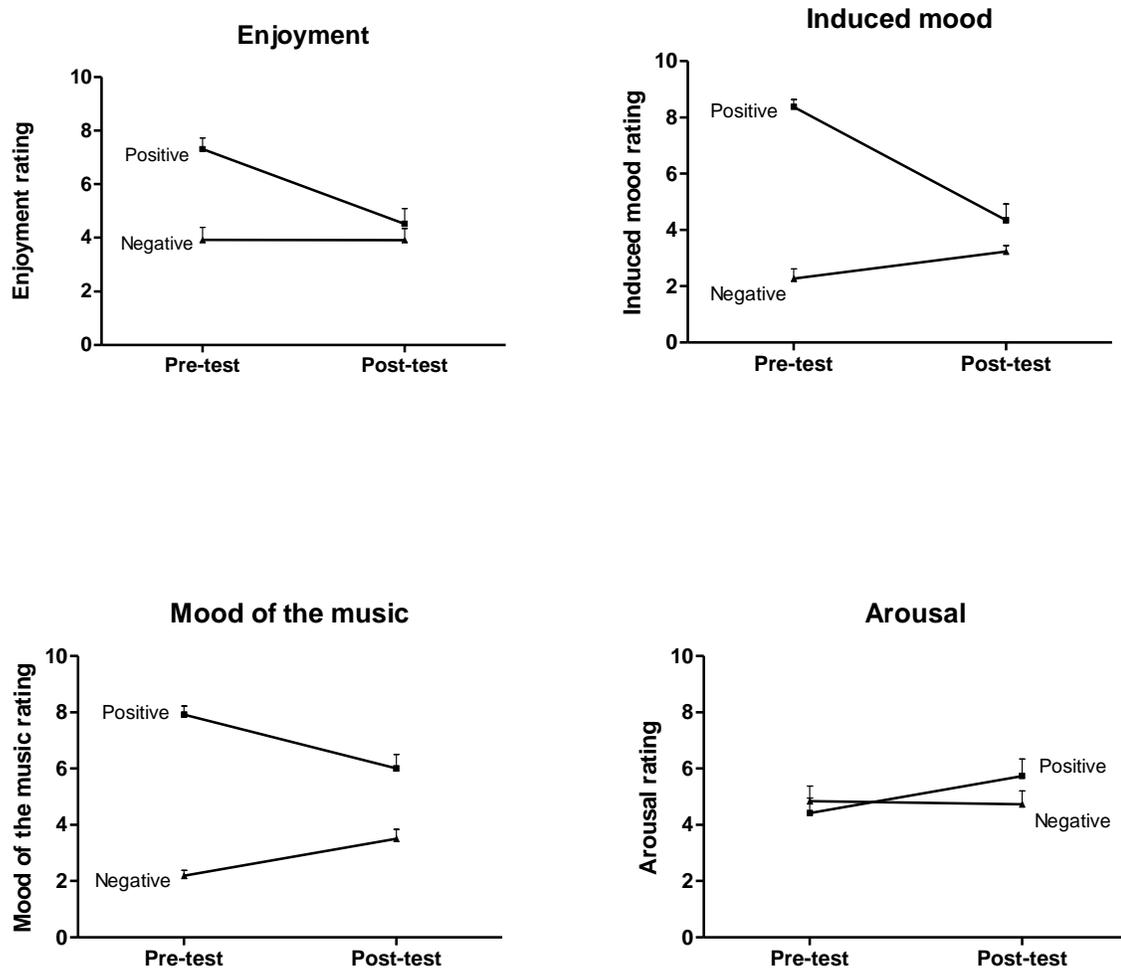
Figure 6. Ratings, out of a 10-point Likert scale with 10 indicating high and 1 indicating low enjoyment, induced mood, mood of the music and arousal. Ratings are of the low-arousal positive and low-arousal negative musical pieces played throughout the adaptation task, taken before and after completion of the task. Before testing, enjoyment and induced mood of the positive music was significantly higher than the negative music; there was no difference after testing. Both before and after testing, the positive music rated as higher in mood of the music than the negative music. Arousal did not differ between positive and negative either before or after testing.

been eliminated for various reasons for the adaptation and deadaptation analyses were included in the ratings analyses. For the post-test ratings analysis, three positive participants and four negative participants lacked post-test ratings due to computer programming error, resulting in 23 positive and 22 negative participants.

