



The role of auditory context in action-effect-related motor adaptation

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ABSTRACT

Previous research indicates that adding auditory effects to a (silent) action can lead to substantial efficiency gains in the performance of the action, while compromising the connection between the motor and the auditory event (e.g., by removing, or by delaying the auditory effects), leads the agent to compensate for the loss of auditory feedback by executing actions in a way which increases the probability of success or enhances feedback in other modalities, thus departing from the optimal action performance. The current study explored how this motor adaptation was affected when the quality of auditory feedback was reduced by contextual factors, while keeping the physical link between the action and auditory effect intact. In two experiments, participants elicited pure tones by pinching a force sensitive resistor (FSR). In some of the conditions action-effect contingency was reduced by intermixing externally initiated tones with the self-induced ones. Pinch-force measurements indicated that action optimization was affected by contextual factors. The influence of auditory context was the most pronounced when the discrimination of self-induced and external tones was made difficult by the similarity and temporal proximity of the self-induced and external tones. In these conditions, tone eliciting actions were more forceful in comparison to conditions in which no external tones were presented, and in comparison to conditions in which the external tones were easily distinguishable from self-induced ones. This suggests that contextual factors can induce similar motor adjustments as manipulating the physical connection between the action and its sensory consequences.

1. Introduction

Most human actions are goal-directed. We plan and perform actions to bring about changes in our environment, and successes and failures to elicit these changes shape our actions. For actions with relatively slowly unfolding, continuous movements, the observation of the action's sensory consequences allows us to adaptively react when the action does not seem to converge to the intended goal ("online" control, Greenwald, 1970; Schmidt & Wrisberg, 2000). Motor adjustments may, however, not only occur during a single - slow - movement, but also from action to action when fast, ballistic actions are repeated several times. A recent line of studies demonstrated that movement parameters systematically change when the actions (e.g., pinches, button presses, tapping on a table) elicit a tone in comparison to cases where such actions are not associated with distinctive auditory or visual effects (Horváth,

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Bíró, & Neszemélyi, 2018; Neszemélyi & Horváth, 2017, 2018). An interpretation of this *action-effect-related motor adaptation* is that distinctive distal action effects (e.g., a beeping tone or a light flash) provided a more reliable, higher quality feedback than “diffuse” proximal action effects (e.g., the tactile sensation of pressing a button), and thus resulted in more effective control of the actions. In the current study it was examined how action execution was affected when the reliability of auditory information was compromised by contextual factors.

When a violinist plays a violin, he/she can immediately correct the position of his/her fingers when he/she hears that the elicited tone is false, or adjust the movement of the bow if the tones are too loud or too soft. However, using the auditory stimuli as feedback becomes more difficult if the instrument is played in an orchestra, where other musicians play similar (or even the same) tones. In such cases it is often hard to tell whether a false tone was elicited by oneself, or by another member of the group. The goal of the current study is to explore such scenarios, where the auditory environment makes utilization of sensory effects in motor control difficult.

In the case of controlled movements, where actions can be adjusted on the fly—like the above example of playing sustained tones on a violin—, the importance of sensory feedback seems obvious. However, for ballistic movements, which are executed very quickly, immediate adjustments are usually unrealistic (Chernikoff & Taylor, 1952; Lashley, 1951; Schmidt & Wrisberg, 2000; although, for a different opinion see: Adams, 1976). The fact that these actions are performed according to predetermined motor plans, often led to the assumption that sensory effects do not play a role in the execution of such movements. (For example, the motor correction method in paradigms examining the action-related auditory event-related potential [ERP] attenuation is based on such presumption, see: Horváth, 2015; Neszemélyi & Horváth, 2017.) The idea that ballistic actions are not sensitive to sensory feedback has been also supported by studies that examined the influence of distal action effects on timing and/or execution of actions like playing a piano (Finney, 1997; Gates & Bradshaw, 1974; Pfordresher, 2005; Repp, 1999) or pushing a joystick (Taylor & Birmingham, 1949). These studies indicated that ballistic actions were unaffected by changes in the quality of distal feedback (even in the face of drastic manipulations like the complete removal of visual or auditory action effects).

The phenomenon of action-effect-related motor adaptation, however, suggests that the effect-independency presumption for ballistic actions does not apply to every circumstance. If actions are executed in a sequential manner, the experience with previous actions can influence, how subsequent ones are executed, even if the speed of the movements does not allow for online motor adjustment. Action-effect-related motor adaptation is presumably an example of such stepwise action optimization processes: When action effects reliably signal that an action was successful, energy investment can be reduced by lowering the force of subsequent actions. According to this interpretation, the execution of ballistic movements is affected by the quality of sensory feedback: When distinctive auditory or visual effects unambiguously signal the success of the action, it is possible to minimize effort investment. However, when participants can only utilize less reliable feedback sources (e.g., tactile)—which do not signal clearly whether the action was successful—stronger actions have to be executed to maintain a high probability of action success.

Previous studies have examined how action execution was affected by changes in feedback quality by removing/adding sensory action-effects (Horváth et al., 2018; Neszemélyi & Horváth, 2017), or by delaying otherwise reliable auditory feedback (Neszemélyi & Horváth, 2018). Both previous paradigms relied on the direct manipulation of the action-effect relationship. However, even if the relationship between action and its sensory consequences remains intact (i.e. a properly executed action always produces the effect), contextual factors might induce changes in the reliability of sensory feedback. In the two experiments of the present study, we investigated how such contextual feedback quality changes would influence action-effect-related motor adaptation. The experimental paradigm manipulated the level of contingency between the action and its auditory effect: Participants elicited tones by pinching a force sensitive resistor (FSR). To keep the physical link between actions and auditory effects intact, tones were consistently elicited when the FSR was pinched, and contingency was manipulated by intermixing self-induced tones with tones that were independently initiated by a computer.

This manipulation can have several effects on the utilization of the auditory action effects as feedback: (1) Reduced contingency might result in weaker associative links (Elsner & Hommel, 2004) between the action and the tone, thus compromising the utilization of sensory consequences in motor control processes. (2) A weaker action-effect association might be also reflected in a reduced sense of causal connection between the action and the tone (Shanks & Dickinson, 1991; Wasserman, 1990), which could hinder strategic optimization processes. (3) When self-induced and external tones are identical, recognizing the source of individual auditory events becomes more difficult: A tone presented in close proximity to an action might signal that the action was successfully executed, but it could also be an unrelated external event simply coinciding with the movement. A tone presented temporally far from intentional actions is likely coming from an external source, but it is also possible that it was induced by an unintentional movement of the participant. This ambiguity might reduce the usefulness of the tones as feedback about action execution.

A recent study (Neszemélyi & Horváth, 2018) indicated that action-effect binding for motor optimization relies on the automatic integration of a motor and a sensory event within a very short time window. It could be possible that such automatic binding would only depend on the temporal separation between the action and its effect and is not affected by contextual factors that require processing a wider range of events. On the other hand, if the experiments provide an evidence for context-related effects, this would suggest that intact physical action-effect links are not sufficient for utilizing effect-based motor control processes, and action control is not only influenced by stimuli that appear within the time-window of action-effect integration, but also by the environment in which the task is situated.

2. Experiment 1

Experiment 1 was designed to follow-up the study by Baess, Horváth, Jacobsen, and Schröger (2011), which investigated action-

related auditory ERP attenuation. We used a force sensitive resistor as an input device, because operating the FSR produces no audible mechanical transient. Although the FSR signal was recorded, it was not analyzed, and the results of the ERP analyses are described elsewhere (Neszmélyi & Horváth, Manuscript in preparation). Prompted by recent developments suggesting that movement execution was affected by the sensory consequences of the actions (Horváth et al., 2018; Neszmélyi & Horváth, 2017, 2018), in the first part of the present study we analyze this FSR dataset. Thus, in Experiment 1 interpretations regarding the relationship between feedback reliability and physical action parameters were only formulated post-hoc, and all analyses for Experiment 1 are exploratory. Since the present study focuses exclusively on the action control perspective, parts of the experiment that are only relevant for examining perceptual processing (e.g., experimental conditions in which no actions were performed) are not reported here.

