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RESEARCH ARTICLE

An experimental paradigm for studying sense of agency in joint human–machine motor actions

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Abstract
In this paper, we propose an experimental technique for studying the sense of agency (SoA) in joint human–machine actions. This technique is based on the use of an electromechanical finger-lifting device that enables a joint motor action initiated by a participant and completed by the machine. The joint action, later referred to as an "active–passive" action, was implemented as a reaction time task and contrasted with other levels of participant's involvement, including active movement, passive movement, and observation of a dummy's movement. In each trial, a feedback sound signal informed the participant whether they had performed the task successfully, i.e. faster than a threshold, which was individually adjusted in the beginning of the experiment. In the active condition, the result depended on the participant, while in other conditions it was preprogrammed for the servo. In context of this task, we studied direct time estimates made by participants and auditory event-related potentials (ERP) in 20 healthy volunteers. The amplitude of the auditory N1 component in the responses to the feedback sound showed no significant effect of activity and success factors, while its latency was shorter in successful trials. Interaction of activity and success factors was significant for subjective time estimates. Surprisingly, the intentional binding effect (subjective compression of time intervals, which is known as a correlate of SoA) only emerged in trials of active condition with negative results. This observation was in contrast with the fact that the active and active–passive movements were both voluntarily initiated by the participant. We believe that studying SoA with the proposed technique may not only add to the understanding of agency but also provide practically relevant results for the development of human–machine systems such as exoskeletons.

Keywords Active movement · Passive movement · Active–passive movement · Feeling of agency · Judgment of agency · Auditory N1 · P300 · Intentional binding

Introduction

The sense of agency (SoA) is a subjective experience essential for the concept of the self (Georgieff and Jeannerod 1998; Gallagher 2000). One of its most important aspects is conscious awareness of authorship; among its other aspects are, for example, the experience of the causal function of intention and the experience of the vivid necessity of making an effort to initiate an action (Bayne and Levy 2006). It is common to distinguish two manifestations of agency, namely the feeling of agency (FoA) and judgments of agency (JoA) (Georgieff and Jeannerod 1998; Synofzik et al. 2008). SoA is distinct from the sense of ownership (SO), which is a pre-reflexive feeling of one's own body moving and may accompany not only active (voluntary) movements but also passive movements (i.e., movements executed by another person or machinery) (Tsakiris et al. 2006, 2007).

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Quantifying the sense of agency

The most straightforward way to measure SoA is by conducting a direct survey. However, the results of such a survey can be more considered as an estimation of JoA rather than of FoA. Moreover, the participant's experience can be changed when he or she knows that its aspects need to be reported. Therefore, there is a need to evaluate SoA indirectly, without conducting a direct survey. Such indirect evaluation of SoA can be made using its psychophysical or electrophysiological correlates.

Intentional binding

A psychophysical correlate of agency known as intentional binding has been thoroughly studied in the last decades. This phenomenon was found in the experiments by Haggard and colleagues who reported a connection between the presence of SoA and quantitative subjective estimates of time between motor action and a sensory signal (Haggard et al. 2002; Haggard and Clark 2003). The intentional binding effect refers to the compression of the subject's estimate of an interval between his or her voluntary action and a subsequent sensory signal, compared to such estimate for a movement made by someone or something else in absence of subject's intention (Cravo et al. 2011). In this context, intention means something that is inseparable from action itself and includes representation of its goal (Woodfield and Searle 1986). As a means for estimating time intervals, the original experiment by Haggard et al. involved the Libet clock (Libet et al. 1983), a digital clock face with a single hand. In later experiments, subjects were asked to report their subjective estimations of the intervals in milliseconds made without using clocks or other devices, and this alteration did not suppress the intentional binding effect (Engbert et al. 2008).

The exact mechanisms underlying the intentional binding effect are unknown, although there are candidate theories (Moore et al. 2010). It is generally considered to be a rather robust phenomenon, but some data implies that with prolonged time delays between motor action and subsequent result-defined signal intentional binding may persist while subjects report apparent disappearance of SoA (Wen et al. 2015). A recent study (Suzuki et al. 2019) reported that intentional binding can be observed in the absence of intentional action, suggesting that it may reflect merely causal binding between the action and its effect. Suzuki et al. noted that intentional binding research must account for the magnitude of causal temporal binding before relating temporal binding to the sense of agency. Substantial dissociation between intentional binding and explicit reports was found, suggesting that they may reflect quite different phenomena (Dewey and Knoblich 2014), whose opposition may be akin to that of FoA and JoA. Finally, it was reported (Graham et al. 2015) that intentional binding cannot be equally used as an indicator of agency for different age groups or for people having psychosis-like experiences, thus results of intentional binding studies should not be overgeneralized. While all its limitations should be considered in the interpretation of experimental results, intentional binding remains a unique tool to quantitatively estimate agency without directly asking questions about it.

Intentional binding for active–passive movements

Setting aside polar situations, when the subject either performed an action alone or played only a passive role, the emergence of intentional binding has also been studied in joint actions. These include actions executed by a subject together with a human or machine co-agent. Notably, these two conditions were contrasted, as effects of social interaction were considered. Studies reported that intentional binding occurred in human–human but not in human–machine joint actions (Obhi and Hall 2011; Sahaï et al. 2019). These results were interpreted as a failure of the emergence of collective "we"-agency when a machine was getting involved into action (Sahaï et al. 2019). Yet we could not find studies where a machine helped the subject to perform motor actions being an instrument rather than a full-fledged co-agent. To emphasize this quality, we will call these joint actions active–passive.

