Designing Sense of Agency Experiments to Study Joint Human-Machine Grasping Actions

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Abstract. In this paper, we present a novel experimental design for studying sense of agency (SoA) in joint human-machine actions than involved grasping movements. The joint actions were implemented by using an electromechanical grasping device propelled by a servo drive. The device completed a grasping action initiated by a participant. These actions were contrasted with other levels of the participant's involvement, including active movements, passive movement and observation of a dummy's movement. Our experimental setup allows us for studying the possible correlation between the level of involvement into action and quantitative distance estimates. The proposed experimental design was tested in a pilot study involving 9 heathy volunteers. In particular, the survey results showed a significant correspondence between the score of reported SoA and participant's role in action. We suppose that our new design for studying joint actions will contribute to the development of exoskeletons, rehabilitation technologies and advanced human-machine systems.

Keywords: Joint actions · Active-passive actions · Sense of agency · Intentional binding · Spatial binding

1 Introduction

1.1 Sense of Agency

The sense of agency (SoA) is an essential part of human self-consciousness [1]. It refers to the subjective experience of discovering oneself as the author of an action. This sense may dramatically fail in some situations as for instance in cooperative problem solving and in swift joint attention [2]. One of the most important issues in SoA studies is quantifying it in various conditions. The early discovered problem is that a direct interview with the subject can force them to reevaluate their experience, and will only grant access to the high-level judgements of agency, leaving aside the low-level feeling of agency [3]. This obstacle urges the experimenters to search for behavioral and physiological correlates of SoA. The correlates would make the implicit evaluations of SoA possible, which in turn would help to discover the necessary conditions for the emergence and dissipation of SoA.

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1.2 Intentional Binding and Spatial Binding

A probable behavioral correlate of SoA known as intentional binding has been widely discussed in literature. Intentional binding refers to an effect in quantitative subjective estimates of time reported by Haggard et al. [4]. The participants estimated a time interval between an action and its outcome as significantly shorter than it actually was, but this effect was observed only when the action was voluntary, and not induced by transcranial magnetic stimulation. A similar effect called spatial binding was reported for the subjective estimates of distance [5]. A distance travelled by the mark from the moment of action to a certain event was perceived as shorter by the participants when the action and the event were causally connected. Since causal binding has been observed in time intervals as well [6], it could be fruitful to study the relation between the subject's involvement into action and their subjective estimates of distance.

1.3 SoA in Joint Actions

It is common for the experimental studies of SoA to contrast voluntary actions with the involuntary ones. However, new advancements in exoskeletons and rehabilitative technologies raise the issue of SoA in joint human-machine actions. Accordingly, the array of situations where an intermediate level of involvement of the human subject takes place has to be considered. Would the subject experience sense of agency as in regular voluntary actions, if the action they intended were completed by a machine? The case we view as even more interesting is the possibility of enhancement of the human actions using mechanical devices. Few studies were dedicated to SoA in joint human-human [7] and human-machine [8] actions, but we were unable to find any published studies of SoA in actions enhanced by the machine, or committed with the machine acting as an instrument, rather than an independent co-agent. However, in our recent study of SoA [9] we had already considered interaction between human agent and assisting device, though the assisting device in that experiment did not boost one's performance.

In the current paper we present an experimental design for studying the possible connection between the subjective estimates of distance and the level of subject's involvement into action. The action implemented in our design is a grasping movement, that is made with a thumb and an index finger. By creating an exoskeletal claw-like device, we were able to include joint actions into the design. Also, we made a silicone dummy of a human hand to organize a condition where the subject is only an observer. In total the design we propose features four levels of human involvement. The method was tested in a preliminary study, which yielded promising results, that yet have to be verified in a full-scale experiment.

2 Methods

2.1 Apparatus

We designed an experimental setup (see Fig. 1) in order to probe the supposed correlation between the subjective estimates of distance and subject's degree of involvement into action. The setup included two devices: a wire lifting device and a grasping device (the "claw") that aided a participant in grasping the wire.