The goal of the analyses was to assess how action-effect-related motor adaptation was affected when the quality of auditory feedback was reduced by contextual factors. We compared forces applied during tone-eliciting actions in two auditory contexts, created by manipulating the level of action-tone contingency: In the *motor-auditory single condition*, tones were only induced by the participants' actions, whereas in the *motor-auditory mixed condition* tones were also initiated independently from the participants' actions (i.e., these were presented in addition to the self-induced tones). These external tones were identical to the self-induced tones.

As a second manipulation, irrespective of the auditory context, a visual effect was introduced in one half of the experiment, but not in the other. If force adjustments are indeed affected by the reliability of sensory action-feedback, the inclusion of visual action effects might reduce the effects of the auditory context manipulation, because the visual stimuli unequivocally signaled action success across all levels of action-tone contingency. Thus, in conditions with visual feedback, similar levels of force optimization would be observable regardless of auditory context. This setup also provided an opportunity to test whether an action with a reliable distal feedback in one modality was affected by the addition of another distal action consequence in a different sensory modality.

2.1. Method

2.1.1. Participants

28 healthy young adult volunteers recruited through a student part-time job agency participated in the experiment. All of them gave written informed consent after the experimental procedures were explained to them, and they were reimbursed for participation. Participants reported normal hearing and had no history of neurological disorders. Two datasets were excluded from the analysis. One because the participant did not complete all conditions, and another because an input device malfunction might have resulted in unintentional changes in action-tone contingency. The final sample consisted of 26 participants (mean age: 22 years, range: 18–27 years, female: 16, right handed: 21).

2.1.2. Task, stimuli and experimental conditions

During the experiment participants were comfortably seated in a sound-proofed room. They were instructed to hold a paper-thin (0.3 mm) force sensitive resistor (FSR 400, Interlink Electronics) mounted on a thin plastic sheet between the index finger and the thumb (in a thumb above position), and pinch it briefly (i.e. apply force impulses) with a constant between-pinch interval of 4 s. The FSR changes its resistance as a monotonic function of the applied pressure. When the FSR signal exceeded a pre-set threshold (0.158 N), an auditory and/or a visual action effect was presented in some of the conditions (see below).

There were two types of experimental manipulations, one affecting the auditory, the other the visual stimulation. The auditory manipulation consisted of three levels of action-tone contingency. (1) In *motor-auditory single conditions* actions elicited a 50-ms long (including 10-ms linear rise and fall times), 1000 Hz pure tone of 90 dB SPL intensity (measured by an artificial head, HSUIII.2, Head Acoustics, Germany), presented through open headphones (HD-600, Sennheiser, Wedemark, Germany). Due to hardware limitations, tone delivery was delayed by 5 ms. (2) In *motor-auditory mixed conditions*, tones initiated by the computer were intermixed with the self-induced tones. These additional tones had the same acoustic features as the self-induced tones, and were presented at random intervals, sampled from a uniform distribution in the 1–7 s time range. As this presentation rate also results in an average onset-to-onset tone interval of 4 s, the number of self- and computer-initiated tones was about equal in this condition. (3) In *motor conditions*, pinches did not initiate a tone. The experiment was divided into block triplets (each triplet included one block of each action-tone contingency condition). Within the triplets, the sequence of the three action-tone contingency conditions was randomized (but the order was constant across all triplets). Participants completed four triplets, that is, four blocks of each action-tone contingency condition. Each block consisted of 50 actions. (Conditions simply replaying sound sequences previously generated in single and mixed conditions were also administered. In these blocks participants just listened to the replay without performing actions. Since these conditions were only relevant for the analyses of the EEG recording, these will not be discussed here.)

The two levels of visual manipulation were *visual feedback* and *no visual feedback*. In *visual feedback* conditions, actions elicited a red, 50-ms long light emitting diode (LED) flash immediately. In *no visual feedback* conditions, no LED flash occurred. Visual feedback was manipulated between the first and second halves of the experiment, that is, the first two block triplets were administered with visual feedback and the other two without visual feedback, or vice versa (counterbalanced across participants). The order of the three action-tone contingency blocks within the triplets was the same in both visual feedback settings. In conditions with no visual feedback, participants were instructed to look at a fixation cross displayed on a computer screen in front of them. In conditions with visual feedback, they were instructed to look at the LED placed in front of the screen. The screen and the LED were placed ca. 100 cm in front of the participant.

At the end of each block, participants received feedback about their performance on the interval production task: Mean and standard deviation of between-pinch intervals, as well as the number of actions following previous actions in less than 3 s or more than 5 s were displayed on the screen.

Before the experiment, participants familiarized themselves with the force-level that was necessary to produce successful interaction with the device. The FSR-signal was displayed on the screen in the form of a vertical bar, which changed its height as a monotonic function of the applied force. The initially blue bar turned green when the threshold was exceeded. To keep the applied force within the measurement range of the FSR, an upper threshold was also implemented: if the applied force exceeded 5.970 N the bar turned red. Participants were encouraged to freely interact with the device, and explore how performing the action in different ways affected the on-screen representation of the signal. After this, participants completed two shorter (20 trial) training blocks of the *motor-auditory single* condition with or without visual feedback depending on whether the participant was assigned to start the experiment with or without visual feedback. In contrast to the experimental blocks, immediate feedback was provided after each action: the last inter-pinch interval was displayed on the screen, and participants were alerted if the pace was too fast (between-action interval shorter than 3 s) or too slow (between-action interval longer than 5 s). Between the two practice blocks, participants were prepared for EEG recording. After the training phase, participants performed the first half of the experiment. After the visual setting was changed at the halfway point (LED activated or disabled), participants first repeated the practice block with the new setting before continuing with the experimental blocks.

2.1.3. Data acquisition

The FSR voltage signal was recorded with a voltage-divider setup using 5 V input voltage and a 10 kOhm resistor. The applied force - FSR signal relationship in this setup is well approximated by a log-linear function, therefore, force was calculated from the FSR signal by an exponential transformation. The FSR signal was co-recorded with the EEG, using the high-level input of a Synamp2 amplifier (Compumedics Neuroscan, Victoria, Australia). The signal was recorded with a sampling rate of 1000 Hz (with a 200 Hz online low-pass filter) and then transformed offline to force-values. 2-s epochs (including a 1-s interval preceding and a 1-s interval following the time-point when the FSR-signal exceeded the threshold) were extracted from the continuous signal. Epochs were discarded if no force peak could be identified in the 750-ms post-action time window¹, or if another tone was present in the 600-ms time window preceding the tone-eliciting action². The first 10 trials of each block were also discarded as results of a previous experiment (Neszmélyi & Horváth, 2017) suggested that the first 5–10 trials of a block might reflect a step-by-step adjustment of the applied force to the given stimulation, and thus would not reflect a stabilized force application set.

2.1.4. Data analysis

Mean between-action intervals (time between pinches) were calculated for each participant in each condition. The individual between-action intervals in the different conditions were submitted to a two-way, action-tone contingency (motor-auditory single, motor-auditory mixed, motor) \times visual manipulation (visual feedback, no visual feedback) repeated measures ANOVA. Greenhouse-Geisser correction was applied to correct for potential violations of the sphericity assumption. For the ANOVA uncorrected degrees of freedom, the ϵ correction factor (for factors with more than two levels), and generalized eta-squared measure of effect size (Bakeman, 2005) are reported.

Pinches were characterized by the maximal force in the 750-ms following the crossing of the force-threshold. The median of the pinch force maxima was used to characterize each participant in each condition. Differences in pinch force between various conditions were explored by Wilcoxon signed-rank tests. Wilcoxon tests were only performed for the 9 comparisons that might be of theoretical importance. The three action-tone contingency conditions were compared with each other separately within the two visual settings, and each corresponding action-tone contingency condition was compared across the two visual settings. For the Wilcoxon tests, T -values³ and rank biserial correlation effect sizes (Kerby, 2014; King, Rosopa, & Miniun, 2011) are reported.

As the analysis of Experiment 1 can be regarded as exploratory no hypothesis testing was conducted (i.e., p -values are not reported). Statistical analyses were conducted in R (version 3.0.2., R Core Team, 2015). Initial figures were prepared by the ggplot2 package (Wickham, 2009).