Currently, significant efforts are made to develop brain-computer interfaces (BCIs) that control exoskeletons for making paralyzed persons mobile (e.g. Lebedev and Nicolelis 2017; He et al. 2018) for helping execute movements in post-stroke rehabilitation (Shahid et al. 2010; Cincotti et al. 2012). BCI use involves additional issues related to the agency for active–passive movements, as it may recognize an attempt to make a movement even earlier than it could be started in a natural way, i.e. using muscles. Last but not least, transitions of perceived actions between subjective self-ascription and alienation, i.e. when an action initially reckoned by the subject as alien is being subsequently reassessed as their own, and vice versa, may have important implications for the understanding of fundamental aspects of consciousness.

Electrophysiological correlates of agency

Electrophysiological correlates of agency were searched for in quite many studies employing the brain electrical event-related potentials (ERP). Such studies often involved auditory feedback signals, and therefore parameters of the early auditory ERP component N1 were given much attention. It was reported that the auditory N1 amplitude decreased in response to self-generated sounds (Bäß et al. 2008). The amplitude of the N1 decreased even when action was not executed but the subjects presumed that they were to hear the signal (Lange 2011). Kühn et al. (2011) supposed that amplitudes of both auditory N1 and the P3 component may serve as hypothetical electrophysiological correlates of explicit judgements of the agency. There is substantial evidence that increased amplitude of the readiness potential accompanies intentional binding (Jo et al. 2014; Sidarus et al. 2017). Unfortunately, only the extreme cases, pure active and pure passive movements, were considered in the ERP studies.

Summarizing, none of SoA correlates proposed so far were shown to be able to estimate reliably intermediate states of agency and distinguish FoA from JoA.

Quantitative control for the involvement into a complex active–passive movement

One reason why agency for varying degrees of active involvement into a complex active–passive movement has not been studied yet can be the difficulty to quantify such degree of involvement in joint human–human action. This obstacle seems to be difficult to overcome. Parameters of human–machine interactions are easier to quantify, as at the machine's side they can often be measured precisely. However, the lack of devices that could assist to make a movement with varying and precisely enough measured degree of involvement hinders progress in this direction. In a few studies featuring passive (involuntary) movements, assistive devices either confined the subject's movement to the machine's movement trajectory (Mima et al. 1996) or supported not sufficiently goal-directed action, for instance, pushing a button (Moore et al. 2009). We think that to become truly cooperative a joint action should have a goal and presuppose the possibility of failure. To study agency in joint actions, the design should also allow variation of human involvement into action from complete execution to the idle observation of the action.

In our previous publication, we described a device free of these flaws and reported results of a preliminary study where it was used (Dubynin and Shishkin 2017). Since then the device and the methodology of its use have been modified to let us cover both FoA and JoA using a whole range of subject's involvement in active–passive movements, as well as pure passive and active movements. The current study was aimed at probing potential correlates of SoA, including intentional binding and the auditory N1 component of ERP, in a situation that presupposed a varying degree of involvement of an agent into action. We expected an intermediate degree of involvement to be reflected by these potential correlates in case of active–passive actions. For example, we expected the intentional binding to be significantly weaker for the active–passive actions than for the active actions, but still present as opposed to passive actions.

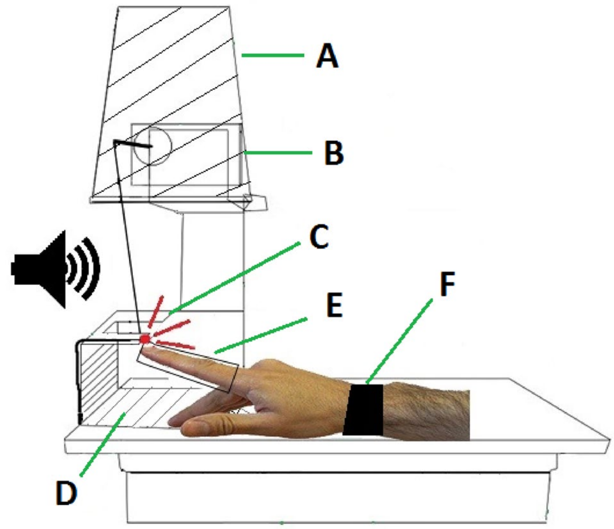


Fig. 1 Sketch of the finger lifting device. **a** Opaque casing, **b** servo drive, **c** upper contact plate with LED, **d** lower contact plate, **e** metallic holder for index finger (here, shown transparent for clarity), **f** strap for fixation of participant's hand

Methods

Participants

Twenty naïve right-handed healthy volunteers [12 males and 8 females, age 23.5 ± 5.5 years ($M \pm SD$)] participated in this study. The sample size was restricted by rigid time constraints and organizational difficulties. All subjects were introduced to the procedure and signed an informed consent. The experimental procedures were in agreement with the institutional and national guidelines for experiments with human subjects as well as with the Declaration of Helsinki.