Independent samples t-tests were conducted to compare the ratings of the positive and negative songs taken before and after testing. For the pre-test ratings, the positive music was significantly higher than negative in ratings of enjoyment, (M [positive]= 7.31, $SD = 2.15$; M [negative] = 3.92, $SD = 2.23$), $t(50) = 5.58$, $p < 0.001$, $d = 1.55$, mood of the music, (M [positive] = 7.92, $SD = 1.52$; M [negative] = 2.19, $SD = 0.94$), $t(50) = 16.35$, $p < 0.001$, $d = 4.66$, and induced mood (M [positive] = 8.38, $SD = 1.30$; M [negative] = 2.27, $SD = 1.04$), $t(50) = 18.73$, $p < 0.001$, $d = 5.23$. Arousal did not differ between positive ($M = 4.42$, $SD = 2.72$) and negative ($M = 4.85$, $SD = 2.51$), $t(50) = 0.58$, $p > 0.05$, $d = 0.16$. For post-test ratings, positive ($M = 4.52$, $SD = 2.78$) and negative ($M = 3.91$, $SD = 2.04$) no longer differed in enjoyment, $t(43) = 0.84$, $p > 0.05$, $d = 0.25$. Positive ($M = 4.35$, $SD = 2.79$) and negative ($M = 3.23$, $SD = 1.63$) no longer differed in induced mood, $t(43) = 1.64$, $p > 0.05$, $d = 0.51$. Positive ($M = 6.00$, $SD = 2.42$) continued to have higher "mood of the music" ratings than negative ($M = 3.50$, $SD = 1.63$), $t(43) = 4.06$, $p < 0.001$, $d = 1.24$. The song used as serene music ($M = 6.93$, $SD = 1.98$) in the original study by Bock (2010) was rated as higher in arousal than the sad song ($M = 3.77$, $SD = 2.18$), $t(57) = 5.84$, $p < 0.001$, $d = 1.52$. The serene music was also higher in the rating of mood of the music (M [serene] = 7.14, $SD = 1.66$; M [sad] = 4.00, $SD = 1.76$), $t(57) = 7.03$, $p < 0.001$, $d = 1.84$, and induced mood (M [serene] = 6.66, $SD = 1.74$; M [sad] = 4.77, $SD = 2.27$), $t(57) = 3.58$, $p = 0.001$, $d = 0.94$. The two songs did not differ

in ratings of enjoyment (M [serene] = 6.03, SD = 2.31; M [sad] = 6.23, SD = 2.25), $t(57)$ = 0.34, $p > 0.05$, d = 0.09.

Discussion

The purpose of the present study was to examine how inducing positive or negative mood states with music alters visuomotor adaptation performance. Experiment 1 aimed to replicate a previous finding that low arousal, positively valenced music increased adaptive rate but did not affect retention compared to neutral and sad music (Bock, 2010). In contrast to the previous study, Experiment 1 showed no effect of music on initial rate and extent of adaptation. However, positive and negative music elicited more persistent aftereffects in the deadaptation phase, suggesting greater retention of the adapted movement. Based on previous evidence that reinforcement affects retention (Shmuelof et al., 2012), and that music can elicit dopamine reward responses, it was hypothesized that music increased retention by acting upon reward mechanisms throughout the task. To test this hypothesis, Experiment 2 introduced reward feedback in the adaptation phase but the results were unexpected in that the music-induced positive mood had lower retention than either of the other two groups.

The effects on deadaptation were surprising given that the only previous study examining the effects of music on sensorimotor adaptation found an effect on learning but not retention (Bock, 2010). One major weakness in the previous study was that the music was chosen based on the author's opinion of which pieces induced positive or negative affect (Bock, 2010). Although the author's categorization of the music was later confirmed by ratings from other participants (personal communication), the present study used pieces of music that have been extensively rated to ensure better reliability of this

music to induce the intended affect. Interestingly, when the two songs used to induce positive and negative affect in Bock's (2010) study were rated by our participants, the song described in the previous study as low in arousal and positive in mood was actually significantly higher in arousal than the low arousal, negatively valenced song. The present study kept arousal low and constant to closely replicate the previous study, but the ratings that we collected of the songs used in Bock's (2010) study suggest that they may actually have been comparing high arousal, positively valenced music with low arousal, negatively valenced music. To determine if this difference could explain the differences in findings between the present study and the one it was trying to replicate, exploratory data were collected using the Experiment 1 paradigm and high arousal, positively valenced music. However, this group did not differ from the other groups in adaptation, and had deadaptation directional errors very similar to those of participants listening to low arousal, positively valenced music. Therefore differences in music-induced arousal cannot explain the inconsistency in results of the present study and Bock's (2010) study. Further research will be able to reveal whether the finding that positively valenced music improved adaptation rate (Bock, 2010) is reliable. The present study, however, found that music did not have an effect on extent or rate of adaptation; rather, it influenced retention of the adapted movements in the deadaptation phase.

