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# THE INFLUENCE OF SENSORY-MOTOR INTERACTIONS ON THE PRODUCTION AND PERCEPTION OF SELF-INITIATED SOUNDS

PhD Thesis Booklet

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## General background and aim of the thesis

Sensory consequences of the actions play an important role in action control: They can serve as goals of the agent, prompting the initiation of a movement (Hommel, 2009; Hommel, Müsseler, Aschersleben, & Prinz, 2001) and they also give feedback about action execution, signaling when adjustments are necessary because the movement deviated from its intended path (Adams, 1971, 1976). Thus, current theories of action control usually emphasize the importance of sensory effects (Hommel, 2009; Todorov, 2004; Wolpert, Diedrichsen, & Flanagan, 2011). However, effect-based control processes are often thought to be constrained to certain action types: Ballistic movements—for example, swinging a bat, or pressing a button—are executed so fast that by the time processing of sensory feedback could start, the movement is already finished (Chernikoff & Taylor, 1952; Lashey, 1951; Schmidt & Wrisberg, 2000). Thus, it is often assumed that such quick actions are not influenced by the sensory consequences of the actions (Finney, 1997; Gates, Bradshaw, & Nettleton, 1974; Pfordresher & Palmer, 2002, 2006). Experimental paradigms that investigate interactions between the motor and sensory systems are also often characterized by this approach. In particular, studies that explore the influence of actions on the processing of self-induced sounds tend to disregard the possibility of a reverse effect, that is, the influence of sounds on the actions that elicit them (Horváth, 2015).

In the thesis, the action-related auditory ERP attenuation paradigm (Baess, Horváth, Jacobsen, & Schröger, 2011; SanMiguel, Todd, & Schröger, 2013; Schäfer & Marcus, 1973)—which also relies on the assumption that sensory effects are irrelevant from a motor control perspective—was used as a starting point for exploring the role of sensory information in the execution of ballistic actions. While it is indeed unrealistic to use sensory feedback for adjusting ballistic actions in an “online” manner, during the execution of the movement, in the case of sequential actions, sensory information might be used for “offline” adjustments that can be completed in the “rest” phase between actions (Wolpert, 1997). Furthermore, expected sensory consequences might also influence the planning of actions before the initiation of the movement (Hommel, 2009). The four studies reported in the thesis explore the prerequisites and consequences of such effect-based motor control mechanisms.

In most experiments involving the production of sounds, common input devices, like buttons or gamepads are used. In the studies reported in the thesis, participants induced sounds by interacting with a force sensitive resistor (FSR). The use of the FSR enabled us to record the force applied during the tone-eliciting movements. In several experiments, we observed that movement parameters were affected by the sensory consequences of the actions: Participants used the auditory action effects to optimize the force of the tone-eliciting actions. The thesis focuses on this phenomenon—which we termed action-effect-related motor adaptation—and the force-measurement method was used to explore the utilization of effect-based motor control processes when ballistic actions are executed.

In *Study 1*, participants were administered a standard ERP attenuation paradigm, and physical parameters of the actions were co-recorded with the EEG signal. The goal of the study was to examine whether actions are indeed executed in the same way when they elicit tones and when they do not result in external auditory effects. Furthermore, we explored how effect-based motor-control processes might bias the interpretation of the action-related auditory ERP attenuation effect. In *Study 2*, the FSR was attached to conventional input devices to examine if the effect-based motor control processes observed in Study 1 can be generalized to a wider range of ballistic actions. *Study 3* explored the temporal constraints of action-effect-related motor adaptation. Finally, in *Study 4*, action-effect contingency was manipulated while participants performed tone-eliciting actions. The study investigated how action-effect-related motor adaptation is affected by changes in the auditory context.

## New scientific results

### *Thesis 1: Exploring the role of auditory action-effects in the control of ballistic actions: Action-effect-related motor adaptation*

In studies examining the influence of actions on the processing of auditory stimuli, participants are often required to elicit tones by quick, ballistic movements. Such studies are usually based on the assumption that actions are invariable regardless of their sensory consequences (Horváth, 2015). This assumption was put to the test by co-recording the physical parameters of the actions with the EEG signal in a standard action-related auditory ERP attenuation experiment. Participants executed ballistic action sequences that resulted in tones in one condition while in another condition no auditory effects were elicited. To study the role of auditory effects in motor control processes, forces applied during tone-eliciting and silent actions were compared to each other. Pre- and post-action motor ERPs were also examined to assess effect-based differences in the brain signal reflections of the actions, and to explore if they could bias the interpretation of the action-related ERP attenuation effect. We observed that actions that elicited auditory effects were executed with smaller force than silent interactions with the device, suggesting that participants used the auditory stimuli to optimize the tone-eliciting actions. These results challenge the assumption that in similar paradigms self-generated stimuli can be regarded as irrelevant side-effects of the actions, and they indicate that motor control processes are affected by the sensory consequences of ballistic movements. Differences that might be related to the motor utilization of action-effects were found in movement-related potentials both before (i.e., in the readiness potentials) and after the start of action initiation. A force-related effect in the time range of the N1 attenuation effect suggested that effect-based motor control processes might contribute to the action-related attenuation of auditory ERPs which has been regarded previously as an effect related to perceptual processing of the stimuli (Hughes, Desantis, & Waszak, 2013).

