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Force and electromyography reflections of sensory action-effect weighting during pinching

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ABSTRACT

Ideomotor theories suggest that different action-effects are not equally important in goal-directed actions, and that task-relevant information are weighted stronger during the representation of actions. This stronger weighting of task-relevant action-effects might also enable to utilize them as retrieval cues of the corresponding motor patterns. The aim of the present study was to investigate how the consistent presence or absence of a sound action-effect influenced the retrieval of the motor components of a simple, everyday action (pinching) as reflected by the pattern of force application and surface electromyogram (sEMG) recorded from the abductor pollicis brevis (APB) and first dorsal interosseous (FDI). Participants applied pairs of pinch impulses to a force sensitive resistor (FSR). The presence or absence of a sound action-effect and the between-action interval (BAI, 2 or 4 s) were manipulated blockwise, whereas the target force level (low or high) was randomly cued from trial to trial. When actions resulted in a sound, force and sEMG activity were reduced. This effect was more pronounced for low target force level trials, which is compatible with a stronger weighting of the sound action-effect when the intensity of the tactile and proprioceptive action-effects is low. Surprisingly, the FDI activity was more variable within actions pairs in the 2 s BAI conditions, which suggests that action pairs separated by the longer time interval might have been represented differently from those separated by the shorter interval.

1. Introduction

Successful interactions with our environment and tool use require a complex and continuous interplay between sensory, motor and cognitive systems. For example, when pressing a button to activate the doorbell at somebody's house, our intention is to signal that we have arrived, and our force application results in proprioceptive, tactile (i.e., pressure on our finger), and auditory (i.e., the doorbell sound) effects. However, action-effects are not equally important when our intentions are taken into consideration: as long as the doorbell rings, a wide range of tactile and proprioceptive effects, as well as movement trajectories and muscle activation patterns are acceptable. Ideomotor theories (Hommel, 2009; Hommel, Müsseler, Aschersleben, and Prinz, 2001) propose that the effects forming the goal – the task-relevant consequence – of the given action play a leading role in the activation of the corresponding motor components. According to these theories, the motor and sensory components of actions are represented in integrated networks of bi-

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directional connections (e.g., *event files*, see e.g., Hommel, 2019), and the selection of the appropriate muscle activation patterns occurs through the activation of the relevant sensory effect representation (Elsner and Hommel, 2001; Memelink and Hommel, 2013). The notion of a leading role of sensory effects in the activation of the motor components of the action is compatible with studies showing that participants have difficulties when force exertion patterns are to be repeated or accessed consciously in the absence of the initially elicited action-effects (de Graaf et al., 2004; Frith, 1995; Hommel, 2013). Most studies supporting this view utilized complex actions and action-effect relationships, and used kinematic measures to characterize the motor components of the actions (e.g., bimanual coordination, Kovacs, Buchanan, and Shea, 2010; Mechsner, Kerzel, Knoblich, and Prinz, 2001; or moving a computer mouse to a target position, Pfister, Janczyk, Wirth, Dignath, and Kunde, 2014). The leading role of sensory action-effects should, however, be observable for simple, ballistic actions as well. Furthermore, such effects should be present not only in the kinematic, but also in the dynamic characteristics of the actions. The goal of the present study was to investigate how the consistent presence or absence of a sound action-effect influenced the retrieval and weighting of the motor components of a simple, everyday action – pinching – by measuring muscle activity reflected by surface electromyogram (sEMG) and the applied force.

Several recent studies investigated how manipulations of action-effects elicited by simple actions influenced the motor characteristics of the action. It was found that when an interaction depended on exceeding a force threshold, smaller forces have been applied when actions consistently resulted in an auditory effect in comparison to interactions not producing the auditory effect (see e.g., Cao, Kunde, and Haendel, 2020; Horváth, Bíró, and Neszmélyi, 2018; Neszmélyi and Horváth, 2017, 2018, 2019; see also Kunde, Koch, and Hoffmann, 2004). Although this *action-effect related motor adaptation* was present for various interactions (e.g. pressing a button, or tapping), it might have been amplified in experiments in which participants pinched force sensitive resistors (FSRs) glued to a thin plastic sheet, because this type of interaction is relatively free of transient mechanical events in contrast with tapping or button pressing, where successful interactions provide well-distinguishable tactile or proprioceptive feedback (impacts, clicks, sudden displacements). Neszmélyi and Horváth (2017) suggested that in such paradigms, participants optimize their motor behavior: they prefer motor patterns which require less effort but still result in successful interactions, especially, when an action is repeated several times. That is, auditory feedback provides a better opportunity for the optimization of the action than the other (proprioceptive and tactile) action-effects, and thus plays a dominant role in shaping the motor components of the actions, even if the task is not directly related to the sound effect itself (e.g., performing actions at a slow, even pace).

Since the consistent auditory action-effect results in a marked behavioral change, it seems plausible that the elicited sound not only provides feedback with a clarity that the other action effects cannot provide, but it may also become the primary way in which the action is represented. This idea fits well with the concept of event files within the framework of ideomotor theories, such as the theory of event coding (TEC – Hommel et al., 2001; Hommel, 2019). Event files are episodic representations which automatically integrate the motor and sensory features of the actions (Elsner and Hommel, 2001; Hommel, 2004, 2019). It is also assumed that information within the event files is weighted so that features which provide task-relevant information will be weighted stronger during action planning (Memelink and Hommel, 2013), and serve as retrieval cues of the corresponding motor patterns (see e.g., Frings et al., 2020; Hommel, 2004, 2019). That is, adding a sound effect to pinching the FSR not only creates a "richer" event file, but it may also substantially alter the weighting of its constituent features. To put it simply, the consistent presence of the sound effect yields a cognitive action representation according to which participants are no longer "pinching a device", but "eliciting sounds".

Encoding the action with more distinguishable sensory effects may also allow a more efficient retrieval of the corresponding motor patterns, thus adding a sound effect to the action may well provide better access to the motor components of the actions, which are otherwise accessible for conscious processing to a lesser degree (de Graaf et al., 2004; Hommel, 2013). For example, participants initiated and performed motor sequences faster when their actions resulted in audiovisual action-effects compared to auditory or visual action-effects alone (Luan, Maurer, Mirifar, Beckmann, and Ehrlenspiel, 2021). This suggests that when actions result in salient and meaningful sensory consequences, these representations become rich and informative, leading to better performance as well as to lower effort (e.g., Neszmélyi and Horváth, 2017). Also, consecutive actions were found to be less variable when synchronized to auditory stimuli (Du, Clark, and Whitall, 2017) or when these elicited marked visual (Du et al., 2017; Therrien and Balasubramaniam, 2010) or vibrotactile (Thébault, Pfister, Michalland, and Brouillet, 2020) effects.