Apparatus

This study was conducted with the use of a finger lifting device designed to reproduce the finger lifting movement via a servo drive (Fig. 1). The design of this device generally followed the device described in detail in our previous paper (Dubynin and Shishkin 2017). Unlike in the previous study, an upper contact plate (Fig. 1c) was attached to set the termination point for the movement. Finger rising from the lower contact plate (Fig. 1d) (its default position) to the upper (up to touching it) one was considered a "movement" (or "action"). The principle difference in the study design,

Table 1 Group statics of movement duration for all combinations of activity and success factor levels

	Act	Actpas	Pas	Dum
Success, M ± SD, ms	87.1 ± 21.2	72.8 ± 7.3	68.9 ± 7.7	74.9 ± 4.6
Failure, M ± SD, ms	87.1 ± 21.9	235 ± 16.9	216.3 ± 17.7	248.7 ± 8.6

compared to our previous study, were arbitrariness of action timing (in the previous study, the participants had to immediately respond to stimuli). In the current study, a participant performed an action any time when they felt them ready within a 15 s time interval commenced by a tick sound. We also replaced direct assessment of agency with an indirect index presumably based on the intentional binding phenomenon, the subjective estimation of time elapsed between the action and the subsequent sound signal.

A metallic holder (Fig. 1e) was used to support the participant's index finger. A servo (Fig. 1b) was attached to the finger holder by a string. The distance between the lower and upper plates (Fig. 1c, d) was 7 cm.

Design

The participant was seated in a comfortable armchair. The device resided on a stand on the right side. During the experiment, the participant placed their arm on the base of the device so its position would not lead to muscle fatigue.

In different experimental conditions (each consisting of multiple identical trials) the movement could be executed in four different ways, presumably with varying involvement of a participant:

- Active movements (Act)—a participant raised the finger on their own;
- Active–passive movements (Actpas)—a participant initiated the action with a slight move, whereas the servo completed it;
- Passive movement (Pas)—the servo lifted the finger while the subject was idle (Passive movement, Pas).
- Finger dummy movement (Dum)—the servo lifted a finger dummy placed in the finger holder instead of the participant's finger, while the participant watched this movement.

All these activities were perfectly safe for the participants and required minimal physical effort. Average durations of different types of movements can be seen in "Results" section (Table 1).

The experimenter explained the Actpas condition to a participant as a part of the experiment where the device served as "the assistant", helping them to make the trial successful. To spark an interest in interaction the Actpas block always followed the Act block, so the participant started working together with the servo after a large sequence of failed attempts. We anticipated that it could make cooperation more useful from the participant's point of view.

Procedure

The execution of a finger lifting movement presupposed a degree of success, which varied according to the duration of action. If movement duration (measured as the time between the loss of electrical contact between the finger holder and the lower plate and achieving the electrical contact between the holder and the upper plate) was below a preprogrammed threshold, an attempt was deemed successful ("S"). To provide feedback to a participant, the LED (Fig. 1c) lighted up and a consonance chord (75 dB) sounded. Otherwise, the attempt was recognized as a failed one ("F"), the LED stayed unlit and a dissonance chord (75 dB) sounded. The participants were instructed to try making actions successful.

The threshold changed gradually over the course of the Act condition, decreasing by 5 ms after each successful attempt, given that the overall number of failed attempts did not exceed 6. When this number exceeded 6, the threshold was fixed for the rest of the Act block. The initial threshold value was set at 250 ms. The values were selected so that the participants would typically succeed in the first part of the Act condition and would be unable to pass the threshold in the majority of trials approximately by the middle of the block. The participants were informed of the gradual complicating of their task. Since successful execution of each attempt still depended on the participant, F trials could sometimes occur in the first part of the block due to possible distractions. If we observed that the participant was able to succeed multiple times after the threshold was fixed, the Act block was started over from the beginning. The ratio of S and F trials in the Act condition was tracked to be approximately 1 to 1. In the Actpas and Pas sections the experimenter supervised the participant's EMG: if a muscle contraction was visible after the servo activated, the trial was discarded as inconsistent with the experimental design.

In other conditions, the servo speed was set in each trial in such a way that a trial duration was approx. 80 ms (S trials) or approx. 250 ms (F trials). A trial in these conditions was set to be S or F pseudo-randomly so that 30% of trials in each condition were F trails. In Actpas, Pas and Dum sections the F trials were presented to participants as consequences of "the assistant's" malevolent intent. The result was determined by the device, which was competent at moving fast, yet did not always "choose" to do so. The 70:30 ratio of trials was meant to convince the participant of "the assistant's" general reliability in the Actpas condition, yet it had to be even enough to generate sufficient number of F-trials for the analysis. In our experimental design failed attempts in the Actpas, Pas and Dum sections were implemented as the “oddball” stimuli. At the same time in the Act section the result of each trial depended on the participant, and also the complication of the task took place, so the order of trials in the Act section and other sections was different.

The feedback sound signals were presented at fixed time intervals from the moment of finger holder tipping the upper plate. Time intervals were pseudo-randomly altered between 300, 400 and 500 ms. The participants, however, were told that the actual duration of intervals was arbitrary and made up to a few hundreds of milliseconds. After each trial, the participant verbally shared their subjective estimate of the time interval between the moment of touching the upper plate and the feedback sound. Participants were informed that estimates should be in the range of 1 to 999 ms, otherwise they could not be accepted. Before each block, the participant was presented with the standard intervals (300, 400, 500 ms) linked with both types of chords (all 6 combinations) to ease the procedure of subjective evaluation. During this presentation, the experimenter announced interval duration and what chord it would be followed by, then the subject raised their finger and the chord sounded after the declared amount of time.