Music modulates reinforcement mechanisms during adaptation

Previous research indicates that retention is influenced by reinforcement and repetition (Huang et al., 2011). Repetition alone appears unlikely to fully explain the current findings as all experimental conditions contained the same number of adaptation trials, thus enforcing similar amount of repetition of the adapted movement after attaining

performance asymptote. We interpret the greater retention in the music conditions compared to silence in Experiment 1 to result from reinforcement. Music is a rewarding stimulus; it evokes similar basal ganglia dopaminergic responses as primary rewards such as food and sex (Blood & Zatorre, 2001; Mitterschiffthaler et al., 2007) and is related to the release of dopamine (Salimpoor et al., 2011). Therefore, we suggest that music exerted its effects on retention through reward mechanisms. Our suggestion that music increases retention by acting upon reinforcement mechanisms is consistent with previous findings of greater retention when the adapted movement is reinforced with reward feedback (Shmuelof et al., 2012). In Experiment 2, we explored the effect of music on reinforcement by re-running Experiment 1 with the addition of reward feedback when directional errors were within 10 degrees of the target in the adaptation phase.

Binary reward combined with positive mood music elicits faster deadaptation

For silence, reinforcement produced higher retention in the deadaptation phase than no reinforcement. These findings suggest that the reward feedback used was an effective reward as its effects were consistent with those of reinforcement used in previous studies (Shmuelof et al., 2012). In the music condition, we expected a compound effect of reward feedback and music on retention of adaptation. Specifically, we predicted that the combination of reward feedback and music, particularly positive music which produced the greatest retention in Experiment 1, should further facilitate retention in Experiment 2. Unexpectedly, positive music with reward feedback resulted in less persistent aftereffects than without reward feedback. There was no difference in retention between Experiments 1 and 2 for negative music. These results were unexpected, given that positive music and, to a lesser extent, negative music, increased

retention in Experiment 1, indicating that the music acted as a reward to have a similar effect on retention as other types of reinforcement (Shmuelof et al., 2012). The novel finding was that the combination of two rewards resulted in an effect opposite to that elicited by either of the rewards alone.

This finding of faster deadaptation with the combination of music and reward than either music or reward alone can be understood in light of the perspective that deadaptation involves actively over-riding the memory for the adapted movement with the memory for the pre-adaptation movement, not passively forgetting the adapted movement (Vaswani & Shadmehr, 2013). In one study, a distortion was introduced using a robotic arm-induced force field, followed by error-clamp trials in which the force field constrained the movements between the start point and a specified end point, with the extent of compensatory force the participants used against the constraint as a measure of the persistence of adapted movements (Vaswani & Shadmehr, 2013). Several findings from this study provide evidence that a memory for the adapted movements persisted (Vaswani & Shadmehr, 2013). Movements in the error-clamp trials always remained a fraction of the adapted motor output learned rather than completely decaying; if deadaptation is a process of passive forgetting, the decay of adapted movements should eventually reduce to zero (Vaswani & Shadmehr, 2013). Furthermore, some participants showed a lag whereby deadaptation occurred after many more error-clamp trials than the average; an explanation for this inter-individual variability is that deadaptation does not occur until the brain detects a change in the task, and individuals vary in how quickly they detect a change and therefore in how quickly they deadapt (Vaswani & Shadmehr, 2013). In these first experiments, the error-clamp trials produced significant changes in