Furthermore, the shared features of consecutive actions might also influence their performance. Studies utilizing paradigms in which the execution of an action (A) had to be postponed until performing another action (B) demonstrated that performance of action A could benefit from action B when their features overlapped (Mocke, Weller, Frings, Rothermund, and Kunde, 2020; Stoet and Hommel, 1999). This indicates that if a stimulus or action is repeated, it triggers the retrieval of the corresponding event file, and if the event file matches the required response, it will facilitate responding (Frings et al., 2020). On the other hand, there is also evidence that already activated but postponed responses might interfere with succeeding actions (Mocke et al., 2020; Takács, Bluschke, Kleimaker, Münchau, and Beste, 2021). These interactions between consecutive actions may serve as the bases of more complex action sequence representations (Moeller and Frings, 2021).

Based on this, the goal of the present study was to investigate how the consistent presence of an auditory action-effect affected the retrieval of the motor components of an action, by measuring motor activation (as reflected by sEMG) and force application patterns for repeated actions. We instructed participants to perform consecutive pairs of actions so that the two actions would be as similar as possible. We hypothesized that the consistent presence of a sound effect would allow a better retrieval of the motor patterns, and thus result in smaller between-pair motor activation and force differences than in the consistent absence of an auditory action effect.

To provide reliable, consistent action-effect contingencies, the auditory effect was either present or absent in each experimental block (i.e. a between-block manipulation). Because this may reduce variability in the motor patterns, participants were also instructed from trial to trial to exert a high or low target force level in the next action-pair (for a similar manipulation see, Kunde et al., 2004, but in contrast to their arrangement, in the present study the same tones were presented for both target force levels). Comparable results were found when several seconds long pinches were performed at different force levels instead of short impulses, and force accuracy and force variability were measured. In studies in which participants produced long pinches with 5–40% of their maximal pinch force either in presence or absence of visual feedback on the exerted force, visual feedback led to overall lower forces, and force variability was the largest in case of the lowest target force levels (De Serres and Fang, 2004; Li, Li, Wang, Chen, and Liu, 2020). These results further imply that the voluntary control of force becomes more difficult at lower than at higher force intensities, especially when participants can rely on the tactile information only.

Additionally, the between-action interval within the action pairs was manipulated: in each block, participants were instructed to produce either 2 s or 4 s between-action intervals. We hypothesized that repetition performance will be worse at the longer between-action interval. Previous studies used various between-action intervals ranging from 2 to 8 s (Cao et al., 2020; Horváth et al., 2018; Neszmélyi and Horváth, 2017, 2018), that is, the optimal force level can apparently be retrieved after these time periods, but force modulations were not compared between different between-action intervals. The spontaneous decay of event files was found to be over 1–5 s for simple actions (Hommel and Frings, 2020) while studies on motor memory suggested somewhat longer decay intervals ranging from 5 to 120 s for complex actions (Adams and Dijkstra, 1966; Marshall, Wyatt, Moore, and Sigman, 1975). Further evidence is present from tasks in which participants had to continue action sequences with a pre-defined force after auditory cues and visual feedback were removed. Softer and less variable forces were produced in case of faster than in slower pace (Inui, Ishida, and Yamanishi, 1999: 200 vs 400 vs 800 ms and 500 vs 1000 vs 1500 ms: Du et al., 2017; Therrien and Balasubramaniam, 2010). On the other hand, longer between-action intervals (1–4 s) had no effect on performance in a pinch force matching task (Hashemirad, Fitzgerald, Zoghi, Hashemirad, and Jaberzadeh, 2017).

Although exerted force has been widely used as indicator of motor aspect of actions, myoelectric signals (sEMG in the present study) may provide additional information on motor activity patterns. The relationship between EMG and force is typically curvilinear for smaller muscles with narrow motor unit recruitment force ranges (Jahanmiri-Nezhad, Hu, Suresh, Rymer, and Zhou, 2014; Konrad, 2005; Lawrence and De Luca, 1983; Maier and Hepp-Reymond, 1995; Zhou and Rymer, 2004) while larger muscles can be characterized better with nonlinear EMG-force relations (Lawrence and De Luca, 1983). The linear relationship also means that in case of higher force levels, more EMG is needed to increase force (Konrad, 2005). More specifically, in case of hand muscles during sustained pinch actions, highest correlation coefficients between EMG and force were demonstrated in adductor pollicis brevis and first dorsal interosseous (FDI), while other muscles like abductor pollicis brevis (APB) and opponens pollicis (OP) showed higher variability (Maier and Hepp-Reymond, 1995).

Whereas the effects of action-effect contingency on force exertion have been extensively investigated, results on its EMG correlates are scarce. Lower EMG activity and force were measured in a typing task with auditory feedback on actions compared to the absence of auditory feedback (Gerard, Armstrong, Rempel, and Woolley, 2002). Furthermore, as EMG provides information both on the condition of muscles and their function, it is widely used for example in rehabilitation and sports. In these areas, the technique of sonification is often applied which exploits the action-sound effect contingencies by transforming movement parameters into sounds turning them as specific feedback signals which might facilitate the obtainment of preferred movement parameters (for a review, see: Schaffert, Janzen, Mattes, and Thaut, 2019).

In summary, we recorded sEMG from two hand muscles (APB and FDI) simultaneously with force signals from a force sensitive resistor (FSR) while participants produced identical pinch actions in pairs with their dominant hand. The presence or absence of an action-effect sound (motor-auditory vs motor blocks) and the between-action intervals (BAI; 2 or 4 s) were defined blockwise, and in order to interrupt the uniformity of actions, the instruction on target force level (low vs high) was defined from trial to trial. As the consistent sound action-effects were supposed to dominate in retrieval the motor components of actions (Memelink and Hommel, 2013) and accompanied with better performance (Gerard et al., 2002; Thébault et al., 2020) and lower effort (e.g., Horváth et al., 2018; Neszmélyi and Horváth, 2017, 2018, 2019), we hypothesized overall lower forces and sEMG activity for these trials as well as higher similarity between actions within a pair when actions resulted in sound. We also expected that similarity of pinches will be higher in case of high compared to low target force levels both in case of force and sEMG signals. Finally, lower force exertion and higher similarity were assumed in case of the 2 s BAI compared to the 4 s BAI.