EEG recording

In the course of the experiment, the EEG was recorded using an *actiCHamp* device with active electrodes (*BrainProducts*, Germany). We mounted 28 electrodes (Fp1, F7, F3, Fz, FC5, FC1, T7, C3, Cz, CP5, CP1, P7, P3, O1, Oz, FP2, F4, FC6, FC2, FCz, T8, C4, CP6, CP2, P8, P4, Pz, O2). Digitally linked earlobes served as the reference. The vertical and horizontal electrooculogram (EOG) and electromyogram (EMG) were recorded bipolarly with the same device. A pair of EMG electrodes were placed at the right arm above the *m. extensor digitorum*, 3 cm from each other. Impedance was maintained below 10 kΩ for all electrodes. The sampling frequency was 1000 Hz. The recording was made with 50 Hz notch online filter. The signals were bandpass filtered (0.01–50 Hz for the EEG and EOG, 5–500 Hz for the EMG). Unfortunately, the EMG recordings were lost before we proceeded with data analysis.

Data analysis

Processing of electrophysiological data was carried out with the *EEGLAB* v13.6.5b (Delorme and Makeig 2004) under *Matlab* 2013b (*MathWorks*, USA). Statistical analysis was carried out using *Statistica* 10 (*StatSoft*, USA).

Trials with artifacts in the EEG were detected at the threshold of ± 100 μV in any channel of the EEG signal and by visual inspection (together with the EOG) after applying the independent component analysis (ICA). Less than 10% of trials were removed in total. Prior to ERP averaging, the data were filtered in the 0.1–15 Hz band.

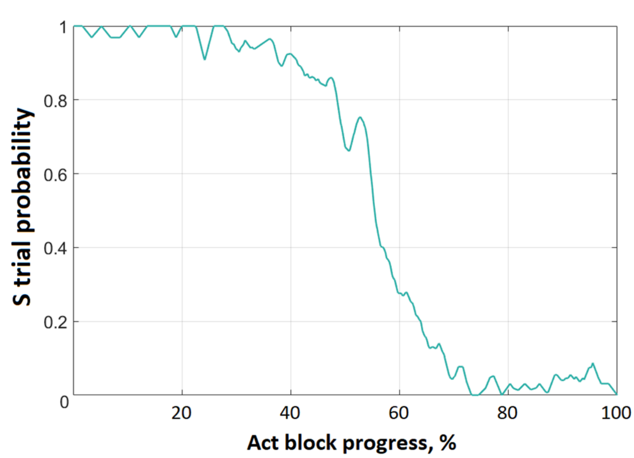
To analyze the effects of the activity and the factor of success for time estimates and ERP data, repeated-measures ANOVA was used. Further comparisons were made using the Fisher LSD post-hoc criterion. For survey results, the Friedman test was used and post hoc analysis with Wilcoxon signed-rank tests was conducted with a Bonferroni correction applied.

Results

Behavioral results

Durations of movements in the Act condition highly varied across participants, being more stable in other conditions (Table 1). This was not surprising, given that movement duration in the Act condition was fully participant-depended, while it was partly device-depended in the Actpas and Pas condition and fully device-depended in the Dum condition.

The distribution of trial types in Actpas, Pas and Dum conditions was pseudorandom. In the Act block, the result depended on the participant. The trial received positive feedback if the movement was performed faster (in ms) than the preprogrammed threshold, and the threshold changed over time. The participants typically succeeded in the first part of the block and failed in the second part. We calculated the share of S trials in the Act block for the data collapsed over all the participants as a function of block progression (in %) normalized per participant. As it can be seen, the share of S trials drops significantly approximately in the middle of the block. The F trials prevailed in the block after the threshold was set low enough, which meant that the participant could not perform the action as fast as it was needed. In total 55.4% of trials were successful.



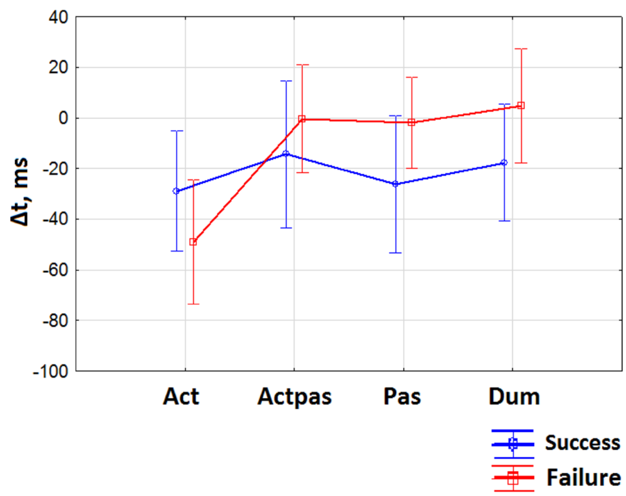


Fig. 2 Group means of differences between subjective estimations and actual time intervals. More negative values correspond to shorter estimates of time intervals. Vertical lines denote 95% confidence intervals

Average proportion of successful trials during the Act block.

To study the subjective estimates of time intervals, actual durations of time intervals (300, 400, 500 ms) between the moment of finger holder touching the upper contact plate and feedback sound signal were subtracted from numeric subjective estimates of these intervals. Results were averaged for each of the eight combinations of activity level and success/failure (Fig. 2).

According to 2-way repeated-measures ANOVA, the effect of the "Success" factor was not statistically significant ($F(1, 19) = 1.13$, $p = 0.28$), while "Activity" factor and its interaction with the "Success" factor were significant ($F(3,57) = 13.28$, $p < 0.001$ and $F(3,57) = 5.26$, $p = 0.003$, respectively). Post-hoc analysis revealed differences between the Act/F condition and all the other conditions (lower time estimates in the Act/F condition, $p < 0.001$) and between S and F trials in the Act ($p = 0.03$), Pas ($p = 0.014$) and Dum ($p = 0.015$) conditions.