### *Thesis 2: Action-effect-related motor adaptation in interactions with everyday devices*

According to the first study, actions with distinctive auditory effects are executed with smaller force than silent interactions with the same device (action-effect-related motor adaptation). These results indicate that changing the set of effects associated with a motor act might directly influence action planning and control. In the second study, we examined whether this observation can be generalized to a wider range of ballistic actions. In three experiments, participants executed different action types that are often used during interactions with everyday devices: pinches, button presses, and finger taps. In each experiment, actions were executed both with and without external auditory effects, and the forces and force-peak-latencies of tone-eliciting and silent interactions were compared with each other.

Results of the first study were replicated: When eliciting tones by pinching the FSR, participants utilized auditory effects for optimizing the force of the actions. The results also suggested that the effect-based adjustment of ballistic actions is not limited to the setup used in the first study: Action-effect-related motor adaptation was also observed with the two other action types: button presses and finger tapping. These results indicate that auditory effects contribute to the optimization of action forces, even if the devices that are used also provide reliable proximal feedback about the movemnts. This observation dovetails with previous research about tool use that suggest that participants prioritize distal modalities over proximal ones if feedback from multiple sources is available (Kunde, Müsseler, & Heuer, 2007; Ladwig, Sutter & Müsseler, 2012).

## *Thesis 3: Temporal constraints of action-effect-related motor adaptation*

The first two studies indicated that external auditory effects can be used as feedback to optimize the force of tone-eliciting actions. In the third study, the temporal constraints of this action-effect-related motor adaptation were explored: We examined whether participants can use auditory action effects for force optimization if a delay is inserted between the action and the elicited stimulus. Participants elicited pure tones by pinching an FSR. The delay between the action and the elicited auditory effect was manipulated in a block-wise manner. In two experiments, the 0-1600-ms time range was explored. Force of the tone eliciting actions was recorded in all conditions.

The results suggested that auditory effects can only be used for optimizing the force of the tone-eliciting actions if they follow the actions within a very short (ca. 200-ms) time window. When the action-effect delay was longer than that, actions were performed with the same force as actions without external sensory effects. This finding suggests that recognizing the causal relationship (Buehner & McGregor, 2009; Shanks, Pearson, & Dickinson, 1989) between an action and the consequent stimulus is not sufficient for action-effect-related motor adaptation: rather, this effect-based control process might rely on the automatic integration of motor and sensory events (Hommel, 2004).

In a third experiment, it was also explored how initial experience with an action-effect relationship influences later interactions. Two groups of participants had to elicit tones in a similar way as in the first two experiments. The first group was adapted to long action-effect delays (400 ms) in a 9-minute initial practice phase, while the second group was adapted to immediate action-effects. In the subsequent test phase, both groups executed actions that were followed by auditory effects with an intermediate delay (200 ms). Action forces recorded in the test phase were compared between the two groups.

The results indicated that the time window of action-effect-related motor adaptation was not absolute, it could be modified by experience. Participants who were previously adapted to long action-effect delays could utilize effects presented at intermediate delays more efficiently for action optimization than participants adapted to immediate action-effects. This adaptation effect might be explained by the distorted perception of the temporal relation between actions and their delayed sensory effects (Cao, Veniero, Thut, & Gross, 2017; Elijah, Pelley, & Whitford, 2016).

## *Thesis 4: The influence of auditory context on action-effect-related motor adaptation*

The previous experiments investigated motor adjustments that were induced by compromising the link between an action and its auditory consequence (i.e., removing or delaying auditory effects). Study 4 examined action-effect-related motor adaptation in a setting where the physical connection between the motor and sensory event remained intact, but changes in the auditory context resulted in diminished feedback quality. As in our previous studies, participants elicited tones by pinching an FSR. In some blocks (self-induced condition), auditory effects were contingent on the actions. That is, sounds could only be initiated by the participants' actions. In other blocks (mixed condition), action-effect contingency was reduced by intermixing computer-initiated sounds with the self-induced ones. In Experiment 1, computer-initiated sounds always had the same acoustic features as the self-induced stimuli. In Experiment 2, the frequency of the computer-initiated sounds was manipulated in a block-wise manner to control for attentional factors. The pitch of computer-initiated and self-induced tones was identical in some blocks while easily distinguishable in others. The FSR signal was recorded in all conditions of the two experiments.