2. Methods

2.1. Participants

17 right-handed persons participated in the experiment for course credits (14 females, 3 males, mean age: 21, range: 18–24 years). Because of excessive amount of sEMG artefacts (De Luca, Donald Gilmore, Kuznetsov, and Roy, 2010; Stegeman and Hermens, 2007) or excessive number of force impulses in which force application lasted longer than 1000 ms, data from four participants was excluded from further analysis (13 participants remained, 10 females and 3 males, mean age: 21, range: 19–24 years). All participants reported normal or corrected-to-normal vision, normal hearing and the lack of neurological or psychiatrical problems. They gave written informed consent after the experimental procedure was explained to them. The project was approved by the United Review Committee for Research in Psychology (Hungary) and was conducted according to the Declaration of Helsinki.

2.2. Stimuli and procedure

Participants were sitting in a sound-attenuated and electrically shielded room. They were holding a Force Sensitive Resistor (FSR; FSR Model 402, Interlink Electronics, Westlake Village, CA, USA; 0.3 mm thick, circular active area with a 13 mm diameter) mounted on a thin plastic sheet. The sheet was pinched (held) between the thumb and index finger of the dominant hand, with the thumb holding the sheet from above. Participants were instructed to produce pairs of short pinch impulses. The FSR was calibrated to detect impulses when its signal exceeded a threshold of 0.27 N, after being continuously under the threshold for at least 80 ms. The FSR signal was recorded by using the high-level input of a SynAmps2 amplifier (Compumedics Neuroscan, Victoria, Australia) with a sampling rate of 2000 Hz. As the FSR signal is well approximated by a log-linear function, force from FSR signal was calculated offline by an

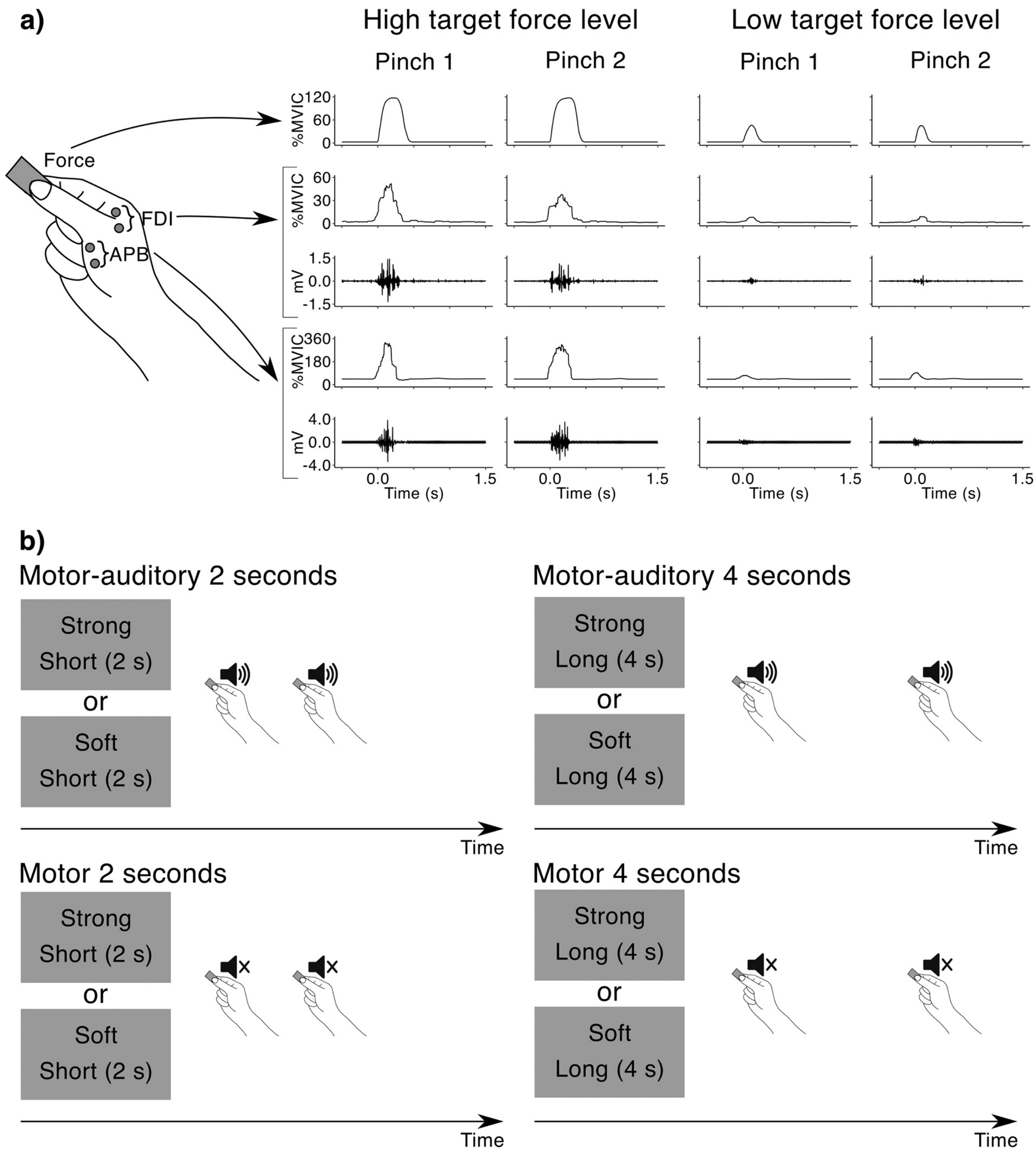

Fig. 1. Setup of the experiment and representative single-trial force and sEMG data from one participant. a) Participants were holding an FSR mounted on a thin plastic sheet between the thumb and index finger of the dominant hand, with the thumb holding the sheet from above. Gray circles on the surface of the hand represent the approximate locations of sEMG electrodes. For sEMG channels, raw and full-wave rectified, MVIC-normalized RMS-smoothed data are provided. b) Participants were instructed to produce pairs of short pinch impulses. The presence of the auditory effect (motor or motor-auditory condition) and BAI (2 or 4 s) were manipulated blockwise, while the target force level (high or low – strong vs soft in the task) was randomly prescribed from trial to trial.

exponential transformation.