¹ The goal of the study was to examine quick interactions with the device that can be regarded as analogous to everyday actions like pressing a button, tapping on a table, knocking on a door (i.e., movements that might be regarded as ballistic). Thus, the algorithm was looking for signal peaks in a 750-ms time window, and events with peaks falling outside this time range were excluded from the analysis, as such instances likely reflect actions where participants continuously apply pressure to the FSR.

² The exclusion of self-induced events preceded closely by another stimulus was motivated by the possibility that the preceding stimuli may interfere with action initiation. A recent study by Novembre et al. (2018) suggests, for example, that sounds presented after longer periods of silence disturb ongoing motor activity. The 600-ms pre-action rejection window was selected to match the criterion used in the processing of the EEG-data (which allowed to minimize overlap by ERPs elicited by preceding stimuli). To check the possibility that this event selection choice influenced the results, as suggested by an anonymous reviewer, processing was also performed without using the 600-ms pre-action rejection window. Removing this rejection criterion did not substantially influence the pattern of results.

³ After calculating the difference of the force measurements in the two conditions, the absolute values of these differences are ranked (the larger the difference, the higher the rank). T is the smaller of the two sums of ranks of the instances when the first condition is larger than the second or when the second condition larger than the first. That is, a small T -value indicates that for almost all pairs, values in one condition are larger than values in the other condition. (With $T = 0$ indicating that all data consistently change in the same direction.) There is no consensus which statistic to report in regard to the Wilcoxon signed-rank test. Most often T , W , and Z statistics are suggested. In the current study, T -value was reported because the interpretation of this statistic is straightforward (if the sample size is known), and values can be easily compared to significance thresholds presented in look-up tables.

Table 1

Group-mean between-action intervals (with standard deviations) in the six conditions of Experiment 1.

	Motor	Motor-auditory single	Motor-auditory mixed
No visual feedback	4.170 ± 0.428	3.896 ± 0.322	4.002 ± 0.381
Visual feedback	4.021 ± 0.433	3.975 ± 0.382	4.100 ± 0.387

2.2. Results

Participants complied with the instructions: group average between-action intervals were close to 4 s in each condition (Table 1). Effect sizes related to the 2-way ANOVA on between-action intervals also indicated that between-action intervals in various conditions did not differ substantially (action-tone-contingency main effect: $F(2,50) = 2.407$, $\epsilon = 0.883$, $\eta^2 = 0.030$; visual manipulation main effect: $F(1,25) = 0.014$, $\eta^2 < 0.001$; visual manipulation \times action-tone contingency interaction: $F(2,50) = 3.130$, $\epsilon = 0.984$, $\eta^2 = 0.021$).

After rejection criteria were applied, 93.739 ($SD = 7.458$) percent of the actions (not counting the first 10 actions of the blocks) were retained for analysis. Pinch forces (Fig. 1) differed substantially across the three action-tone contingency conditions both without and with contingent visual action effects (Fig. 2).

In the conditions without visual feedback, large effect sizes clearly indicated that pinch force was larger in the motor condition than in the single ($T = 0$, $r_c = 1$) and mixed ($T = 1$, $r_c = 0.994$) motor-auditory conditions. In the motor-auditory mixed condition participants applied more force during interactions with the FSR than in the motor-auditory single condition. The effect related to this difference is of medium size ($T = 100$, $r_c = 0.430$).

With visual feedback, a similar pattern was observed: The applied force was substantially larger in the motor than in the single ($T = 10$, $r_c = 0.943$) and mixed ($T = 69$, $r_c = 0.607$) motor-auditory conditions. The comparison of the single and mixed motor-auditory conditions, however, showed only a medium effect size ($T = 107$, $r_c = 0.390$).

Pinches that elicited contingent visual feedback were softer than pinches without visual effects in all auditory conditions. Large effect sizes indicate a substantial force difference related to the visual feedback manipulation, regardless of action-effect contingency (motor: $T = 0$, $r_c = 1$; motor-auditory single: $T = 60$, $r_c = 0.658$; motor-auditory mixed: $T = 76$, $r_c = 0.567$).

2.3. Discussion

The results confirmed previous observations about tone-eliciting actions being softer than similar actions without external auditory effects: Adding a sound to the set of action effects suggested more pronounced force optimization (as indicated by large effect sizes) even in cases in which action-success was reliably indicated by visual feedback or the reliability of this additional auditory feedback was reduced due to the auditory context (externally generated stimuli intermixed with the self-induced ones).

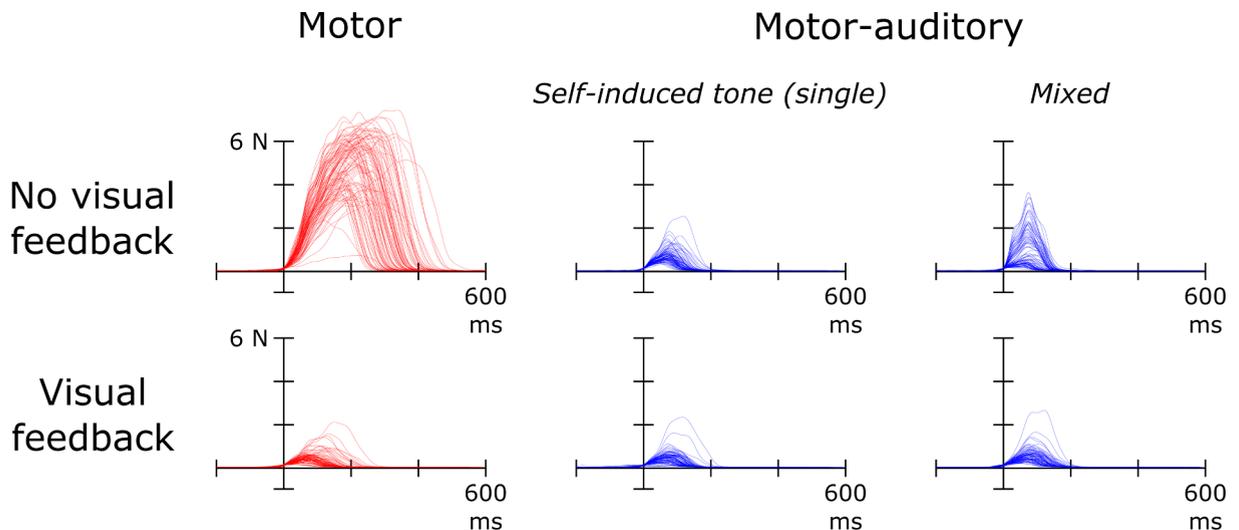


Fig. 1. Action force profiles in Experiment 1. Force application patterns as a function of time, for all actions of a representative participant. Actions without auditory action-effects are presented in red, actions with auditory action effects are in blue. Crossing of the axes represents the time-point where the action was registered and (in the motor-auditory conditions) the presentation of the tone was initiated. (Note, that signal peaks were identified for all participants in the 0–750-ms poststimulus time window. However, on the figure, display of the signal terminates at 600 ms, as the actions of the selected participants were all completed within this timeframe.) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

