



Intentional action and limitation of personal autonomy. Do restrictions of action selection decrease the sense of agency?

S. Antusch^{*}, R. Custers, H. Marien, H. Aarts

Department of Psychology, Utrecht University, The Netherlands

ARTICLE INFO

Keywords:

Autonomy
Action selection
Sense of agency
Intentional binding
Restricted actions

ABSTRACT

The experience of being an intentional agent is a key component of personal autonomy. Here, we tested how undermining intentional action affects the sense of agency as indexed by intentional binding. In three experiments using the Libet clock paradigm, participants judged the onset of their action (key presses) and resulting effect (auditory stimuli) under conditions of no, partial, or full autonomy over selecting and timing their actions. In all cases, we observed a moderate to strong intentional binding effect. However, we found no evidence for an influence of personal autonomy on intentional binding. These findings thus suggest that being unable to decide how and when to perform actions does not affect the perceived temporal binding between action and effect, a phenomenon suggested to be associated with the implicit sense of agency. We discuss the implications of our findings in the context of research on personal autonomy and goal-directed behavior.

1. Introduction

Autonomy, i.e. the ability to make unconstrained decisions and to act on them in the service of personal goals, is a core element of democratic constitutions. Maintaining personal autonomy is a central challenge for modern societies characterized by institutional contexts, which allow for unconstrained actions but have (juridical and moral) limitations to them. For example, while individuals are free to move to reach their travel goal, they are expected to follow traffic rules, such as stepping on the brake upon seeing a red traffic light. This mix of intention-based and environment-based action selection highlights the complexity of the concept of personal autonomy. Crucially, personal autonomy is presumed to depend on the sense of agency, i.e., the pre-reflective experience of oneself as the agent of one's actions and their consequences in the external world. The experience of a sense of agency is essential to goal-directed behavior, and hence, to self-regulation. As a more socially reflective construct, the sense of agency also constitutes the basis for causal blaming or judgment of responsibility, and finally, the understanding of moral behavior (Moretto, Walsh, & Haggard, 2011).

Recent research started to explore the relationship between autonomy and the sense of agency. Sense of agency is reflected in intentional actions and their effects being temporally bound together in the perception of the agent, causing the interval between them to be experienced as compressed – a phenomenon termed intentional binding (Haggard, Clark & Kalogeras, 2002). So far, a set of different personal autonomy restrictions and their influence on binding has been tested, varying from direct brain stimulation of motor movement, to the limitation of behavioral options and coercion (Barlas & Obhi, 2013; Caspar, Christensen, Cleeremans, & Haggard, 2016; Haggard et al., 2002). While there is considerable literature suggesting that autonomy is a desirable state that is crucial for

^{*} Corresponding author at: Utrecht University, Department of Psychology, PO BOX 80140, 3508 TC, Utrecht, The Netherlands.
E-mail addresses: s.antusch@uu.nl (S. Antusch), h.aarts@uu.nl (H. Aarts).

human performance (Koestner, 2008; Ryan & Deci, 2006), studies testing the relation between personal autonomy and the sense of agency show mixed results. The present research aims to contribute to this literature by systematically exploring two core components central to personal autonomy and action selection: the ability to decide how to act and the ability to decide when to act (Brass & Haggard, 2008). Specifically, we tested whether the sense of agency, as indexed by the intentional binding effect, reduces when the action selection and action timing shift from being fully autonomous to being fully non-autonomous.

The most prevalent method to assess intentional binding builds on the Libet clock paradigm, in which participants observe a rotating clock while pressing a single key to cause a tone at a moment they want to (Tanaka, Matsumoto, Hayashi, Takagi, & Kawabata, 2019)¹. Voluntarily pressing a key has been shown to result in the key press and the subsequent effect to be bound together in temporal perception. While the default condition in most intentional binding studies is called ‘voluntary action’, participants usually can only press a single key and are thus constrained in the selection of their action but not the timing. Early findings on involuntary action induction using transcranial-magnetic stimulation (TMS), showed that this binding effect is reversed when autonomy is taken away from the individual, resulting in action and effect to be perceived as repulsed from each other (Haggard et al., 2002). Also, when another agent or a machine induces actions in participants, binding decreases (Borhani, Beck, & Haggard, 2017; Dogge, Schaap, Custers, Wegner, & Aarts, 2012; Haggard et al., 2002). Hence, it could be concluded that personal autonomy restrictions – i.e. not being able to act voluntarily – result in an attenuation of the sense of agency. However, not only is external induction of an action an uncommon occurrence in real life, it also denies any opportunity for the agent to form intentions to execute an action, start up the motor system and thus internally generate the action to achieve goals. That is, personal autonomy is not only a function of oneself acting but also characterized by the agent being able to choose the action and the timing of action execution.