No significant differences were found between conditions across S, while in F trials the difference between the Act condition and all the other conditions was significant ($F(3, 57) = 14.5$, $p < 0.001$). In Act/F trials the subjective time estimates were lower than in other conditions. Since they were significantly lower in comparison to all conditions with involuntary actions, we conclude that in the Act/F condition the intentional binding effect was observed. Remember that the Act condition was the only one where the outcome of the trial (S or F) depended on participants' swiftness, while in the other trials they could not influence it.

Consider that the Actpas condition was close to the Act condition in movement initiation (it was active, i.e. made by the participant, in both cases) while being closer to the Pas and Dum conditions in movement execution (passive in all these conditions). Thus, the intentional binding effect was evident in F trials in the Act condition, but not in any type of trials in the Actpas condition (the latter was close to the Pas and Dum conditions by their time estimates). This fact suggests that perception of time intervals depended on the participant's role in movement execution but not in movement initiation.

Auditory ERP

The auditory N1 is a negative waveform component of the ERP elicited by an auditory stimulus and distributed mostly over the fronto-central region of the scalp. The latency of the auditory N1 peak varies from approx. 80 to 120 ms after the onset of a stimulus. The N1 is preceded by P1 and followed by P2 positive components, which can be used for inter-peak amplitude calculations. As it was already mentioned, the auditory N1 is thought to be a potential correlate of SoA (Kühn et al. 2011; Lange 2011). In this study, we examined inter-peak amplitudes and latency of the auditory N1. An effect potentially related to varying sense of agency was found in latencies of this component. The highest amplitude of the N1 component was observed at FCz, FC1, FC2, Cz locations, which were designated as the region of interest (ROI). Individual ERPs were averaged over this ROI, separately for the successful and failed trials (Fig. 3). Topographical ERP maps can be seen in Fig. 4. High EEG variations in the pre-stimulus area made impossible stable estimation of the auditory component N1 amplitude as related to this baseline, therefore we decided to quantify it using the inter-peak amplitudes. We calculated two inter-peak amplitude estimates: one from the extreme of positive peak to the negative peak (P1 – N1) and the other from the negative peak to the next positive peak (N1 – P2).

Significant differences were found only for the second variant, although it is more probably they were unrelated to varying SoA. Those differences in the N1 – P2 inter-peak amplitudes of the auditory ERP (Fig. 5) were detected only for the "Activity" factor ($F(3,17) = 6.35$, $p = 0.004$). Post-hoc test confirmed significant differences only between the Act condition and all the others: the amplitudes were higher in the Act condition. Between the other three conditions, no effect in the N1 – P2 peak-to-peak amplitude was found. This result can be explained by varying attention to the sound identity across the conditions. In the Act condition, the subject was not aware of their attempt's degree of success (S/F) until hearing the feedback chord. At the same time, in all other conditions, the outcome became clear once the servo started lifting the finger, so the identity of the chord was anticipated by the subject and did not require attendance. The enhanced auditory N1 for selective attention