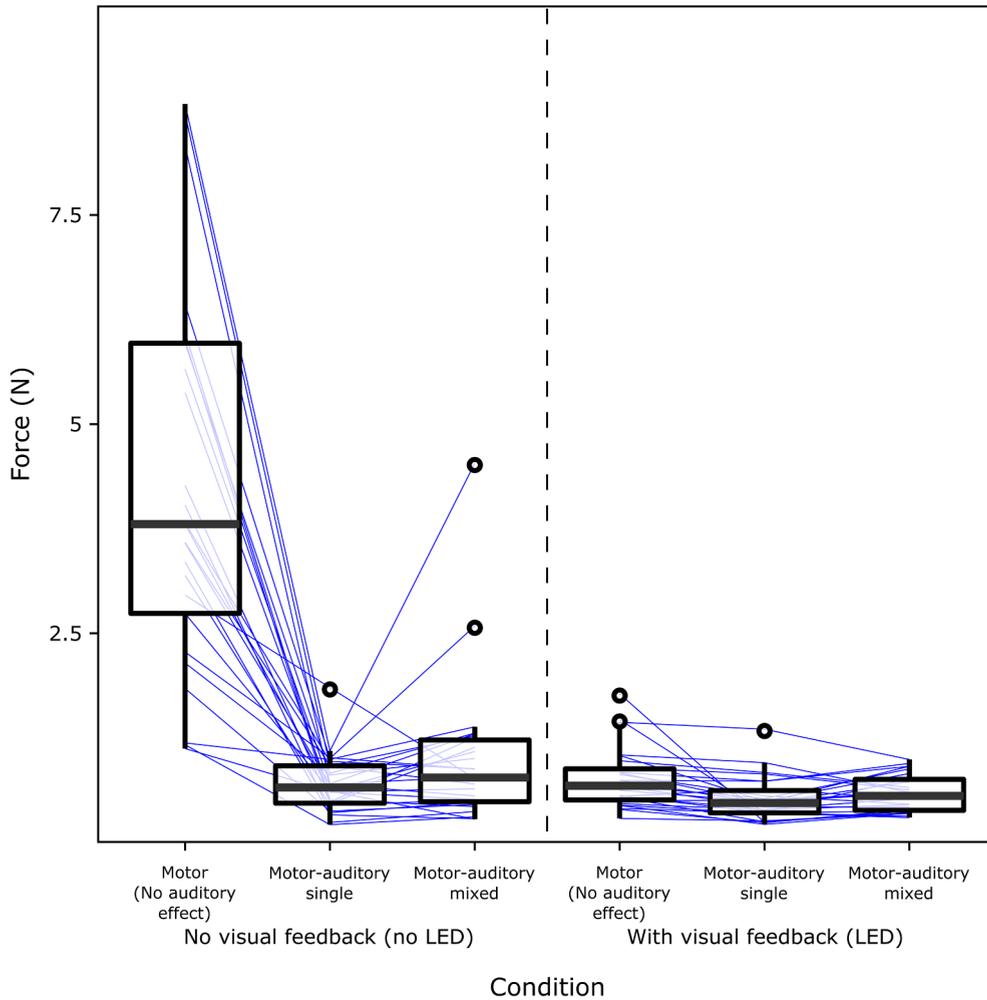


Fig. 2. Distribution of force maxima in Experiment 1. Tukey-plots of the distribution of individual pinch-forces in the three action-tone contingency conditions without (left) or with (right) visual feedback. (Boxes indicate values between the 1st and 3rd quartile, with thick horizontal lines in the boxplot representing the group median. Whiskers cover values in the 1.5 interquartile range below and above the 1st and 3rd quartile, while dots represent datapoints falling outside of this range. Blue lines connect the datapoints of the same participants in the different conditions.) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

In contrast to this general auditory feedback effect, the influence of feedback-reliability on action-effect-related motor adaptation was less obvious. Although both with and without visual feedback, action forces in the motor-auditory single condition were larger than in the motor-auditory mixed condition, relatively smaller effect sizes (biserial rank correlation coefficients of 0.390 and 0.430, indicating medium effect sizes) suggested that, if offline force adjustments are influenced by context dependent changes in the reliability of auditory feedback, these effects are smaller than expected.

Contrary to our expectations, the addition of reliable visual action effects did not abolish the influence of the auditory context. When a visual stimulus was added to the set of action effects, pinch force was reduced in all action-tone contingency conditions, but the pattern of force differences remained unchanged across auditory contexts: Compared to “silent” interactions with the FSR (motor condition), the addition of auditory effects resulted in substantial force optimization in both motor-auditory conditions (i.e., single, mixed). The level of action-effect-related motor adaptation was somewhat larger in the single condition, but the difference between the two motor-auditory conditions was smaller than expected. These results suggest that adding action effects in a new sensory modality allows for more efficient motor control, even if it only enriches the sensory characteristics of feedback without affecting feedback contingency: Action optimization was always more pronounced in conditions with two distal effects (i.e., auditory and visual) compared to conditions in which only one of the effects was available. Improved motor control could be observed even when a sensory effect providing low quality feedback was added to an action that already had completely reliable feedback in another modality (i.e., motor-auditory mixed, with LED).

3. Experiment 2

Results of Experiment 1 suggested that actions can be adjusted to compensate for diminishing quality of auditory feedback when contextual factors are responsible for the reduced reliability of feedback. Due to the exploratory nature of the study, only effect sizes were determined for the relevant comparisons, and no hypothesis testing was applied. Consistent with the idea that reliability of auditory feedback would be reflected in the magnitude of force adjustments, action-effect-related motor adaptation was less pronounced in conditions where computer initiated auditory stimuli were intermixed with self-induced sounds. The difference between conditions with reliable and unreliable feedback, however, was smaller than expected. This might be explained by the fact that the experiment was optimized for the study of perceptual processes (and the requirements of the ERP method), and not for the study of motor control processes. Experiment 2 was designed for a targeted investigation of these motor control phenomena.

In Experiment 1, the effect of context-related changes of feedback quality on force optimization was most clearly reflected in the comparison of the motor-auditory single without LED and the motor-auditory mixed without LED conditions. Thus, the design of Experiment 2 was mainly based on this contrast (the influence of visual stimuli was not investigated), and a sample size was determined that should reveal a significant difference between the two conditions if the medium effect sizes observed in Experiment 1 were indeed realistic. Similarly to Experiment 1, it was expected that action forces would be larger in conditions in which computer-initiated sounds are intermixed with self-induced ones. Such differences would suggest that context-related changes in the quality of auditory feedback can influence action-effect-related motor optimization. Furthermore, the experimental task was modified slightly and two additional manipulations for the presentation of computer-initiated stimuli were introduced with the goal of gaining deeper understanding of the relationship between contextual factors and action optimization.

First, participants were instructed to produce sequences with variable between-action intervals (instead of generating self-induced sounds in an even tempo). The goal of this modification was to accentuate the intentional aspect of the actions—as the predictive relationship between action and its sensory effect is assumed to be typical for intentional actions (Desantis, Roussel, & Waszak, 2011; Haggard & Clark, 2003)—, and to abolish potential “figure-ground separation”-like effects (Andreou, Kashino, & Chait, 2011; Bregman, 1990; Jones, Moynihan, MacKenzie, & Puente, 2002; Lange, 2009) that may be brought about by having a mixture of a rhythmic, evenly paced self-induced and a random external tone sequence. We presumed that abolishing such aids for the perceptual distinction of self-induced and externally generated sounds could accentuate the influence of auditory context, and thus increase the difference between conditions with and without external sounds.

Second, it was a further goal of Experiment 2 to control for attentional factors that could result in similar effects to those that were attributed to changing the quality of auditory feedback: External tones do not only reduce the reliability of auditory feedback, but they also make the interval production task more difficult. The slightly stronger pinches in the mixed condition could be a result of the external sounds disrupting the timing of the movements: It could be hypothesized that in this condition, less resources are available for action-control processes, because distractor events necessitate a stronger attentional focus on the time-production task (Brown, 1997; Gautier & Droit-Volet, 2002; Lejeune, 1998). To exclude this possibility, we also included conditions in which external tones had different—easily distinguishable—itches from the self-induced tones. These sounds should disrupt the interval production task in a similar way as undistinguishable ones, but they should not affect quality of the auditory action-feedback, as source of the stimuli can be reliably determined on a pure perceptual basis. If feedback-reliability indeed contributes to force differences between conditions with and without externally initiated sounds, action optimization should be more effective (i.e., smaller forces) when computer-generated sounds are different from self-induced ones.

Third, we examined the effect of increasing the proportion of external tones that were intermixed with the self-generated ones. The further reduction of action-effect contingency could result in weaker action-effect links, and also hinder the temporal discrimination of self-induced and external sounds (because of increased probability of self-induced and external events overlapping in time). Thus, if motor adjustments are indeed induced by context-related changes in auditory feedback quality, action forces should increase with increasing presentation rate of externally generated stimuli that are identical to the self-induced ones. (On the other hand, increasing the proportion of computer-generated sounds that are different from self-induced ones, should not influence feedback-dependent force adjustments.)