Participant's wrist was fastened on a wooden platform at the base of the device. A metallic stand containing the controller board, servo drive and a capacitive sensor was also fixed on the platform. A wire was attached to the lever, which could be lifted by a servo drive at the top of the stand. The servo drive was covered with an opaque case so a participant would not be distracted when it was operating. The wire went through the base of the device into the wooden box that supported the whole setup. At the bottom of the box the wire was hooked to a weak spring, so the wire always would be straightened. The fragment of the wire within the experimental purview stretched from an opening in the stand to the base of the device, and was visible to a participant. The wire was marked with a solid drop of tin painted black. Three lasers were on the sides of the stand, emitting beams at the sensors on the base parallel to the wire. A holder with two LED lamps illuminating the working area was also placed on the base, as well as a monitor and a numeric keypad used for data input.

The claw consisted of two aluminum plates forming a gear train. A servo drive bolted to the claw could make it clench and unclench automatically safe for a participant. With the claw a participant was able to move only their metacarpophalangeal joints, therefore the grasping motion had a single degree of freedom. The claw was tightly fixed on the participant's thumb and index finger by hook-and-loop fasteners. During the experiment, when the claw was clenching it would cross the laser barrier imposed by three laser beams. This event in turn would trigger the servo drive at the top of the stand, and the wire would start to lift. When participant's fingertips touched the wire, it would immediately stop, the tin drop reaching a certain position. A participant then estimated the distance between the drop and the opening in the stand. After 500 ms would pass, the LED lamps would turn off, leaving no source of light and no means to reevaluate the distance. A participant used a numeric keypad to enter their subjective estimate of distance which appeared on the monitor screen. The screen was adjusted to low brightness and framed by a cardboard shutter so only a small window with a number was left.

Data processing and control of the servo drives and lamps was carried out via a program developed in Delphi 2010.

2.2 Experimental Design

The experiment was conducted in four distinct stages. Each stage consisted of multiple identical trials. In every stage the grasping movement was executed in one of four different ways, presumably with varying involvement of a participant:

- active movements (Act) – a participant grasped the wire 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 grasped the wire while the participant was idle;
- hand dummy movement (Dum) – the participant's hand was unfastened and replaced with a silicon dummy of a human hand. The servo grasped the wire on its own,

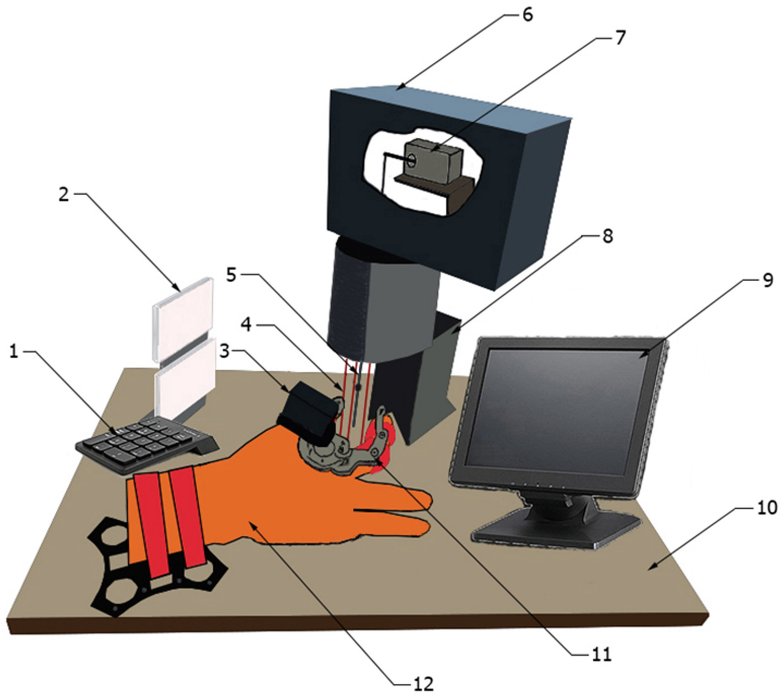

Fig. 1. Sketch of the experimental setup. 1 – Numeric keypad; 2 – LED lamps; 3 – Claw servo drive; 4 – Laser barrier; 5 – The wire; 6 – Opaque case; 7 – Wire lifting servo drive; 8 – Controller board; 9 – LCD monitor; 10 – Wooden platform; 11 – the “claw”; 12 – Participant’s hand or a hand dummy.

while a participant observed the movements and made distance estimates as in other conditions.

All these activities were perfectly safe for the participants. The experimenter presented the Actpas condition to a participant as a part of the experiment where the claw served as “the assistant”, helping them to grasp the wire faster and with minimal effort. We expected these joint actions to be quicker than active movements, the data on action durations is provided in the “Results” section. It has to be noted that active and active-passive movements were voluntary, while passive and dummy movements were committed by the device. During the Pas and Dum stages, the experimenter made sure that the participant did not move by tracing the EMG.