Participants were wearing headphones (HD-600, Sennheiser, Wedemark, Germany) during the experiment and they were instructed to produce two identical pinch impulses on the FSR. In half of the blocks (motor-auditory blocks), every pinch produced a 1000 Hz sine tone with a 50 ms long duration (10–10 ms rise and fall times). Sound loudness was individually calibrated to 50 dB above the 75% hearing threshold determined by an adaptive procedure (Kaernbach, 1990; Shepherd, Hautus, Stocks, and Quek, 2011). In the other half of the blocks, pinches did not result in any auditory effect (motor blocks). The between-actions interval (BAI) was varied block-wise: the two pinches were separated either by 2 or 4 s. The orthogonal combination of the two manipulations (BAI, auditory effect) resulted in four conditions (block types): 2 s motor-auditory, 2 s motor, 4 s motor-auditory, 4 s motor condition. A further (third) manipulation was applied within blocks: each trial started with a visual cue indicating whether the pair of pinches should be produced with high or low target force level. A cue on target force level and BAI ("strong short (2 s)", "soft short (2 s)", "strong long (4 s)" or "soft long (4 s)" in Hungarian, respectively) was displayed. Following this, participants had to wait at least 1 s and then produce the first pinch and then the second one. The cue remained displayed on the screen until 1 s after the second pinch onset. In case when the first pinch was produced within 1 s from starting cue, a warning message ("Too early!" in Hungarian) was displayed for one second, followed by a blank screen for another second. Between successive pinch pairs a random interval between 4 and 6 s was introduced. At the end of each block, participants received feedback on their performance: the average between-action time and within-pair peak force differences were displayed separately for high and low target force trials, as well as a graph of between-action intervals, and force peaks for high and low target force trials were presented for each trial. The experimental setup and single-trial sample data from one representative participant is presented in Fig. 1.

For each block type, three blocks were administered in a semi-random order with the restriction that two identical blocks could not follow each other, and each block type occurred once in the 1–4th, 5–8th, and 9–12th block position. Each block contained 40 pinches, that is, 20 pinch pairs. In each block, 10 pinch pairs were high and 10 pinch pairs were low target force trials (in random order), resulting in a total of 30 pinch pairs for each participant for each condition and target force level. To normalize individual differences in force between participants, at the beginning of the experiment an additional block was administered in which participants were instructed to produce 20 pinch impulses with the maximal force possible (maximal voluntary isometric contraction – MVIC).

2.3. sEMG recording and data processing

During the experiment, surface electromyogram was recorded from the abductor pollicis brevis (APB) and the first dorsal interosseous (FDI) by Ag/AgCl electrodes separated by cca 1.5 cm from each other in a bipolar setup (2000 Hz sampling rate, the same SynAmps2 amplifier as above).

The first two pinch pairs of each block and consecutive pinches within 1 s in the 2-s conditions, and consecutive pinches within 2 s in the 4-s conditions were removed from further analysis. Following the guidelines by Konrad (2005), sEMG data was filtered offline with a 20–400 Hz bandpass filter (Kaiser-windowed sync finite impulse response filter with a transition bandwidth of 1 Hz, stopband attenuation at least 50 dB, beta: 4.5335), then full-wave rectified and smoothed with the root mean square (RMS) with a 100 ms window. Because of the potential trial-to-trial variability of the recruitment of motor units, the RMS-smoothed sEMG and force data were normalized by the mean of maximum peak amplitudes of trials in the MVIC block (Lohse, Sherwood, and Healy, 2011) with minimum of 2 N peak force. The normalized sEMG and force data were segmented to epochs of 2 s, from −500 ms to 1500 ms relative to the timepoint when the force signal exceeded the threshold.

In the next step, windows of analyses were defined separately for the force and sEMG signals for each action. For the force channel, the windows started at time point 0 and ended when the signal dropped below 0.27 N (i.e., the threshold value), and remained below that for at least 10 ms. Because EMG activation typically starts about 10–150 ms earlier than the resulting force (electromechanical delay: Begovic, Zhou, Li, Wang, and Zheng, 2014; Hug and Tucker, 2018; Ngeo, Tamei, and Shibata, 2014), the windows for the sEMG signals were extended to start 150 ms earlier than those of the corresponding force signals.

For each pinch, the area under the curve (AUC – integrated EMG; Konrad, 2005; Stålberg et al., 2019) was calculated as an integral of the data points within the windows of analysis, as well as the ratios of AUCs for the first and second pinch in each pair. Furthermore, for each participant, Spearman correlation coefficients between the AUCs of first and second pinches were calculated for each condition. In the following, AUCs for sEMG and AUCs for force are referred to as sEMG activity and force, respectively.

2.4. Data analysis

Participants were characterized with the median AUC of the APB, FDI (sEMG activity) and force signals as the data exhibited skewed distribution. Because of the potential correlations between sEMG (APB, FDI) and force (Jahanmiri-Nezhad et al., 2014; Konrad, 2005; Lawrence and De Luca, 1983; Maier and Hepp-Reymond, 1995; Zhou and Rymer, 2004), multivariate analysis of variance (MANOVA) was conducted. Significant effects were followed-up by repeated measures analyses of variance (ANOVA).

The effects on the experimental manipulations on force and muscle activity were investigated from three aspects. First, the *median sEMG activity and force of the first and second pinches* was analyzed by a PINCH NUMBER (first/second) × BAI (2 s/4 s) × SOUND (motor-auditory/motor) × TARGET FORCE LEVEL (high/low) MANOVA. Second, *the absolute value of force or sEMG activity change from the first to the second pinch was expressed as a percentage change of the first force or sEMG activity,* respectively. These were submitted to a BAI (2 s/4 s) × SOUND (motor-auditory/motor) × TARGET FORCE LEVEL (high/low) MANOVA. Finally, then the *Spearman correlation coefficients between first and second pinches* were analyzed in a BAI (2 s/4 s) × SOUND (motor-auditory/motor) × TARGET FORCE LEVEL (high/low) MANOVA.

Partial eta squared (η_p^2) effect size values are reported (Lakens, 2013). In order to reveal the sensitivity of our analyses on the present sample size, sensitivity analysis was implemented using G*Power 3.1.9.4 (Faul, Erdfelder, Lang, and Buchner, 2007).