3.1. Methods

3.1.1. Participants

50 healthy young adults completed the experiment. All of them gave written informed consent, and they either received course credit or were reimbursed for their participation. Participants reported normal hearing and no history of neurological disorders. Because of device-malfunction, 9 datasets were excluded from the analyses. The final sample consisted of 41 participants (mean age: 21 years, range: 18–27 years, female: 29, right handed: 34).

3.1.2. Stimuli and task

Participants' task was to pinch the same device used in Experiment 1. Pinches always resulted in an auditory effect: When the applied force exceeded the preset threshold (same setting as in Experiment 1) a sine tone (75 dB SPL—measured by an artificial head: HSUIII.2, Head Acoustics, Germany; 50 ms long, including 10-ms linear rise and fall ramps) was presented with a delay of 10 ms. Participants were instructed to perform tone-eliciting actions so that at the end of the blocks, the distribution of the between-action intervals would show a uniform distribution in the 2–6 ms time range.

There were 5 experimental conditions. In all of these, participants performed the time-interval production task described above.

In the *single condition*, only tones initiated by the participants were presented. In the other four conditions (*mixed conditions*), tones (referred to as *external tones*) were randomly presented in addition to, but independently from the self-induced tones. The four mixed conditions resulted from the orthogonal manipulation of the presentation rate, and pitch of the external tones (identical frequent, different frequent, identical rare, and different rare external conditions): In *rare external* conditions the SOAs between consecutive external tones were sampled from a uniform distribution in the 0.5–7.5 ms time range (resulting in average SOA of 4 s, and a self-induced vs. external tone ratio of approximately 1:1). In *frequent external* conditions, SOAs between consecutive external tones were sampled from a uniform distribution in the 0.5–3.5 s time-range (average SOA of 2 s, approximately 1:2 self-induced vs. external ratio). In *identical external* conditions, external tones were identical to self-induced tones. In *different external* conditions, externally initiated and self-induced tones differed in pitch. The role of the two (500 and 1440 Hz) pitches was counterbalanced between participants.

3.1.3. Experimental procedure

As in Experiment 1, participants were sitting comfortably in a sound-proofed room, and auditory stimuli were delivered through headphones. They were instructed to look at a fixation puppet placed in front of the computer screen during the experimental blocks.

Before the experimental blocks were administered, participants completed a two-step training procedure to familiarize themselves with the device and the task. First, they performed 30 actions according to the instructions of the time-interval production task. The distribution of the between-action intervals was continuously displayed and updated after each action on the screen. Second, they performed the same task with 60 actions, but the distribution of the between-action intervals was only displayed after they completed the block. During training, participants' actions always induced tones, but no external tones were presented. After the training phase, the 5 experimental blocks were delivered in random order, with short breaks between them. Participants performed 90 pinches in each block. As in the second training phase, feedback about the distribution of the between action intervals was only provided at the end of each block.

3.1.4. Data acquisition

The timing of self-induced and external tones and the FSR-signal were recorded and processed in the same way as in Experiment 1. Since blocks were longer than in Experiment 1, instead of the first 10, the first 15 trials were discarded in each block.

3.1.5. Data analysis

The comparison of the single and mixed condition (no visual feedback) in Experiment 1 yielded an effect size of 0.430 (rank biserial correlation). The main goal of Experiment 2 was to reproduce this effect and establish whether the difference between conditions with and without externally generated sounds was significant. An estimated sample size of 39.308 should be sufficient to reveal an effect of this magnitude with a statistical power of 80%, at an alpha level of 0.05. The sample size used in the study (41 subjects) allows for the detection of effect sizes higher than 0.422 (corresponding to T -values below 248.966) with a statistical power of 80%. The sample size of the study should be sufficient to reveal differences between forces in the single and rare identical external mixed condition, even if the effect sizes are identical to the one observed in Experiment 1. However, Experiment 2 also had the goal of creating an auditory context for self-induced stimuli that would induce a more pronounced degradation in the quality of auditory feedback than what was accomplished in Experiment 1. Thus, it could be assumed that the manipulations would have a stronger effect on action-effect-related motor adaptation in Experiment 2 than in Experiment 1. (Due to the change from constant to random interval production task, increased effect size was expected even in the replicated comparison outlined above. However, in the frequent identical external mixed condition, where the number of computer-initiated tones was increased, an even stronger influence of auditory context was predicted.)

For each participant, the mean between-action interval was calculated in each condition and submitted to a one-way ANOVA. As in Experiment 1, pinches were characterized by the maximal force in the 750 ms following the crossing of the threshold. The median of the pinch force maxima was used to characterize each participant in each condition, which were compared by pairwise Wilcoxon signed-rank tests. Similarly to Experiment 1, T -values and for effect sizes, biserial rank correlation coefficients are reported for Experiment 2.

The analysis focused on 8 comparisons. First, forces recorded in the single condition were compared with forces recorded in the 4 mixed conditions. The hypothesis was that compared to the single condition, pinch force would only increase in the identical external conditions. In the different external conditions no degradation of auditory feedback quality would be induced by the computer-generated stimuli, thus action optimization should be similar to that observed in the single condition. Second, both identical external conditions were compared with the corresponding (i.e., same presentation rate of computer-initiated sounds) different external condition. Even if the different external sounds would have some effect on force optimization (indicating that interference with the time-interval production task might also induce force adjustments), a larger force increase in the identical external conditions could suggest an additional effect of feedback reliability. Finally, both rare external conditions were compared with the corresponding (same pitch for the computer-initiated sounds) frequent external conditions. According to the presumed role of feedback reliability in action optimization, increasing the presentation rate of computer-initiated sounds should only lead to force adjustments in the identical conditions. (In the different external conditions, the reliability of auditory feedback is not influenced by externally generated stimuli.)

The most important hypothesis of the study is related to the force difference between the tone-eliciting condition without external tones and tone-eliciting conditions with identical self-induced and external tones. To check whether the modifications of the paradigm indeed resulted in an increased contextual influence on action-effect-related motor adaptation, effect sizes related to this