the movement kinematics because of the nature of the restraint, presumably making it fairly obvious when a change in the task occurred (Vaswani & Shadmehr, 2013). When the error-clamp trials were made more similar to the adaptation trials by matching variability of movements, probability of reward and movement duration, and by giving instructions to make movements straight and avoid online corrections, there was higher persistence of the adapted movements (Vaswani & Shadmehr, 2013). In sum, only when a change in the task is detected does output of the adapted movement decrease, suggesting that deadaptation involves actively ignoring the memory for the adapted movement, rather than passively forgetting it (Vaswani & Shadmehr, 2013). The memory for the adapted movement still exists; it is merely overridden by a new motor output when a change in the task is detected (Vaswani & Shadmehr, 2013). Another study using force field distortions has supported this finding: when participants adapted to one rotation and then were exposed to a washout period involving no rotation or a different rotation, movements in error-clamp trials resembled those adapted to the first rotation (Pekny, Criscimagna-Hemminger, & Shadmehr, 2011). These results indicate that the mere presence of sudden errors, indicative of a change in the task, are enough to produce spontaneous expression of a motor memory that had been previously acquired and presumably temporarily repressed during adaptation to the second rotation or deadaptation (Pekny et al., 2011). Particularly relevant to the present experiment is the additional finding that, after adaptation and deadaptation in which reinforcement (pictorial "explosion" of the target) was provided on successful trials, followed by a few trials in which reinforcement was withheld regardless of success, spontaneous recovery of the adapted motor output occurred in error-clamp trials (Pekny et al., 2011). This

indicates that the memory for the adapted output had not been forgotten but merely masked during the deadaptation trials, and the lack of reinforcement encouraged re-expression of this output because it signalled a change in the task (Pekny et al., 2011). In conclusion, learned motor outputs are not forgotten but are actively disengaged when a change in the task requiring different motor outputs is detected (Vaswani & Shadmehr, 2013), and these original outputs can be re-instated when sudden changes in number of errors or in reinforcement indicate that the current output is no longer successful (Pekny et al., 2011). In the present experiment, two movements were learned by all participants: those that were successful during the baseline phase and those that were successful during adaptation. Crucially, both of these movements appear to have been reinforced. Although the reward feedback was only present during adaptation, the music played throughout all three phases of the task (baseline, adaptation and deadaptation). We propose that in Experiment 2 the music reinforced baseline movements but reward feedback "took over" the role of reinforcer during adaptation and reinforced the adapted movements. During adaptation, the baseline movements were not forgotten but merely masked as a new motor output was learned, but they were ready to be re-expressed in the deadaptation phase when a change in the task, indicated by increase in errors and lack of reward feedback, was detected. Two of the factors which contribute to re-instantiation of an old motor output as described by Pekny et al. (2011) were present in the switch from adaptation to deadaptation in the present study: increase in errors as the movements used in adaptation no longer reached the target, and withdrawal of reinforcement as the pictures were not present during deadaptation. Both of these factors would have signalled a change in the nature of the task, which has been shown by previous studies to

encourage expression of a previously successful motor output (Pekny et al., 2011). The tendency to express a previously successful motor output would be expected to be particularly strong in the present study because not only was one reward removed, but in its removal another reward which reinforced a different movement was made more salient. Crucial to this hypothesis is the evidence that a direct reward associated with phasic dopamine release is thought to be more influential on learning and retention than reward associated with tonic dopamine release (Schultz, 2007). Background music appears likely to elicit tonic dopamine release while reward feedback is associated with phasic dopamine release (Schultz, 2007). This would explain why the reward feedback was a stronger salient reinforcer than the music during adaptation, effectively limiting the role of music as a reinforcer to the baseline phase. This would not occur during Experiment 1 because positive music was the only reward throughout the entire task and, given the greater length of the adaptation phase compared to the baseline phase and its closer proximity to the deadaptation phase, it is probable that positive music exerted greater influence on retention of the adapted movements than the baseline movements during deadaptation. Furthermore, there was less of a change from adaptation to deadaptation in Experiment 1 because it was signalled only by changes in error and not by a change in reinforcement. In conclusion, we propose that the positive music interacted with reward mechanisms to influence movements in the baseline phase and, even though the music was also present during the adaptation phase, the reward feedback in this phase was a strong reinforcer and therefore the adaptation movements did not develop a strong affiliation to the music reward. A change in reward feedback and in success rate signifying a change in the task resulted in reversion to the baseline

movement which had previously been reinforced by the only reward present in deadaptation, music.

If this explanation for the interaction between positive music and direct reward is correct, decreased retention for the adapted movement should not occur if the music was not present during baseline because there would be nothing to reinforce and thus influence retention of the baseline movements. Possibly, if music were present only during baseline and deadaptation the retention of baseline movements should be even stronger because it would have no ties to adaptation movements in this situation, unlike in the present study in which its affiliation with adaptation was only weakened by the more salient reward feedback. The ability of music that induces a positive mood to interact with reinforcement mechanisms during sensorimotor adaptation could be further tested in a paradigm similar to Experiment 2 except that the baseline phase with music and no reward feedback could be replaced with a different rotation instead of no rotation. This would make the comparison between the two rewards more reliable as the movements associated with each reward would be more similar in that they both involve a distortion.