Action forces were significantly larger in conditions where externally-initiated sounds were intermixed with the self-induced ones. This effect of externally-initiated sounds was more pronounced when self-induced and computer-initiated tones were characterized by identical acoustic features. The results suggest that even if the physical action-effect connection remains intact, context-related factors can affect the utilization of effect-based motor control processes. Degradation of feedback quality can prompt agents to recalibrate the weighting of different motor control strategies: Instead of relying heavily on force optimization, agents start to prioritize strategies that are associated with increased force levels (i.e., maximizing general feedback level or probability of action success).

## Conclusions

The four studies reported in the thesis provide converging evidence for the motor utilization of auditory action effects. They show that self-induced sounds can be used as feedback to optimize tone-eliciting actions, even if those actions are quick, ballistic movements that cannot be adjusted in an “online” manner. Since participants performed sequences of the same actions, the observed force optimization could be a stepwise process that is based on the trial-by-trial adjustment of motor parameters. Action-effect-related motor adaptation might be regarded as an energy minimizing process (Hatze, & Buys, 1977), during which participants utilize auditory feedback to reduce the effort invested in the control and execution of the movements while maintaining a high probability of action success. However, other influences might also contribute to effect-based force adjustments: Auditory effects provide clearer goals for the movements, than tactile or proximal stimuli associated with the actions, which—according to the ideomotor approach (Hommel et al., 2001)—might account for the increased efficiency of motor planning processes.

In the setup used in the experiment the auditory stimuli only provided limited information about the actions: Stimuli produced via mechanical contact usually reflect various features of the movement (e.g., intensity of the stimulus indicates the force of the movement). In contrast, the auditory effects produced during the reported experiments provided only very limited information on the movements (i.e., whether the action was successful). Our results show that even such limited information can be utilized for optimizing action execution.

We initially hypothesized that action-effect-related motor adaptation was a strategic process based on recognizing the causal relationship between an action and its effect. However, according to the results of Study 3, temporal constraints of force optimization are much stricter than those of recognizing causality: Action-effect-related motor optimization could be observed only if actions were followed by the auditory effects within a ca. 200-ms time window. These results suggest that force optimization might require a more automatic form of action-effect binding, possibly based on integrating the action and elicited stimulus into a single event (Hommel, 2004).

The observations made in the four studies dovetail with recent theories of cognition that emphasize the interwoven nature of perception and action (Hommel, 2015; Noe, 2006) and challenge the validity of approaches that rely on the distinct separation of sensory and motor processes. Beside contributing to theories of motor control, the studies reported in the thesis might also have practical and methodological implications. The phenomenon of action-effect-related motor adaptation casts doubts over the principles and methods utilized in the auditory ERP attenuation paradigm, and results of Study 1 indicated that force optimization might contribute to auditory ERP attenuation effects that were previously attributed to predictive mechanisms (Knolle, Schröger, Baess, & Kotz 2012; Schröger, Marzecová, & SanMiguel, 2015). From an applied perspective, delay and context-effects effects might be relevant for the construction of digital devices. The reflection of context-related information in motor parameters might be a principle that could contribute to the development of adaptive interactive systems and be implemented in everyday devices like smart phones or tablets. As it is apparent from this short summary, the studies reported in the thesis touch upon a wide range of topics. Further studies could explore questions and possibilities that were introduced here.

## List of publications related to the theses


I. Neszmélyi, B., Horváth, J. (2017). Consequences matter: self-induced tones are used as feedback to optimize tone-eliciting actions. *Psychophysiology 54*(6), 904-915. http://dx.doi.org/10.1111/psyp.12845

II. Horváth, J., Bíró, B., & Neszmélyi, B. (2018). Action-effect related motor adaptation in interaction with everyday devices. *Scientific Reports, 8,* 6592. https://doi.org/10.1038/s41598-018-25161-w

III. Neszmélyi, B., & Horváth, J. (2018). Temporal constraints in the use of auditory action effects for motor optimization. *Journal of Experimental Psychology: Human Perception and Performance, 44*(11), 1815-1829. http://dx.doi.org/10.1037/xhp0000571

IV. Neszmélyi, B., & Horváth, J. (2019). The role of auditory context in action-effect-related motor adaptation. *Human Movement Science*, *67*, 102503. https://doi.org/10.1016/j.humov.2019.102503

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