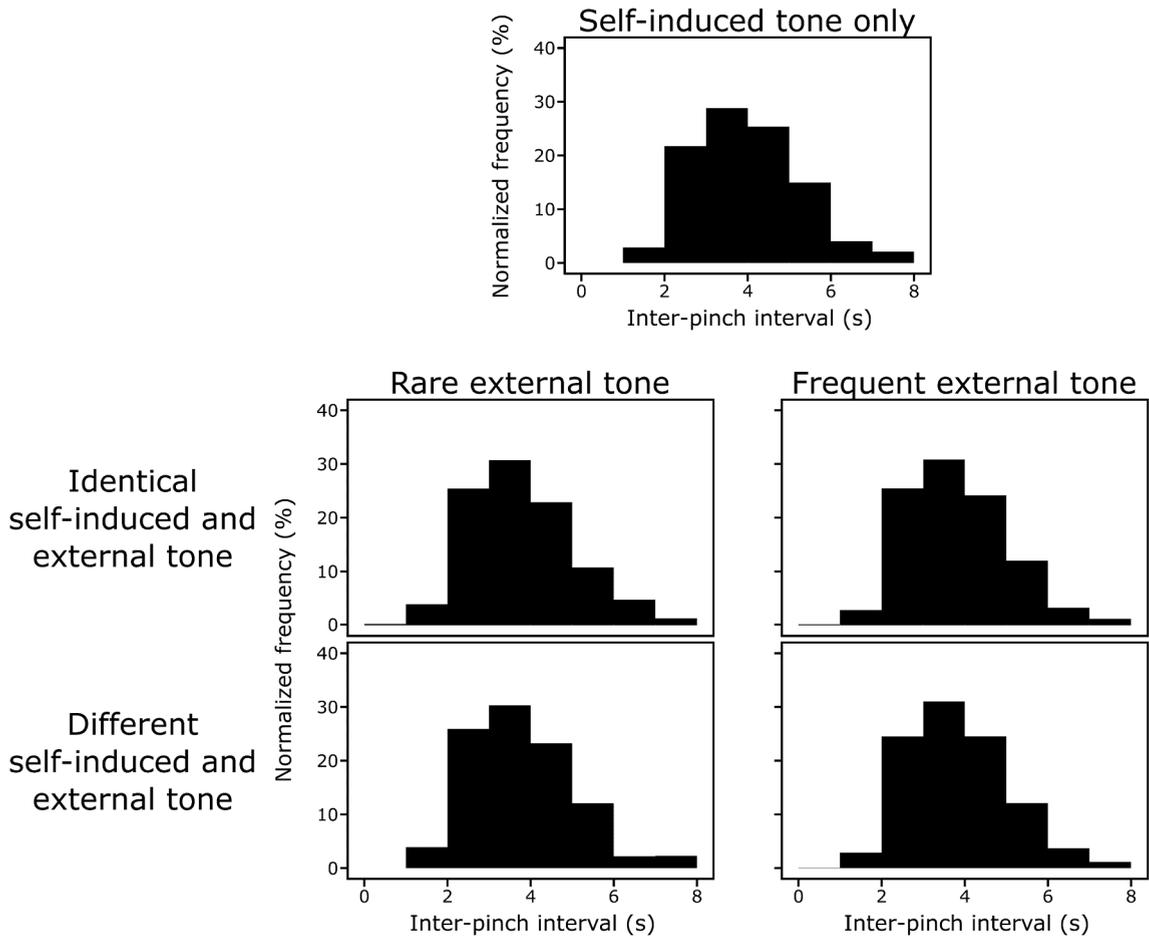


Fig. 3. Between-action intervals in Experiment 2. Histograms of between-pinch intervals in the five conditions (summary data of the 41 participants included in the analysis: all pinches of each participant). All registered between-action intervals are presented, including those that were later excluded from analyses.

difference were compared across the two experiments. To base the comparison on similar contrasts, the single, without led and the mixed, without LED conditions were selected from Experiment 1 and the single and the rare identical external conditions from Experiment 2. (There were no visual stimuli in either of the conditions, and the mixed conditions both had a self-induced – external ratio of ca. 1:1.) As the two experiments differed in several factors (i.e., number of participants, number of events, task, stimuli), a direct comparison was not possible. Thus, comparison was based on confidence intervals of the respective effect sizes. Confidence intervals were estimated with a bootstrap procedure (Carpenter & Bithell, 2000; Efron & Tibshirani, 1993; Kirby & Gerlanc, 2013) using 10,000 iterations. To enable comparison at an alpha level of 0.05, 87.9 percent confidence intervals were chosen according to the variance-based adjustments described by Payton, Greenstone, and Schenker (2003).

3.2. Results

3.2.1. Behavioral data

Participants produced between-pinch intervals that mostly fell into the 2–6 s time-range (Fig. 3), and deviated from the uniform distribution in the expectable patterns (see: Horváth, 2013; Horváth, Maess, Baess, & Tóth, 2012; Neszmélyi & Horváth, 2017, 2018): Whereas the distributions sharply rose at 2 s, the transitions were more gradual at the 6-s boundary (reflecting the decrease of temporal accuracy with the increase of the interval). The mean between-action interval did not significantly differ between conditions (single: 4.009 s, identical rare external: 3.823 s, identical frequent external: 3.838 s, different rare external: 3.864 s, different frequent external: 3.845 s), that is, external tones did not significantly disrupt the time-interval production task.

3.2.2. Pinch force

After rejection criteria were applied, 81.771 ($SD = 12.004$) percent of the actions (not including the first 15 tones) were retained for analysis. Pinches were stronger in all mixed conditions than in the single condition (rare identical $T = 52$, $p < .001$, $r_c = 0.879$; frequent identical: $T = 55$, $p < .001$, $r_c = 0.872$; rare different: $T = 269$, $p = .036$, $r_c = 0.375$; frequent different: $T = 227$, $p = .008$,

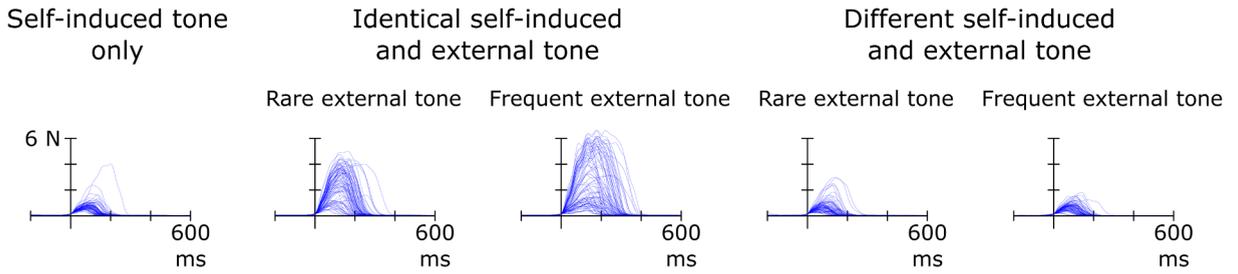


Fig. 4. Action force profiles in Experiment 2. Force application patterns as a function of time for all actions of a representative participant. Crossing of the axes represents the time-point where the presentation of the sound was initiated. (Note, that signal peaks were identified for all participants in the 0–750-ms poststimulus time window. However, on the figure, display of the signal terminates at 600 ms, as the actions of the selected participants were all completed within this timeframe.)

$r_c = 0.478$).

Importantly, pinches were consistently stronger in the identical than in the different external setting (Figs. 4 and 5), both in rare ($T = 140, p < .001, r_c = 0.675$) and in frequent external conditions ($T = 84, p < 0.001, r_c = 0.805$).

In the identical external setting, pinches were stronger in the frequent than in the rare condition ($T = 255, p = .022, r_c = 0.407$).