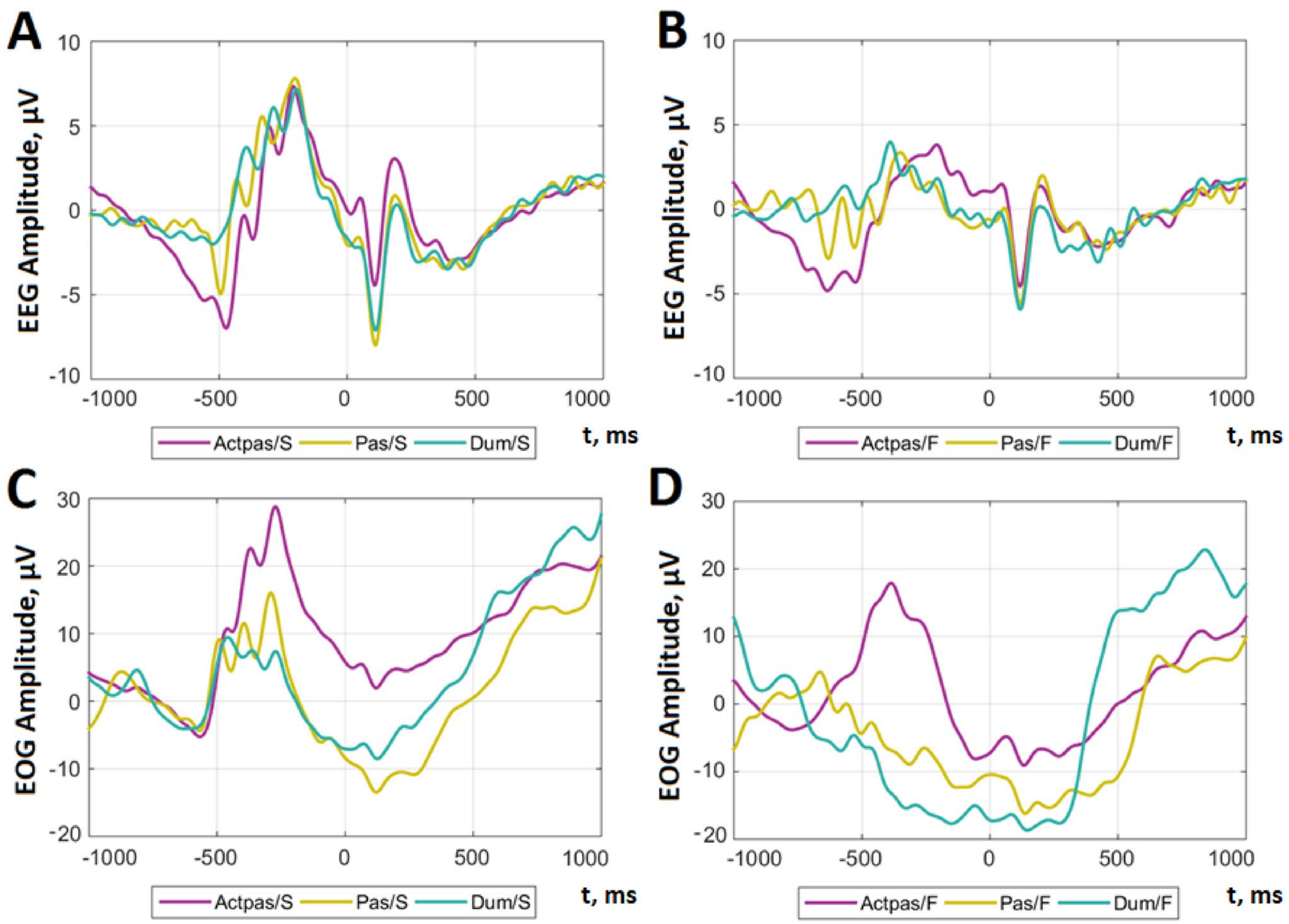


Fig. 3 **a**, **b** Grand average auditory ERP in ROI to the feedback sound following the action in Actpas, Pas and Dum conditions, **a** for S attempts, **b** for F attempts. **c**, **d** Vertical EOG, **c** for S attempts, **d** for F attempts. 0 ms corresponds to the beginning of the sound feedback signal. Baseline −1000…−500 ms (used for the purpose of visualization only; the interval was chosen to avoid its contamination by EOG artifacts and action-locked activity). The auditory N1 can be observed after approx. 100 ms after the onset of a feedback signal

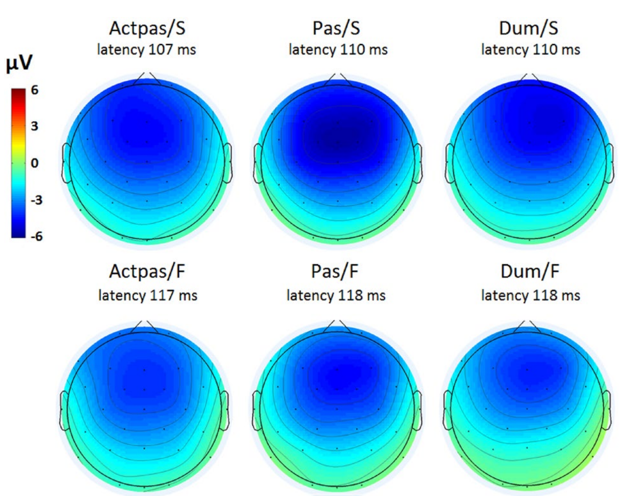


Fig. 4 Maps of grand average auditory ERP amplitude for different combinations of activity and success factor levels at the time points corresponding to the maximum amplitude of the N1 component for each combination

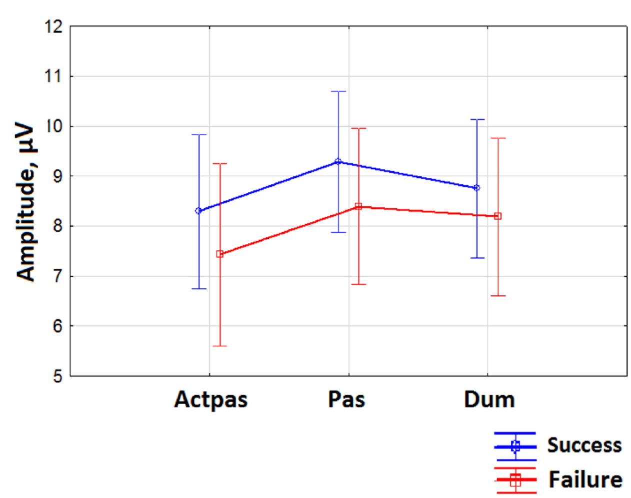


Fig. 5 Group average N1 – P2 inter-peak amplitudes of the N1 component of auditory ERP. Vertical lines denote 95% confidence intervals. Act condition was excluded

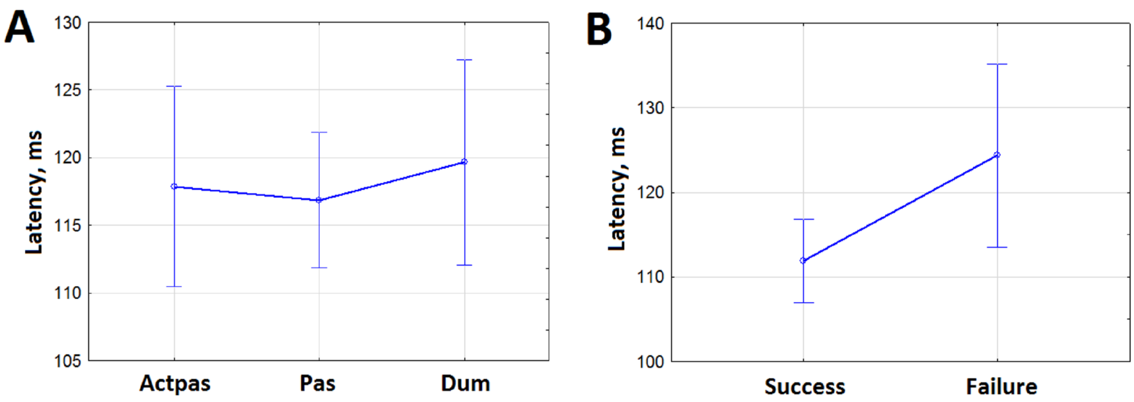


Fig. 6 Average group latencies of N1 component of auditory ERP as dependent on: **a** "Activity" factor; **b** "Success" factor. Vertical lines denote 95% confidence intervals