After the experimental session the experimenter asked the participant to evaluate their experiences of sense of agency in every block of trials using a Likert-type scale that ranged from 0 to 9. The exact formulation of the question was the following: “Evaluate your sense of authorship over each kind of actions; 9 – you are the author of the action, 0 – the action was perceived as externally caused.

2.3 Participants

The group of 9 naïve right-handed healthy volunteers (5 males and 4 females, average 20.7 years) participated in the pilot experiment. Due to the well-known epidemic situation of the year 2020, we were unable to involve a larger sample size of subjects for testing this novel method in a full scale. All subjects were introduced to the procedure and signed an informed consent. The experiment procedures were in agreement with the institutional and national guidelines for experiments with human subjects as well as with the Declaration of Helsinki.

2.4 Data Processing and Analysis

Statistical analysis was carried out using *Statistica* 10 (*StatSoft*, USA). To analyze the effects in distance differences, 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.

3 Preliminary Results

3.1 Enhanced Action Speed in the Actpas Condition

In this study we intended to create an instance of the joint human-machine actions with enhanced performance. The reasoning behind this idea was simple: we reckoned that acceleration provided by the device would make the interaction seem more useful and ergonomic for the participants. We compared the characteristic durations of grasping actions in the Act and the Actpas blocks, thus juxtaposing the unaided movements with those performed together with the device. The action time durations of respective actions were calculated as differences between two events: the participant's exceeding of the EMG threshold and activation of the capacitive sensor when the wire was caught. In two participants the durations could not be calculated due to invalid registration of EMG threshold exceeding in the Act block. In Pas and Dum conditions the durations were impossible to determine, because the EMG threshold exceeding was simulated in these conditions. We conducted tests of significance for the mean durations using 1-way repeated measures ANOVA. The analysis showed a significant effect: Wilks' $\lambda = 0.03$, $F(2, 5) = 25.08$, $p < 0.0002$. As we intended, on average, grasping actions in the Actpas block were completed faster than in the Act block. The group means of action time durations can be seen in Fig. 2.

3.2 Subjective Estimates of Distance

In the present study we investigated the non-verbal subjective estimates of distance in condition with varying degree of involvement into action. According to our hypothesis, the shortened subjective estimates of distance may be an implicit correlate of SoA, not unlike intentional binding that refers to shortened estimates of time intervals between the action and its effect. The distance we considered in this experiment was the displacement of the tin drop that happened before the capacity sensor activated. The drop began to

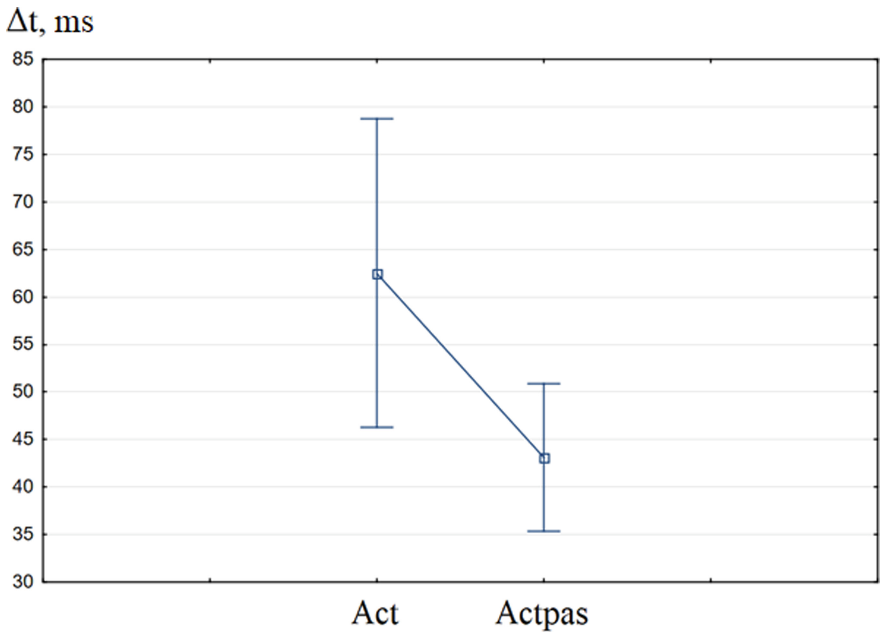

Fig. 2. Group means of action time durations. Vertical lines denote 95% confidence intervals.

ascend swiftly when the laser barrier was crossed, i.e. when the action commenced, and it stopped in result of the action having been performed. We calculated differences between the actual and subjectively estimated distances and averaged them in every participant.