Differences in induced mood on retention

Although in Experiment 1 the negative music group tended towards higher directional errors than silence, and was not significantly lower than the positive music group, suggesting that the effect of negative music was similar to that of positive music, it is plausible that negative music does not interact with reward mechanisms in the same way as positive music. Indeed, the data regarding the rewarding neural properties of music refer specifically to music inducing positive emotion (Blood & Zatorre, 2001;

Mitterschiffthaler, et al., 2007; Salimpoor, et al., 2011), while music inducing negative

affect appears to elicit neural regions traditionally associated with negative emotions

(Mitterschiffthaler, et al., 2007). At this time it is unclear whether negative music has

any real effect on retention or whether the higher retention of negative music compared to

silence in Experiment 1 was an anomaly. It is clear, however, that the same interaction

occurring between positive music and reward feedback did not occur with negative

music; instead, presence of reward feedback in combination with negative music made no

difference on retention of adapted movements. Future studies should help to elucidate

the uncertainty regarding the role of music-induced negative mood on sensorimotor

adaptation.

The ratings data were somewhat surprising. As expected, pre-test ratings put

positive much higher in mood of the music, enjoyment, and induced mood, but equal in

arousal to negative music. However, post-test ratings of positive music had reduced so

much in enjoyment and induced mood that they no longer differed from negative music.

It was hypothesized that this reduction was due to the constant repetition of the same

short clip of music over the entire adaptation task, which took approximately 40 minutes.

Even though the music was initially enjoyable and evoked positive emotions, its

repetition made it unenjoyable and unable to elicit positive emotions. However, the

ratings of musical mood of the positive music did not decrease from pre- to post-test,

suggesting that even though the participants no longer enjoyed the music or felt happy

listening to it, they were still able to recognize it as happy music. These results suggest

that the mood-enhancing effects of music are most relevant during the beginning of the

task rather than near the end, when positive music was no longer reliably eliciting

positive moods. If the mood-enhancing effects of music were maintained throughout the entire task, for example by playing more variety of positive music instead of just one clip, the reinforcing effects of positive music might be even stronger.

The present study is one of the first to combine two very different fields of research, those on musical mood and cognition and sensorimotor adaptation. The results support previous findings that music has a similar effect on the brain and behaviour as reward (Blood & Zatorre, 2001; Mitterschiffthaler et al., 2007; Salimpoor et al., 2011; Gold et al., 2013) and clarifies some factors which affect retention in motor learning. Inducing a positive mood with music increases the retention of an adapted motor output, as shown by larger aftereffects in the deadaptation phase of Experiment 1. However, with the addition of reward feedback in the adaptation phase in Experiment 2, positive music resulted in significantly smaller aftereffects in the deadaptation phase. Crucially, positive music was present throughout the pre-adaptation baseline phase, the adaptation phase, and the deadaptation phase. We suggest that in the deadaptation phase, removal of the phasic reward resulted in faster reversion to the baseline movements that were reinforced with positive music in the preadaptation baseline phase.

The present study corroborates previous evidence that reinforcement protects the adapted movements from decay (Shmuelof et al., 2012; Izawa & Shadmehr, 2011), and provides new evidence that music has a similar effect on retention as standard reinforcement paradigms. It contributes to the hypothesis that a learned motor output is not forgotten but merely disengaged until a change in task and reinforcement re-activates it (Vaswani & Shadmehr, 2013; Pekny et al., 2011) by demonstrating the effects of competing motor outputs associated with different rewarding stimuli. It also highlights

the importance of ensuring that only the desired movement is reinforced in order to promote retention, as the combination of music played throughout the entire task and reward feedback present only during adaptation resulted in the unintended retention of the baseline movements. Sensorimotor adaptation is essential to many types of rehabilitation following injury or disease but adapted movements are typically unlearned at a very fast rate (Patton et al., 2006; Reisman et al., 2007), and therefore knowledge of the factors that improve retention is vital to providing optimal treatment, particularly in rehabilitation settings where long-term adaptation is the goal. The discovery that music interacts with reward mechanisms to increase retention of these movements is particularly relevant because it produces the possibility that music can be used throughout treatment to facilitate rehabilitation. Future studies should assess whether music-induced improvements in retention in one task can generalize to long-term improvements in rehabilitation. The present study confirms that reward feedback increases the longevity of adapted movements (Shmuelof et al., 2012) and provides new evidence that music that induces a positive mood has a similar effect.

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