A first attempt to examine autonomy restrictions in an action selection task is offered by research conducted by Wenke and colleagues (2009). In their study, they used the Libet clock to assess intentional binding and manipulated whether participants could freely choose or were instructed to press one of two possible keys (free vs. restricted action selection) and when to press it (free vs. restricted action timing). Findings were that binding magnitude depended on the combined mode of action selection and of action timing. That is, an action that was generated based on two unmatched modes (i.e., internal action selection & external timing or external action selection & internal timing) resulted in less intentional binding than when the modes matched (i.e., both internally determined, or both externally determined). The authors speculated that individuals establish a more coherent or fluent experience of behavior when actions result from a single (versus different) mode of selection, thereby increasing binding between action and effect. In other words, an action that is either entirely self-determined or entirely externally determined produces an experience of voluntary action. Whereas this metacognitive account might explain the results, it is important to note that participants had to postpone their action, such that they were still able to freely enact their action intention after considerable time (after one rotation of the clock) and within a large time window (during the second rotation of the clock) in the external timing condition. Thus, while suggestive, these findings are not conclusive with regard to the influence of autonomy restrictions on action-effect binding.

In another set of studies, autonomy restrictions were examined in a multiple choice option context. In one study (Barlas et al., 2013), participants were given seven buttons, and they could freely choose which button to press, or they were restricted to three or only one action alternative. They then had to press the button at a self-determined moment while watching the rotation of the Libet clock. Results suggested that intentional binding was strongest when participants had a high level of choice (seven buttons to choose from) as compared to a medium level (three buttons) and no choice (one button). Suggesting that maximal autonomy in action selection and timing facilitates a sense of agency, these findings would be in line with related research on ideomotor learning indicating stronger ideomotor learning effects when autonomy is high (Pfister, Kiesel, & Hoffmann, 2011). A possible mechanism herein might be alleviated muscular efficiency due to autonomy support (Iwatsuki, Shih, Abdollahipour, & Wulf, 2019).

In a more recent study, Tanaka and Kawabata (2019) adapted the paradigm and compared a high choice condition (free choice out of eight buttons) against a no choice condition (one button) while also manipulating outcome valence. While emotional valence of the action-outcome affected binding (see also Takahata et al., 2012; Yoshie & Haggard, 2013), the findings of Barlas and colleagues turned out to be difficult to replicate. Although the difficulty to replicate the choice effects on binding might be the result of slight differences in task setting, it is interesting to note that participants in the original study by Barlas and colleagues (2013) did not show binding in the one button (no choice) condition. This is peculiar given that this equals the default ‘voluntary action’ condition in intentional binding research and usually results in robust binding effects. While this divert finding still needs further clarification, it is conceivable that participants in the study by Barlas et al. might have been more aware of the lack of control or otherwise experienced explicit cognitive reactance because they felt that their freedom was limited. Thus, whereas these studies do not directly compare conditions in which an action is either entirely self-determined or entirely externally controlled, they do suggest that intentional binding could be affected by conscious experiences of restrictions in personal autonomy.

Recent research by Schwarz and colleagues (2019) actually hints at a distinct influence of such autonomy restrictions on explicit agency experiences but not implicit markers such as intentional binding. Using a self-paced Libet clock paradigm in conjunction with an explicit agency measure, they found no difference in intentional binding between instructed and free action while the subjective explicit experience of agency differed significantly. Participants reported experiencing less control when they had to select one of two key options but this was not reflected in a weaker binding effect. This finding suggests distinctive mechanisms for the effect of

¹ Note that there is a substantial amount of IB research using the interval estimation method. However, the interpretation of those findings is not always clear as some studies suggest that underestimation equals binding while others interpret overestimation as binding (Damen et al., 2015). Whereas both may be true, a more logical way to interpret time interval estimation is to assume that underestimation represents more binding and overestimation more repulsion (see for a discussion on this issue, Antusch, Custers, Marien, & Aarts, 2020).

autonomy on the *judgment* of agency and the *feeling* of agency (cf. Synofzik, Vosgerau, & Newen, 2008). While judgments of agency seem to be affected by explicitly viewing oneself as an agent, feelings of agency as reflected by intentional binding seem to show a more implicit experience of agency. This also explains why agents who only observe an action but do not execute it report no explicit agency but show intentional binding (Obhi & Hall, 2011). This leads to the question of whether full autonomy restrictions in choosing and timing an action affect implicit experiences of agency at all.