3. Results

Because mean absolute deviation (MAD) can be regarded as more robust dispersion measure than SD, data points of force modulation higher than 2.5 MAD were removed from further analysis (Leys, Ley, Klein, Bernard, and Licata, 2013). For high target force level trials, the average number of remaining pinch pairs was 22.53 (SD = 3.26) in the 2 s motor condition, 21.46 (SD = 4.24) in the 4 s motor condition, 24.62 (SD = 3.38) in the 2 s motor-auditory and 24.77 (SD = 2.13) in the 4 s motor-auditory condition. For low target force level trials, the average number of pinch pairs was 20.54 (SD = 4.12) in the 2 s motor condition, 19.08 (SD = 3.50) in the 4 s motor condition, 18.69 (SD = 4.00) in the 2 s motor-auditory and 17.23 (SD = 4.69) in the 4 s motor-auditory condition, respectively. The minimal number of pinch pairs was 11, and the maximum was 28. The mean peak force in the MVIC block was 6.71 N (SD = 1.4). For high target force level trials, the mean peak force was 6.85 N (SD = 1.15), whereas for low target force level trials it was 2.37 N (SD = 1.73).

3.1. Force and sEMG activity differences

Descriptive statistics of the AUC values of sEMG activity and force are presented in Table 1. The PINCH NUMBER × BAI × SOUND × TARGET FORCE LEVEL repeated measures MANOVA on *median sEMG activity and force* showed a significant main effect of SOUND (Wilk's $\Lambda = 0.928$; $F(3, 190) = 4.897$, $p = .003$; $\eta_p^2 = 0.072$) and TARGET FORCE LEVEL (Wilk's $\Lambda = 0.127$; $F(3, 190) = 435.541$, $p < .001$; $\eta_p^2 = 0.873$), and a significant SOUND × TARGET FORCE LEVEL interaction: Wilk's $\Lambda = 0.959$; $F(3, 190) = 2.680$, $p = .048$; $\eta_p^2 = 0.041$. Detailed PINCH NUMBER × BAI × SOUND × TARGET FORCE LEVEL MANOVA results are presented in Table A.1 and A.2.

The follow-up repeated measures ANOVAs indicated a significant SOUND main effect in force ($F(1, 192) = 14.751$, $p < .001$; $\eta_p^2 = 0.077$). Regarding sEMG activity, a marginally significant SOUND main effect was present for FDI ($F(1, 192) = 2.833$, $p = .094$; $\eta_p^2 = 0.015$) but not for APB activity ($F(1, 192) = 0.162$, $p = .688$; $\eta_p^2 < 0.001$), which shows stronger force application and slightly higher sEMG activity when no auditory feedback was present. The follow-up comparisons for TARGET FORCE LEVEL main effect indicated significantly higher APB ($F(1, 192) = 88.921$, $p < .001$; $\eta_p^2 = 0.463$), and FDI activity ($F(1, 192) = 141.531$, $p < .001$; $\eta_p^2 = 0.736$), as well as stronger force application ($F(1, 192) = 1222.434$, $p < .001$; $\eta_p^2 = 6.360$) for pinches intended as high than for those intended as low target force level. The SOUND × TARGET FORCE LEVEL interaction was significant for force ($F(1, 92) = 4.395$, $p = .037$; $\eta_p^2 = 0.023$) and marginally significant for APB ($F(1, 192) = 2.915$, $p = .089$; $\eta_p^2 = 0.015$) but not for FDI activity ($F(1, 192) = 0.176$, $p = .676$; $\eta_p^2 < 0.001$), showing that force differences at the low target force level were larger (stronger in the motor condition) than at high target force level. No other effects were significant. SOUND and TARGET FORCE LEVEL main effects as well as SOUND×TARGET FORCE LEVEL interaction are presented in Fig. 2.

3.2. Absolute force and sEMG activity percentage change

Descriptive statistics of the absolute change in sEMG activity and force expressed as a percentage of those of the first pinch are presented in Table 2. The BAI × SOUND × TARGET FORCE LEVEL repeated measures MANOVA showed a significant main effect of TARGET FORCE LEVEL and BAI (Wilk's $\Lambda = 0.753$; $F(3, 94) = 10.255$, $p < .001$; $\eta_p^2 = 0.247$; and Wilk's $\Lambda = 0.907$, $p = .027$; $\eta_p^2 = 0.093$, respectively). The follow-up repeated measures ANOVAs revealed that the absolute force change percentage between the first and second pinches was significantly larger in low target force level than in high target force level trials: $F(1, 96) = 21.738$, $p < .001$; $\eta_p^2 =$

Table 1
Group mean and standard deviation of the area under the curve (AUC – % ms) values normalized by the maximal voluntary isometric contraction level for sEMG activity and force for each pinch and trial type.

Condition	BAI	Target force level	Pinch number	APB	FDI	Force
Motor	2 s	High	Pinch 1	647.81 ± 371.70	755.43 ± 414.44	793.44 ± 202.01
			Pinch 2	672.74 ± 378.98	740.69 ± 383.71	799.99 ± 201.23
		Low	Pinch 1	284.98 ± 216.99	285.36 ± 169.68	161.22 ± 62.33
			Pinch 2	277.69 ± 212.00	273.06 ± 177.52	158.27 ± 67.88
	4 s	High	Pinch 1	663.83 ± 342.38	765.13 ± 380.35	794.34 ± 180.06
			Pinch 2	667.78 ± 351.57	747.89 ± 374.05	758.04 ± 218.34
		Low	Pinch 1	288.59 ± 239.15	294.64 ± 172.67	175.21 ± 69.03
			Pinch 2	284.38 ± 247.22	278.88 ± 163.27	156.23 ± 69.53
Motor-auditory	2 s	High	Pinch 1	764.92 ± 638.95	663.25 ± 335.50	737.44 ± 146.52
			Pinch 2	816.27 ± 724.52	695.41 ± 370.73	757.97 ± 166.20
		Low	Pinch 1	181.64 ± 141.55	204.78 ± 164.10	52.91 ± 46.82
			Pinch 2	171.06 ± 126.00	199.40 ± 165.14	45.28 ± 51.49
	4 s	High	Pinch 1	631.16 ± 324.37	729.43 ± 420.46	758.32 ± 156.66
			Pinch 2	696.03 ± 403.42	714.33 ± 383.81	759.67 ± 195.18
		Low	Pinch 1	186.91 ± 137.95	196.71 ± 148.45	55.75 ± 41.64
			Pinch 2	181.64 ± 127.87	187.22 ± 142.56	46.33 ± 42.85