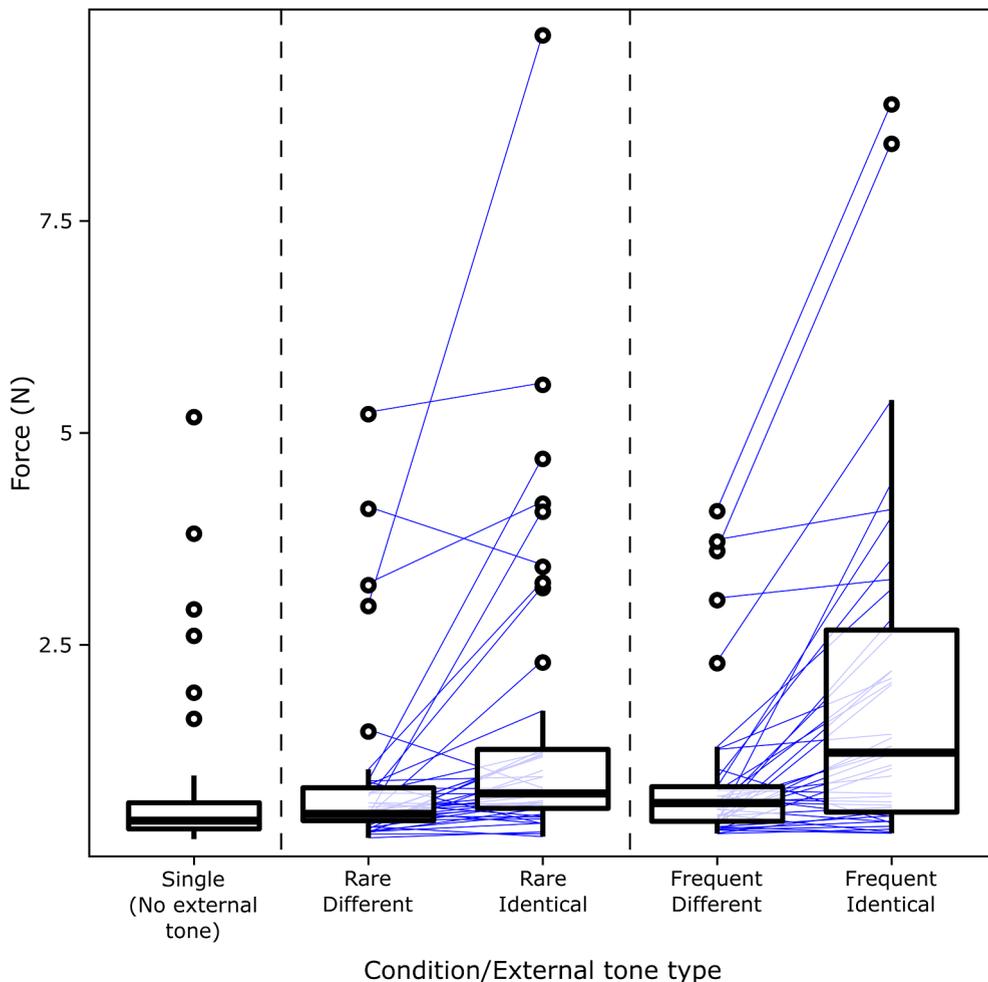


Fig. 5. Distribution of force maxima in Experiment 2. Tukey-plots of the distribution of individual pinch-force values in the five conditions of Experiment 2. (Boxes indicate values between the 1st and 3rd quartile, with thick horizontal lines in the boxplot representing the group median. Whiskers cover values in 1.5 interquartile range below and above the 1st and 3rd quartile, while circles represent data points that fall outside of this range. Blue lines connect data points of the same participant between conditions.) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

In the different external tone setting, no significant difference was found between pinch forces recorded in the rare and frequent external tone conditions ($T = 354$, $p = .328$, $r_c = 0.178$).

Confidence intervals (87.9 percent) for the comparison between the conditions with only self-induced, and conditions with equal number of self-induced and externally generated sounds were $CI = [0.1168, 0.7151]$ in Experiment 1 and $CI = [0.7282, 0.9884]$ in Experiment 2. As the two intervals do not overlap, it can be stated that at an alpha level of 0.05 the two effect sizes are significantly different, with the influence of external tones on action optimization being larger in Experiment 2.

3.3. Discussion

In Experiment 2, adjustments in the experimental design indeed resulted in a more pronounced expression of the tendency observed in Experiment 1. Reducing action-effect contingency (by adding external tones) induced modifications in the execution of the actions which can be interpreted as compensation for the decline in the quality of auditory feedback. When deprived of reliable auditory feedback, participants tended to abandon force minimization strategies, and maintain the high probability of successful actions by increasing the force of the actions. The results also show that increasing (doubling) the number of external tones leads to a further increase in applied force, when acoustic features of externally generated and self-induced stimuli are identical, which is consistent with our hypothesis that increasing the number of external tones would make it more difficult to extract the auditory information relevant for assessing action success. The results suggest that the utility of auditory action effects for motor control is a monotonic function of the information that these effects provide about the success of the interaction.

The results of the experiment also indicate that changes in pinch force primarily depend on the feedback role of the self-induced sounds, and task-related attentional processes only provide minor contribution to the observed effects of auditory context: Although some minor increase in pinch force was also observed when self-induced sounds were intermixed with distinguishable external tones (different pitch) the motor adjustment induced by external tones was much larger when they were identical to the self-induced ones.

4. General discussion

The results of the two experiments indicate that even subtle changes in the sensory environment can affect how sensory consequences are used for controlling sequential ballistic actions. When self-induced sounds were generated in an auditory context that reduced the reliability of the auditory feedback, the force of the tone-eliciting pinches increased significantly. The results reported in the study are consistent with previous interpretations of action-effect-related motor adaptation (Horváth et al., 2018), which explained the phenomenon within an optimization framework (Bays & Wolpert, 2007; Davy & Audu, 1987; Pandey, Garner, & Anderson, 1995; Todorov, 2004; Uno, Kawato, & Suzuki, 1989). It was suggested that feedback quality determined which optimization goals are prioritized by the agents: Reducing feedback reliability can result in agents abandoning the objective of effort minimization, and execute more effortful actions, which increases the probability of action success. Whereas previous studies (Horváth et al., 2018; Neszmélyi & Horváth, 2017, 2018) directly manipulated the action-effect relationship (by removing the dominant feedback modality, or delaying the auditory action effect), the current study demonstrates that differences in the sensory context of the effects influence action planning or control even if the causal action-effect relationship is the same. These results indicate that the role of auditory feedback in action-effect-related motor optimization does not simply rely on the automatic binding of simultaneous motor and sensory events. Apparently, the motor utility of sensory stimuli elicited by ballistic actions is established on a larger time scale, by also taking into account the relationship between those sensory events that are related to movements and those that can be regarded as agent-independent elements of the environment.

The results of the present study may be interpreted as an extension to the sensory weighting principle, which suggested that cognitive representations of actions relied more on the task relevant, than on task irrelevant action effects (Memelink & Hommel, 2012). The current study indicates that weighting of various sensory action consequences is not only determined by task-relevancy: Perceptual properties of the action consequences and the environment might determine the “value” of information that certain sensory effects can provide about the actions, and this value in turn would determine the role that the effects play in motor control processes.

The reported results raise several questions: (1) How do increased pinch forces compensate for reduced feedback quality? (2) The manipulations of auditory environment applied in the study (intermixing self-induced and externally generated sounds with identical acoustic features) affect several factors of the action-effect relationship that can induce a decrease in feedback quality. Which one of these factors was responsible for inducing motor adjustments? (3) Can the context-related motor adjustments only be explained by compensation for reduced feedback quality, or are there also other plausible accounts of the observed effects?

Previously, action force increases induced by physical manipulations of the action-effect relationship have been interpreted in two ways. These interpretations can be also applied to motor adjustments induced by changes in the auditory context. First, increasing applied force may allow one to increase the chance of a successful interaction with the device (Horváth et al., 2018). One could picture this as jumping over a hurdle in complete darkness: The strategy with the highest probability of success is to jump as high as possible. In the current study, performing actions with a force that is well above the threshold is a good strategy to ensure a high rate of interaction success (if one disregards the cost of effort).

Second, increasing the applied force may also allow one to directly compensate for the loss of sensory feedback in one modality by increasing feedback in other modalities (Aschersleben & Prinz, 1997). When distal (auditory or visual) effects are reliable, participants primarily utilize these for controlling the actions. The preference of auditory (and visual) feedback can be explained both by the fact that they provide more reliable feedback than other action consequences (e.g. tactile) in the current paradigm, but also by the

inherent general preference of distal feedback modalities (Hommel, 1993; Kunde, Müsseler, & Heuer, 2007; Ladwig, Sutter, & Müsseler, 2012; Massen & Prinz, 2007; Müsseler & Sutter, 2009; Sutter, Müsseler, Bardos, Ballagas, & Borchers, 2008). However, if the quality of the distal feedback is reduced, proximal feedback might become more relevant. In the present study, as feedback information provided by the auditory stimuli decreases, overall feedback level can be kept constant by increasing the amount of information coming from the tactile modality. This might be achieved by executing stronger actions. That is, increasing force may reflect a goal to increase the intensity of the tactile stimulation during the interaction with the device.

A further question is how the addition of external tones reduced the quality of auditory feedback in the current paradigm. In the introduction, three closely interconnected possible frameworks were outlined, which can provide an explanation about the relationship between action-effect contingency and feedback quality: action-effect-binding, recognition of causality, and source attribution to auditory stimuli. For the most part, all three explanations would predict a similar effect of the applied context manipulations on feedback quality. (For example, increasing the number of external tones—as was done in Experiment 2—would be expected to similarly reduce action-effect binding, the estimated strength of causal connections, and certainty of source attribution.) It was not a goal of the current experiment to determine the contribution of these factors, however, differences between results of the first and second experiment indicate that the role of source attribution might be more important than other influences.

Taking only the level of contingency into account, the conditions with about equal proportion of self-induced and external tones in the two experiments (no visual feedback mixed condition of Experiment 1, and rare external identical condition of Experiment 2) are very similar. Surprisingly however, the observed adjustments induced by the external tones (compared to conditions with only self-induced tones) appear to be substantially larger in Experiment 2. This difference might be brought about by any of the experimental design differences between Experiments 1 and 2: The higher sound intensity in Experiment 1 might have caused a stronger automatic binding of simultaneous motor and auditory events in Experiment 1, reducing the effect of external sounds. Also, the conditions that were administered beside the conditions that were equivalent in the two experiments were very different (e.g., in Experiment 1 there was a condition without any distal sensory action effects; in Experiment 2 there were conditions with different external sounds, and conditions with an increased number of external sounds). It has been shown previously that motor adaptation to a given action-effect relationship could persist for longer periods (at least in the order 5–10 min; Neszemlyi & Horváth, 2018). These long-term adaptation effects might have affected action forces of the self-induced only and 1:1 self-induced/external conditions differently in the two experiments.