is discussed in the literature (Woldorff et al. 1993). Taking this into account, we further analyzed the data only from the other three conditions, i.e. Actpas, Pas, Dum. This difference between the conditions was entailed by the experimental design, specifically by the fact that only in the Act condition the result was determined by subject's actions. No effect for the "Activity" factor was detected without considering the Act condition ($F(2, 38) = 1.5$, $p = 0.24$), just as for the "Success" factor ($F(1,19) = 2.01$, $p = 0.17$).

Latencies of the auditory N1 were determined as the average time corresponding to the minimum of the peak in ROA. Average values of N1 latencies for different conditions are shown in Fig. 6a. For these data, the effect of "Success" factor was significant, $F(1,19) = 22.7$, $p < 0.001$ (Fig. 6b), the "Activity" factor showed no significant effect ($F(2,38) = 0.85$, $p = 0.44$) and its interaction with the "Success" factor was also nonsignificant ($F(2,38) = 1.07$, $p = 0.35$). The post-hoc analysis demonstrated the significance of differences in all S-F pairs ($p < 0.001$).

In the control sound signal presentations, we found significant differences between latencies of the auditory ERP component N1 for S and F chords ($F(1,9) = 8.2$, $p = 0.019$); however, unlike in the main experimental conditions, latencies of the consonant chord were higher (Fig. 7). No significant effect was found for P1 − N1 and for N1 − P2 interpeak amplitudes ($F(1,9) = 0.7$, $p = 0.413$ and $F(1,9) = 0.01$, $p = 0.904$, respectively).

Discussion

In the present study, we developed a method for studying a new kind of motor actions, the "active–passive" movements (Actpas). With the method, we looked for psychological and psychophysiological correlates of SoA at intermediate levels of human involvement into action. The designed "active–passive" action is a voluntary joint motor action, i.e. it is initiated by the subject when needed, whereas its completion depends on machinery, and the action's result can be made fully dependent on the settings of the "partner" device. In our experiment, this mode of cooperation was implemented as a finger lifting movement assisted by a servo drive.

Implications from the behavioral results

We compared the Actpas movements to the active movements (Act), committed without external help, and to the passive movements (Pas), fully made by the device that moved a participant's finger. Another kind of movement was also performed by the device, but with the finger substituted by its dummy (Dum). The participants were informed of success (S, for movements judged as fast) or failure (F, for movements judged as slow) of their attempts by related sound signals and (for S only) by lighting a red LED. We assessed the effects of action type and success factors on subjective estimates of time between the action and its result and the ERP data, the latter including

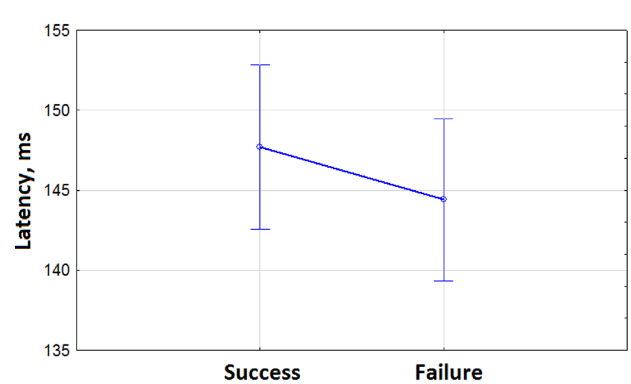


Fig. 7 Average group latencies of N1 component of auditory ERP in the control recordings

amplitude and latency of the auditory N1 and the P3 components.

In the Act/F condition, the numerical subjective time estimates were significantly lower than in all other conditions. It was the only condition where the intentional binding effect was confirmed statistically: there was a difference between the time estimates in Act/F and all Pas and Dum conditions, where the action was not voluntary. In the Act/F condition, the finger movement was made voluntarily with no servo involved, and it was not swift enough, causing a negative feedback signal. In contrast, when an external agent, the servo, took part in voluntary action, i.e. in the Actpas condition, or when the active action was successful, we detected no intentional binding effect. Note that the relatively small sample size restrains us from making conclusions about the possible absence of intentional binding in these conditions. We expected that different types of movement would demonstrate a hierarchy of binding effect linked to the "Activity" factor: the more the subject is involved into action, the stronger the binding effect. This hypothesis was not confirmed.

The time estimates in F trials were lower than in S trials only in the Act section. In the Actpas condition the time estimates did not vary significantly, while in Pas and Dum conditions successful trials encouraged the participants to give lower estimates than the unsuccessful ones. It could be the consequence of the experimental design we used, e.g. specific disposition of trials in the Act condition, where all S attempts were in the first half and all F attempts in the second half of the condition. It should also be noted that in the Act condition the chords and LED were the earliest sources of information about the outcome of a particular attempt, while in other conditions (Actpas, Pas, Dum) the result was evident after the movement was initiated. Had we arranged the trials similarly in other sections, the difference between the two kinds of trials could have been alike in all sections. The experimental design of the current study did not let us test whether or not it is true.