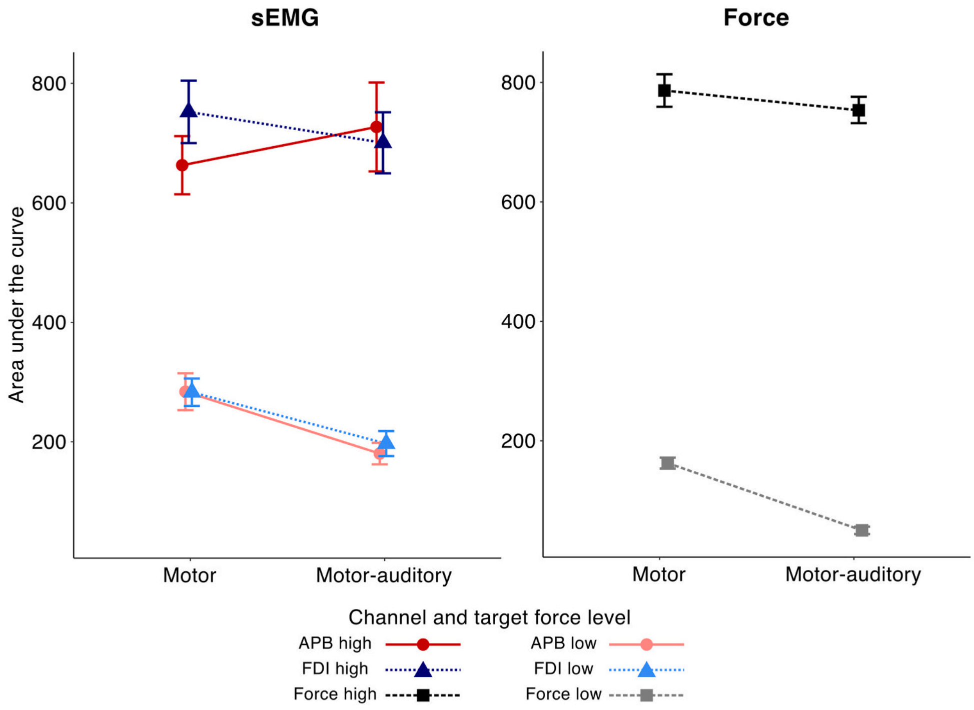

Fig. 2. Group mean area under the curve (AUC – % ms) values for sEMG activity at APB and FDI (left panel) as well as force (right panel). Significantly larger AUCs were measured in the high compared to low target force level trials at all channels. Force difference between motor and motor-auditory conditions were larger at low compared to high target force level trials. Error bars denote the standard error of the mean.

0.226 (Fig. 3. right panel). In contrast, no significant differences were found in sEMG activity (Fig. 3. left panel; APB: $F(1, 96) = 1.734$, $p = .191$; $\eta_p^2 = 0.018$; FDI: $F(1, 96) = 0.520$, $p = .472$; $\eta_p^2 = 0.005$). The follow-up repeated measures ANOVA for BAI showed that FDI activity difference was significantly larger in the 2 s condition compared to the 4 s condition: $F(1, 96) = 6.911$, $p = .010$; $\eta_p^2 = 0.072$ but this effect was not significant in case of APB activity ($F(1, 96) = 0.145$, $p = .705$; $\eta_p^2 = 0.001$) or force ($F(1, 96) = 0.019$, $p = .891$; $\eta_p^2 < 0.001$) (Fig. 3). No other effects were significant. Detailed BAI × SOUND × TARGET FORCE LEVEL MANOVA results are presented in Table A.3 and A.4.

3.3. Correlation between areas of first and second pinches

Finally, when comparing *Spearman correlation coefficients between first and second pinches*, the BAI × SOUND × TARGET FORCE LEVEL repeated measures MANOVA showed no significant effects. Detailed BAI × SOUND × TARGET FORCE LEVEL MANOVA results are presented in Table A.5 and A.6.

It is important to note that due to the lack of prior studies with the present arrangement, no data-based a priori calculation to estimate optimal sample size was possible. The sensitivity analysis revealed that MANOVA with a sample size of 13 was sufficient to detect effects of Cohen's $f = 0.61$ ($\eta^2 = 0.271$) with 80% power. That is, small or medium sized effects might have remained undetected.

Table 2
Group mean and standard deviation of the absolute change in sEMG activity and force expressed as a percentage of those of the first pinch, for each trial type.

Condition	BAI	Target force level	APB	FDI	Force
Motor	2 s	High	7.837 ± 8.136	4.682 ± 4.449	7.048 ± 5.576
		Low	4.756 ± 3.280	7.129 ± 6.502	9.461 ± 7.974
	4 s	High	8.818 ± 5.526	4.847 ± 3.293	7.697 ± 6.797
		Low	8.653 ± 6.425	4.481 ± 5.123	14.513 ± 10.593
Motor-auditory	2 s	High	10.602 ± 8.933	9.043 ± 7.802	8.974 ± 7.203
		Low	7.104 ± 6.306	8.462 ± 5.890	17.067 ± 13.574
	4 s	High	7.490 ± 5.717	3.760 ± 3.701	4.078 ± 4.591
		Low	7.331 ± 7.504	5.268 ± 5.193	17.155 ± 6.507