We analyzed the mean differences between distances using 1-way repeated measures ANOVA. All four kinds of conditions were considered. The analysis showed a significant effect: Wilks' $\lambda = 0.02$, $F(5, 4) = 25.08$, $p < 0.04$. Post-hoc analysis revealed differences between the Act and Dum conditions ($p < 0.03$), and also between the Act and Pas conditions ($p < 0.02$). No significant differences in other pairs of conditions were found. The group means of differences between the subjective estimates and real distances can be seen in Fig. 3.

3.3 Survey Results

After the experimental session the participant was asked to evaluate the experienced sense of agency in every block of trials. For that purpose, a Likert-type scale ranging from 0 to 9 points was used. To analyze the scores, we used the Friedman test, and the post-hoc analysis was conducted by means of Wilcoxon signed-rank test with Bonferroni correction. The Friedman test demonstrated a significant effect ($\chi^2(3) = 21.6375$, $p < 0.001$). The interquartile range equaled 0 (from 9 to 9), 1.75 (from 6.75 to 8), 4 (from 0 to 4) and 0 (from 0 to 0) in the Act, Actpas, Pas and Dum conditions respectively. Post-hoc analysis showed a significant difference between the Act and Actpas conditions

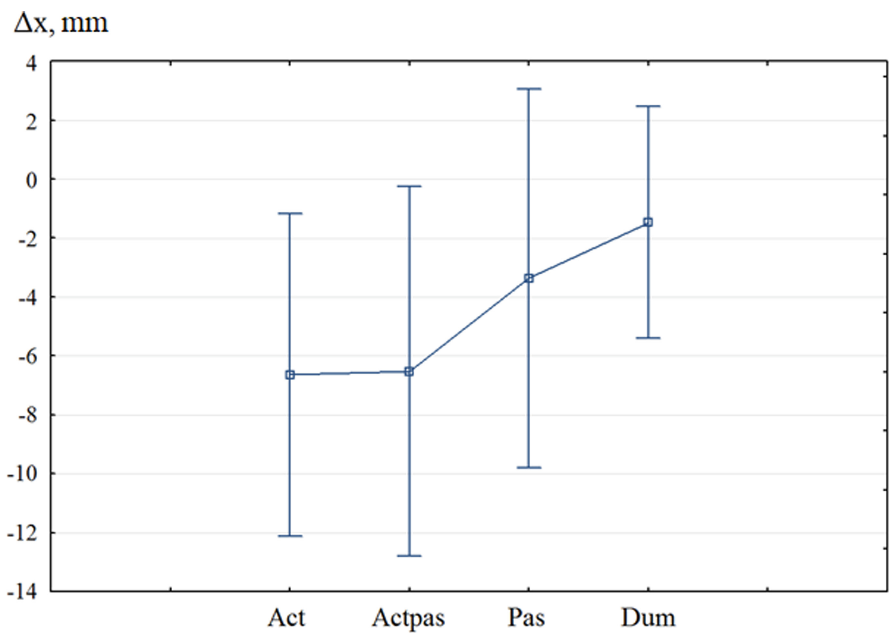

Fig. 3. Group means of differences between the actual distances and subjective estimates. Vertical lines denote 95% confidence intervals.