This feature of the experimental design also lets us make an assumption about time estimates in the Actpas condition. If intentional binding accompanies voluntary actions, then the Actpas movements, in spite of being initiated by the participant, lacked certain properties to evoke SoA better than actions requiring from the participant no effort at all. It could be that having control over the result of an action is crucial for the emergence of SoA. However, it is also possible that joint action executed together with a machine generally does not produce intentional binding, as previous studies indicate (Obhi and Hall 2011; Sahaï et al. 2019).

It should be also considered that the movement in this study encompassed a very simple case of human–machine interaction. Complex movements, implemented in the framework of beneficial interactions between humans and machinery, should be explored in further studies.

The lower subjective time estimates in the Act/F compared to the Act/S and Dum/F combinations of activity and success factor levels may contradict conclusions made earlier (Desantis et al. 2012; Haering and Kiesel 2014) about the lack of correlation between the result of an action and the emergence of intentional binding. However, this fact is consistent with the idea of the connection between binding and subject's high-level expectations (Desantis et al. 2011). In their study Kumar and Srinivasan (2017) observed intentional binding when participants could not achieve the goal in an aiming task. Interestingly, no binding was evident in trials with positive results. Our results for the Act series are somewhat consistent with this fact. On the other hand, diminishing of SoA due to negative outcomes has been shown in another study (Yoshie and Haggard 2013). Anyway, it is not clear whether or not the distribution of trials in our paradigm was responsible for the shortening of time estimates in Act/F compared to Act/S. Is the difference in feedback self-sufficient, or is the sudden block of the goal after a sequence of successful trials responsible for this effect? It is also noteworthy that the sensitivity to action's output was observed in the case of passive and dummy movements, those potentially able to generate only JoA. This also supports the hypothesis that high-level processes associated with assessment of result affect SoA.

There is another explanation of the difference between intentional binding in the Act/S and the Act/F conditions. Some studies indicate intensified deliberation increases intentional binding (Jo et al. 2014). It is possible that once the participants found themselves unable to pass the threshold, they preplanned their actions more carefully to succeed. If such behavior of the participants took place in our study, the intentional binding could be influenced by the time of preplanning or increased deliberation, and not the type of feedback signal following the action. In order to discern the effects of increased deliberation and success factor further research is required.

Implications from the ERP results

The difference in parameters of two chords used for feedback in S and F trials had no influence on amplitude of the auditory N1 component, as followed from the analysis of the additional (control) recordings. The amplitude turned out to be significantly higher for the Act movements compared to all other conditions. As already mentioned, high amplitudes in the Act condition likely originated from an intrinsic difference between the Act condition and all the other conditions: performing an active movement, a participant learned whether or not they had accomplished the task only from the feedback, while in other conditions the mode of servo's operation (fast or slow) determined the outcome. Thus, participants payed high attention to the feedback only in the Act condition. These results were consistent with already known facts about the factors influencing the amplitude of auditory N1 (Lange 2011) and they did not require an appeal to agency for their explanation. Since no difference was found among the other three conditions (Actpas, Pas, Fake) for the N1 amplitude, we could not conclude about any relationship between this ERP parameter and SoA.

The additional (control) recordings showed a difference between latencies of the auditory N1 component for consonant and dissonant chords (used for the feedback in S and F trials, relatively), the former having significantly higher latencies. In the experiment, the auditory N1 latencies were also dependent on the "Success" factor, but in S trials latencies were lower, therefore the different nature of sounds could not undermine this effect. This observation could additionally highlight the importance of an action's result when considering sense of agency. The concurrence with the behavioral results that show the influence of outcome on time estimates suggests that the N1 latencies could be related to the judgment of agency. However, since we could not compare the N1 latencies in the Act condition with others (see the previous paragraph for the explanation of the difference between them in respect to the feedback), we cannot yet conclude that the auditory N1 latency correlated with the agency.[1]

Conclusion

In this study, we implemented an active–passive paradigm for studying the sense of agency. We created an experimental setup where the finger lifting movement initiated by a participant could be completed by a servo, thus leading to cooperation between the two. Other kinds of movements included active movements, passive movements, and observation of dummy's movements. Intentional binding was not observed in active–passive actions and active actions with positive results, even though they were voluntarily initiated by a participant. There was a significant difference between active movements, those fully committed by a participant with a negative outcome, and all the other conditions. The action itself was represented as a reaction time task, and its output affected time estimates and latencies of the auditory N1 component. The N1 latencies were shorter for successful attempts, and time estimates for them were shorter in Pas and Dum conditions. Taking all together, our results suggest that the latencies of the N1 component in responses to feedback stimuli can be related to the judgment of agency, and subjective time estimates can be affected by the result of an action with the emergence of intentional binding when the goal of an action is not achieved. It has yet to be clarified what properties should a voluntary movement have to evoke intentional binding, whether it be a joint action or not.

[1] We also examined the P3 component related to the end of an action (the holder touching the upper contact plate). It appeared, however, that it overlapped with an eye movement artifact and was highly instable, especially in F conditions. Thus, this analysis was abandoned.

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Declarations

Conflict of interest The authors declare no conflict of interest.

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