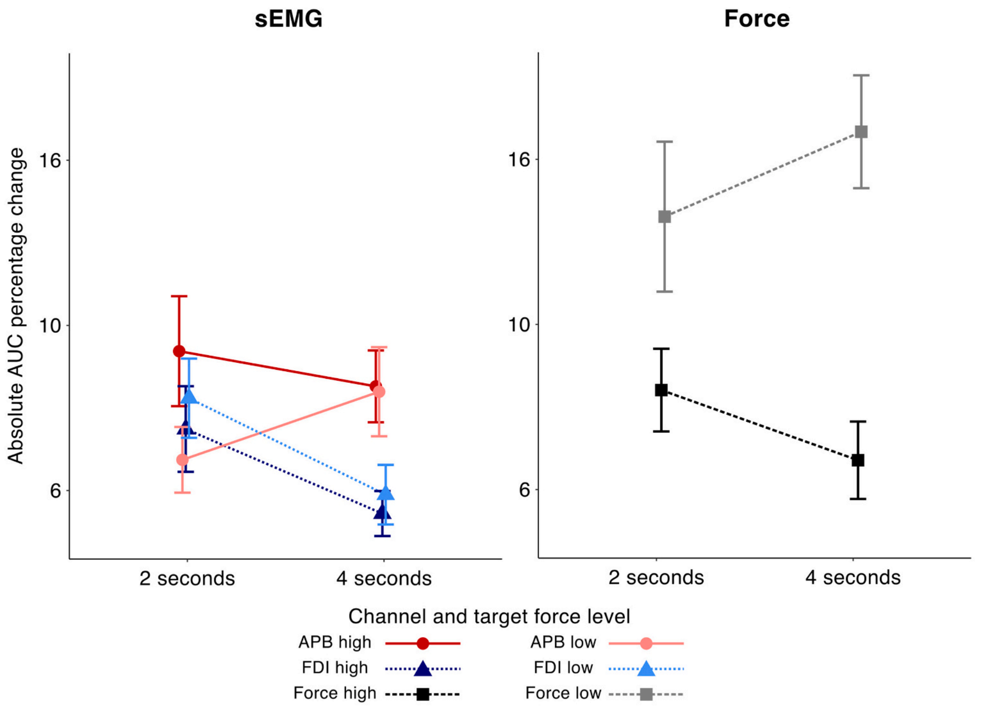

Fig. 3. Absolute change in sEMG activity at APB and FDI (left panel), as well as force (right panel) as expressed as a percentage of those of the first pinch. Force changes were significantly larger in low target force level trials but not sEMG activity. Furthermore, differences were larger at APB in the 4 s compared to the 2 s between-action intervals. Error bars denote the standard error of the mean.

4. Discussion

The aim of the present study was to investigate how the consistent presence or absence of a sound action-effect influenced the retrieval of the motor components of simple repeated ballistic actions. In short, although the pattern of results replicated previous studies showing lower forces when actions consistently resulted in sound effects (motor-auditory blocks) in comparison to actions without sound effects (motor blocks), the presence of sound effects did not result in significantly reduced variability in motor activity pattern within action pairs. Nonetheless, several observations regarding force application could be made. First, when participants were instructed to apply a low force level, action-effect-related motor adaptation was more pronounced (i.e., the addition/removal of the sound effect resulted in more substantial force application differences) in comparison to high force levels; and within-pair force application variability was also larger in comparison to high force levels. Second, the within-pair force application variability was larger when the target between-action interval was short (2 s vs 4 s).

The decreased force in the motor-auditory conditions in comparison to the motor conditions replicates previous results on action-effect-related motor adaptation (Cao et al., 2020; Horváth et al., 2018; Neszmélyi and Horváth, 2017, 2018, 2019) as reflected by applied force and sEMG (FDI) activity, and supports the notion that sound action-effects allowed participants to reduce effort, while still producing successful actions. It is also compatible with the idea that the absence of auditory action-effect leads to a reliance on proprioceptive or tactile feedback, and more forceful pinches result from a compensatory mechanism providing more information on the interaction from different modalities (Aschersleben and Prinz, 1997; Kunde et al., 2004). Furthermore, it fits well to studies showing lower muscle activity when typing resulted in tones (Gerard et al., 2002), as well as to results from sonification studies: when movements were accompanied by sounds, the repetitive performance of actions and learning was enhanced (Conde, Altenmüller, Villringer, and Ragert, 2012; Dyer, Stapleton, and Rodger, 2015, 2017; Effenberg, Fehse, Schmitz, Krueger, and Mechling, 2016).

It is important to highlight that sonification is mostly utilized in the acquisition of complex movement patterns in which kinematics such as movement trajectory or limb or joint positions are well observable. Comparably to sonification, when participants had to perform bimanual coordination tasks, the presence of visual feedback on the trajectory of their movement enhanced performance, while the removal of feedback following practice significantly impaired the reproduction of the required movement patterns (e.g., Kovacs et al., 2010; Swinnen, Lee, Verschueren, Serrien, and Bogaerds, 1997). On the other hand, the dynamics of movement such as exerted force or energy are less accessible for consciousness (de Graaf et al., 2004). In the present study participants were instructed to produce small ballistic pinch actions which resulted in minimal finger displacement or movement. Therefore – based on studies utilizing complex actions mentioned above – we hypothesized the enhanced role of auditory action-effects in action production and more similar actions in the motor-auditory conditions. However, we could not demonstrate any difference in similarity of actions between motor and motor-auditory conditions neither in terms of force or sEMG activity. This suggests that although auditory action-effect allowed the optimization of effort, it did not substantially improve the retrieval of motor components of simple pinch actions.

When actions were produced with low target force level, force differences between motor and motor-auditory trials increased, which indicates that the relative importance of the sound action-effect increased when the intensity of proprioceptive and tactile action effects decreased. More importantly, the variability within pinch pairs was higher at low target force level than at high target force level trials. That is, at low force levels, participants' ability to repeat the actions with similar force was impaired. This observation is compatible with studies suggesting that action control becomes more difficult at lower force levels. In a study by Li, Nataraj, Marquardt, and Li (2013), when participants produced precision pinch actions with linearly increasing and decreasing force from 0 to 12 N, the force vectors of thumb and index fingers were less stably controlled below 2 N, especially in case of decreasing force, suggesting increased difficulty in the online control of dexterous manipulation at lower force levels. Using lower force levels also leads to increased variability in EMG signals (Li et al., 2020; Maier and Hepp-Reymond, 1995; Valero-Cuevas, 2000). Moreover, in the present experiment, in order to detect even the softest actions, the threshold of the FSR was set to a very sensitive level which could make the task even more demanding for trials with low target force level. Furthermore, this pattern of results is in line with studies using visual feedback as well: in force matching tasks, the lowest force levels corresponded to the lowest performance, further suggesting that motor optimization and retrieval of motor aspects of actions might be especially difficult in these conditions (De Serres and Fang, 2004; Li et al., 2020). It is important to note that in the present study the average applied force was nearly identical between actions in the MVIC block and in trials with high target force levels. This may indicate that participants utilized different strategies for high and low target force level trials. While in low target force level trials, they likely produced soft pinches by actively adjusting force, which led to higher variability, in high target force trials they likely aimed to perform two consecutive maximal-force actions instead of repeating the first action, which resulted in higher similarity within action pairs.