The difference between the tasks (constant interval vs. random interval production) might have also contributed to the enhanced context-related effects in Experiment 2. Random interval production might have increased the intentionality of the actions in Experiment 2 (see: 1. Introduction). However—as previous studies did not suggest substantial difference in action-effect-related motor adaptation with constant and random interval production tasks (Neszemlyi & Horváth, 2018) — it seems more likely that in Experiment 1, the even tempo (every ca. 4 s) of self-induced tones and the random presentation intervals of the external tones (1–7 s with uniform distribution) resulted in two, better distinguishable auditory streams, and thus a more unequivocal source attribution for auditory events. The abolishment of this contrast in Experiment 2 might have made it more difficult to identify the source of the tones on a perceptual basis, which might have also made it more difficult to determine whether a tone in close temporal proximity to an action attempt can be regarded as feedback about the success of the attempt. According to this explanation, the connection between the frequency of the external tone and the level of force adjustment—as observed in Experiment 2— might also be determined by the difficulty of source discrimination and not by the level of action-tone contingency.

The considerations above explain the results within a traditional computational motor control framework (Adams, 1976; Todorov, 2004). The findings can also be explained, however, in a predictive framework based on the ideomotor principle (Hommel, Müsseler, Aschersleben, & Prinz, 2001; Prinz, 1987, 1990; Shin, Proctor, & Capaldi, 2010). According to this framework, context-related differences in the execution of actions would not reflect differences in the amount of information provided by sensory action consequences (i.e., differences in the reliability of feedback), but differences in action goals. The ideomotor theory is a teleological approach, which assumes that action control is based on the goals of the person (Elsner & Hommel, 2001; Hommel, 1996, 2009), that is, motor plans are activated by the anticipation of the action effects. It can be argued that action goals are easier to formulate in terms of distal effects, because these are usually more distinctive, and better defined than proximal effects, and thus, they would enable more efficient action-control. In the present study, the unavailability of such distinctive distal effects might have forced participants to rely on the internal or proximal (tactile) effects in the motor condition. Similarly, in mixed conditions, the abolishment of the one-to-one action-tone correspondence might have also reduced the efficiency of ideomotor control processes because reducing action-effect contingency may result in weaker action-effect links (Elsner & Hommel, 2004).

The ideomotor interpretation of the results would be consistent with studies that show that the role of distal action consequences in motor control is dependent on the action-effect contingency. However, previous research only shows that parameters of movement initiation are negatively affected, when the one-to-one assignment between actions and stimuli is violated (Elsner & Hommel, 2004; Hoffmann, Sebald, & Stöcker, 2001; Stöcker & Hoffmann, 2004; Ziessler & Nattkemper, 2001). The current experiment extends on these results by showing that—even in the case of ballistic movements—the effects of action-effect contingency are not only apparent in the temporal parameters of movement initiation, but also in the force-profiles of action execution.

It has to be noted that the ideomotor approach also suggests another explanation for stronger action forces in conditions in which computer-initiated stimuli are interspersed with the self-induced ones⁴. Response-effect compatibility—as a consequence of common

⁴ We would like to thank the two anonymous reviewers for suggesting the following two explanations for context-related force adjustments (i.e., influence of action-effect compatibility, and compensation for conflicting information about action timing).

representation for motor and perceptual events (Hommel, 1996, 2009)—is a central idea of the ideomotor framework: It suggests that action initiation is more efficient (as reflected in faster reaction times) if the elicited sensory effect shares certain features with the movement. Such compatibility effects have been reported in the spatial (Hommel, 1993; Kunde, 2001) and temporal (Kunde, 2003) domain, but it has been suggested that a similar action-effect relationship can also be observed in the dimension of intensity. In the study of Kunde, Koch, and Hoffmann (2004), response selection, execution and initiation appeared to be more efficient when the intensity of the movement matched the intensity of the elicited effect (i.e., strong button presses eliciting loud tones, or soft actions eliciting soft tones). In the current experiment, increased forces in conditions in which self-induced and computer-initiated tones were intermixed, might reflect the goal of the participants to elicit louder tones, and thus enable identification of action effects based on their perceptual properties (in this case intensity) in a noisy auditory context. The compatibility effect might be so deeply rooted that participants would apply this strategy even if no actual coupling between movement and stimulus intensities was present (as in the current setup).

The interpretations above (with the exception of the one based on action-effect compatibility) suggest that increased force in conditions with external stimuli is caused by action-stimulus binding being compromised by the reduction of action-effect contingency. An alternative explanation, based on external stimuli interfering with the time-interval production task might be also plausible. Timing of self-initiated actions might be judged based on integrating information from various sensory modalities (Aschersleben & Prinz, 1997). A computer-generated sound presented in the proximity of a self-generated event may be involved (accidentally) in the timing task instead of the self-generated one, and thus interfere with timing performance. In the face of such a conflict one may accentuate the relevant information source: Stronger force application may result in a higher signal-to-noise ratio in the tactile domain, which could allow for more accurate timing judgements. That is, action-effect-related motor adaptation might not be caused by uncertainty about the success of the actions, but by the uncertainty about the timing of the actions. A similar explanation was suggested previously for timing errors, and force adjustments induced by delayed auditory feedback (Finney, 1997; Karlovich & Graham, 1967; Pfordresher, 2005, 2006; Ruhm & Cooper, 1963; Yates, 1965), but intermixing external sounds with self-induced ones could also lead to a similar tactile-auditory information conflict: There are, however, a few arguments against this explanation.

First, timing accuracy is, arguably, more relevant for producing a constant pace than for producing random intervals. Thus, according to the timing-related interpretation of force adaptation, the effect of external tones should be more pronounced in the constant interval task. (Timing judgements are similarly influenced by the addition of external sounds in both tasks.) In the study, however the opposite was observed. Second, in fast rhythmic pattern production tasks, where conflicting information about timing is presumed to play an important role in timing errors, and in force adjustments, the effects of conflicting information from various feedback sources is usually larger than the effects of completely removing external feedback (Finney, 1997; Gates & Bradshaw, 1974; Pfordresher, 2005, 2006; Yates, 1965) This is not the case in the current study: In Experiment 1, force increase (compared to the reliable auditory feedback condition) was much smaller in the motor-auditory mixed (unreliable auditory feedback) than in the motor (no auditory feedback) conditions. This gradient of force levels is more in line with way the level of feedback about action success differs across conditions.

5. Conclusion

The results of the study suggest that action-effect-related motor adaptation (i.e., the utilization of auditory effects in establishing an optimal force level for the actions) is not only affected by the physical action-effect links but also by the environment, in which self-induced stimuli appear. Reducing the quality of auditory feedback by intermixing external tones with self-induced ones resulted in similar motor compensation strategies as removing or delaying the auditory effects of the actions. The results strongly suggest that these context-related effects can be attributed to increased difficulty in determining the source of auditory events when action-effect contingency is reduced: As participants are uncertain whether a tone can be regarded as relevant feedback on their actions, they tend to adjust their actions to increase the probability of action success. The findings might also have implications for the designing of digital interaction devices. The experimental paradigm suggests a way how changes in the environment can be tracked through the actions of the user, providing the possibility of automatically adjusting the settings of the device to the requirements of the situation.

6. Data availability

Data recorded and analyzed during the current study will be provided by the corresponding author in the case of request.

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Declaration of Competing Interest

The authors declare that they have no competing interests.

Ethical approval

Experimental procedures were in accordance with the Declaration of Helsinki and the protocol was approved by the United Ethical Review Committee for Research in Psychology (Hungary). All participants signed informed consent.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.humov.2019.102503>.

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