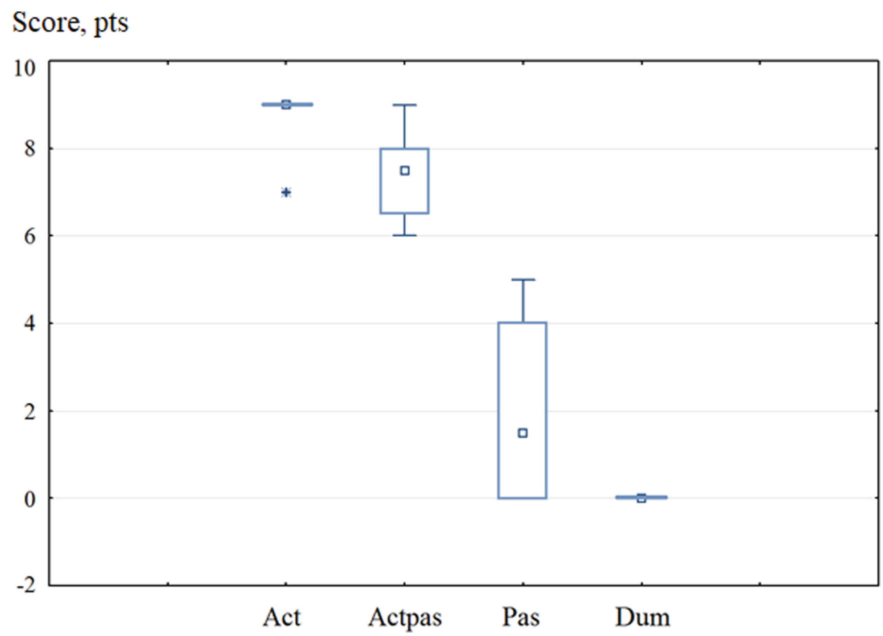

Fig. 4. The box-and-whisker diagrams for mean SoA scores.

($Z = -2.3664$, $p < 0.05$), the Actpas and Pas conditions ($Z = -2.5205$, $p < 0.05$). The box-and-whiskers diagrams for mean SoA scores in all conditions can be seen in Fig. 4.

4 Discussion

In the present study, we successfully tested a novel experimental design for exploring the possible correlation between the subjective estimates of distance and sense of agency (SoA). The main advantage of our design is that it features a wide range of levels of subject's involvement into action. Partial involvement of the subject is a necessary condition for studying SoA in joint human-machine movements, e.g. in interactions with an exoskeleton. A variety of joint actions examined in the present study is referred to as the active-passive (Actpas) action. In our setup, an active-passive action was initiated by the human agent and completed by the "claw" – an exoskeleton fragment created for assistance in grasping movements. We contrasted the active-passive movements with the active ones (Act), the passive ones (Pas) and with the movements of a silicone hand dummy (Dum). In the Act condition, the participants performed an action on their own, while the "claw" was deactivated. In the Pas and Dum conditions the action was involuntary: the "claw" moved in a preprogrammed way, having been attached to the participant's hand (Pas) or a hand dummy (Dum).

We were interested in portraying the device's assistance as beneficial in the Actpas condition, and so we attempted to make the joint movements faster than the active movements. We pursued this endeavor because in real life situations one would rather prefer joint actions if they enhanced one's capabilities, given the agent is able to perform an action on their own. Our preliminary results show that in our setup the active-passive movements were performed significantly faster than in the case of active movements.

A possible correlate of SoA considered in our design was the difference between the estimated and actual displacement of a tin drop. The drop's relocation started when the action was initiated, and ceased, when the action (grasping the wire) was completed. An effect we expected to find may have been similar to intentional binding – the subjective shortening of time intervals between the action and its result. The preliminary results support our hypothesis: the mean differences between the distance estimates and actual distances were significantly higher in the Act condition than in Pas and Dum conditions. In order to make further speculations, a research with a larger sample is required. However the experimental design we presented here seems to be adequate and sufficient for conducting such a full scale study.

While testing the new design, we also conducted a survey where the participants were asked to give explicit SoA scores to all the four movement types. The preliminary results show a significant difference between the Act and Actpas conditions, the Actpas and Pas conditions and the Act and Pas conditions. No differences between the Pas and Dum conditions were detected, reminding some of the out-of-body effects [10, 11]. However, it has to be noted that both types of movement presuppose little agency. The gradation that manifested itself in the results corresponds with varying degrees of involvement implemented in the experimental design. It suggests that the active-passive actions are experienced as actions with intermediate intensity of SoA. Again, as with the subjective estimates of distance, a more substantial research is needed to test this particular hypothesis.

5 Conclusion

We developed a novel experimental design for studying SoA in joint human-machine grasping actions. We successfully tested the proposed design, and the first data was collected. According to these preliminary results, the joint actions were performed faster by the participants than similar unaided actions. There also was a correlation between subject's degree of involvement into action and the subjective estimates of distance travelled by the mark between the moments of action initiation and completion. In addition, survey results showed a significant statistical correspondence between the score of reported SoA and subject's role in action.

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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