Despite the comparable results, essential differences between the present study and force matching studies need to be pointed out. In force matching studies, participants typically produce actions for several seconds with continuous feedback, which allows the continuous monitoring and correction of the applied force. In contrast, in the present study the only feedback was the sound action-effect in the motor-auditory conditions which provided information solely on whether the action exceeded an otherwise low force threshold level not on the exact magnitude of force. The several seconds-long interactions of force matching studies provide better opportunities to monitor and adjust actions than brief force impulses do. There is also evidence that continuous visual feedback led to improved performance in comparison to discrete feedback when participants had to make decisions regarding the outcomes of their own actions (Schmitter, Steinsträter, Kircher, van Kemenade, and Straube, 2021). Considering the above-mentioned differences between feedback types and the basic differences between the nature of auditory and visual processing, one can conclude that in the present study participants had to rely more strongly on their previous actions and on tactile feedback which explains the over-compensation of force in the motor conditions as well. It also implies that in absence of sound action-effect, proprioceptive and tactile aspects of the action become more dominant.

Interestingly, significantly higher variability was found in the motor activity pattern (FDI activity) within pinch pairs in the 2 s, than in the 4 s conditions. This is surprising, as ideomotor theories propose that event files decay or disintegrate over time (within about 4 s, see Hommel and Frings, 2020), thus one would expect lower variability in the 2 s BAI conditions. One speculation that can be put forward to explain this result is that that participants' task representation or strategy differed in the two BAI conditions: for example, while in the 2 s conditions they might have represented the action-pair together as a single “double pinch action”, in the 4 s conditions, the representation might have included only a single pinch, which was then repeatedly activated. That is, in the 2 s conditions, they produced a single action consisting of two pinches without the real intention to repeat the first one. In contrast, 4 s might have been long enough to represent the first action as a single event file and then repeat it. This speculation is compatible with recent studies suggesting that the persistence of event files depends on the task-relevance of the elements they contain: task-irrelevant and distracting elements result in faster decay, while those containing task-relevant features persist longer (Moeller and Frings, 2021), and that bindings between two or more individually planned and executed responses may last as long as 6 s (Geissler, Frings, and Moeller, 2021; Moeller and Frings, 2021).

It is important to highlight that although the significant MANOVA effects demonstrate differences in force application patterns, force signal and sEMG signal contributions to these patterns were not uniform. The partly diverging behavior of the two muscles can be explained with fundamental differences in their anatomical, functional, and neuromuscular control characteristics. In precision pinch tasks, digit forces are governed by finger specific force control, digit coordination, and task-dependent motor adaptation processes, which might differently affect the activity of these muscles (Li et al., 2020). Although the relationship between small muscles and force is mostly linear (Jahanmiri-Nezhad et al., 2014; Konrad, 2005; Lawrence and De Luca, 1983; Maier and Hepp-Reymond, 1995), the level of correlation between EMG and force varies between different muscles (Maier and Hepp-Reymond, 1995). In the present study, while action-effect-related motor adaptation was mostly consistent between applied force and sEMG activity (although different muscles dominated in different contrasts), the effect of BAI was observable at FDI only but not in applied force. Several studies characterized FDI as one of the hand muscles related most strongly to the applied force (Maier and Hepp-Reymond, 1995; Valero-Cuevas et al., 1998; Valero-Cuevas, 2000) while a less consistent relationship was demonstrated with APB (Maier and Hepp-Reymond, 1995). The same fingertip force magnitudes can be theoretically produced by infinite numbers of functionally equivalent muscle coordination patterns (Valero-Cuevas et al., 1998; Valero-Cuevas, 2000). Developing the most effortless movement trajectories is relatively easy in tasks in which the target force level and time interval is constant between actions, which allows participants to learn how to optimize their actions from trial to trial. Indeed, in the study by Neszmélyi and Horváth (2017) force level optimization was observable in the first 5–15 trials in each block. In the present study, however, the required target force level was presented before every trial by a visual cue, which could interrupt the uniformity of the actions: the random trial-by-trial switching between low and high target force levels might have prohibited the building of stable strategies on producing identical actions, and motor planning between the 2 s and 4 s conditions might have also differed (see above). In addition, participants might have slightly changed the position of their hand or fingers between blocks and also between successive trials: as the sounds informed on the success of their actions (Horváth et al., 2018; Neszmélyi and Horváth, 2017, 2018), less voluntary attention might have been directed to the body posture and tactile feedback. This notion is fitting well to studies showing that focusing on the effects of movements in comparison on the movement itself result in more accurate performance and less variable EMG (e.g., Lohse et al., 2011; Wulf, 2013). Finally, individual differences in the states of muscles like atrophy or training as well as fatigue also influence the force-EMG relationship (Bogdanis, 2012; Danna-Dos Santos et al., 2010; Konrad, 2005) which could contribute to different signal-to-noise ratios, and force-EMG discrepancies in our results.

In summary, although we did not find direct evidence that the presence of auditory action effects improved the retrieval of the motor components of simple repeated actions, our main findings are well-interpretable within the framework of ideomotor theories, which suggest that that both actions and their sensory consequences are integrated into an event file (Hommel, 2019). Features which are more relevant to the task are weighted stronger (Memelink and Hommel, 2013), they are easier to retrieve, and their representation also lasts longer (Moeller and Frings, 2021). As participants were instructed to repeat their first actions as similarly as they could with a certain BAI and target force level, all of these aspects of action became task-relevant, as well as the sound action-effect, which resulted in an enriched representation. The lower applied force and slightly lower EMG in the motor-auditory conditions suggests that the presence of sound action-effects led to an optimization of actions, while the absence of sound resulted in exceeding levels of force (Neszmélyi and Horváth, 2017). This effect was even more pronounced in case of low target force which is in line with the notion that the less information can be retrieved from the motor and tactile dimension, the more dominant the sound action-effect becomes (Memelink and Hommel, 2013). On the other hand, BAI impacted FDI but not force similarity within action pairs: more similar FDI activity was present in the 4 s compared to the 2 s condition. This indicates that participants might have represented action pairs in 2 s conditions as one action containing two pinches, while in the 4 s conditions, the first action was actually repeated. It also suggests that the event files did not decay over 4 s, moreover, the longer interval facilitated the retrieval of the appropriate motor features. Finally, our results also suggest that sensory weighting within the same event file is influenced by task parameters, especially target force and BAI.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.humov.2022.102969.

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