Research on coercion, in contrast, suggests that autonomy restrictions can decrease the implicit sense of agency (Caspar et al., 2016; 2017). In a study by Caspar and colleagues (2016), participants could either freely choose to inflict financial or physical pain on another participant or were coerced to do so by the experimenter. It was shown that participants showed less temporal binding when they executed an action based on the experimenter's "command" as compared to when they freely chose to do so. Note however that inflicting financial or physical pain on another person is a strong manipulation of the action-outcome valence, which might be stressful. Moreover, participants benefitted financially (i.e., they earned money for every time that they inflicted pain) when they inflicted pain on another agent, which might have confounded results. Furthermore, rather than using the Libet clock, the coercion studies asked participants to estimate the time interval while action timing was self-determined. This makes the findings somewhat difficult to interpret in the context of previous work on the role of personal autonomy restrictions in the mere stage of action selection and timing on binding in the Libet clock task.

To summarize, the existing literature applied a range of different autonomy restrictions to examine how having control over the action selection process affects the sense of agency. Autonomy restrictions mainly applied to the choice options and the moment of acting. While both aspects are important, the moment of action selection is easily confounded with external control of action. That is, in previous studies participants were told when to press, but they still had sufficient freedom to select and time their action within a large time window. In the present study we therefore aimed to scrutinize freedom of action timing in a more strict sense. Specially, we examined the situation in which participants are told when to exactly press a key, namely when a specific cue would appear on a computer screen. This way, freedom of action timing is narrowed down to a more environment-controlled action selection process and thus rules out the ability to voluntarily time the action.

To systematically examine the role of autonomy with respect to choice and timing in the sense of agency we designed three experiments using the Libet clock task. In the first experiment, we developed a task similar to the one used by Schwarz, Weller, Klaffehn, and Pfister (2019), and measured the strength of intentional binding when participants are forced to select one out of two action options. The timing of action selection was free. Experiment 2 offers a test that compares the effects of partial autonomy (forced choice, free timing) and full personal autonomy (free choice, free timing) of action selection on the sense of agency. In Experiment 3 we compared partial autonomy with no autonomy during action selection by also restricting the timing of action. That is, participants were required to press a specific key immediately when they encountered a specific cue.

2. Experiment 1

2.1. Methods

2.1.1. Participants and design

Twenty-nine (18 females) volunteers with a mean age of 22 years ($M = 22.38$, $SD = 2.4$) participated in the study in return for course credit or a financial reimbursement. All participants gave written informed consent.

The experiment used a 2 (target: action vs. tone) \times 2 (type of trial: baseline vs. operant) within-subjects design. All experiments were approved by the Ethics Review Board of the Faculty of Social and Behavioral Sciences, Utrecht University as part of a project line (FETC approval code: 19–018). Power analyses for all experiments are reported in the Supplementary Materials.

2.1.2. Procedure

Participants were seated in front of a computer screen in a separate cubicle. After written informed consent was obtained, participants put on the headphones and began with the experiment. All instructions were provided on screen. The experiment was programmed in Eprime 2.0 and consisted of an adapted Libet clock task.

Two actions and two auditory stimuli were used in the experiment. The actions were a *x*-key press (left) and a *n*-key press (right) on a QWERTY keyboard. The auditory stimuli consisted of a low (300 Hz frequency) and a high (1000 Hz frequency) sinusoidal tone of 100 ms length each.

Learning phase. The experiment began with a learning phase to familiarize participants with the two actions and the two auditory stimuli. After an initial presentation of the key presses and the tones, the tones were repeated ten times in random order (i.e., five trials per tone) to allow participants to become acquainted with them. Subsequently, participants learned that each key was paired with one of the tones. Hence, each participant learned two key-tone pairs. The combination of the key-tone pairs (i.e., *left*-key and 1000 Hz and *right*-key and 300 Hz or *left*-key and 300 Hz and *right*-key and 1000 Hz) were counterbalanced across participants but remained stable per participant. In ten trials, participants pressed one of the keys, which was then followed by the paired tone.

Finally, participants were presented with the two learned as well as two novel (i.e., obtained by pairing a key with the tone of the respective other pair) key-tone pairs and had to correctly identify the learned and negate the novel pairs. Incorrectly answered trials were repeated. Participants could only commence with the experimental trials after correctly answering all trials.

Experimental trials (altered Libet clock trials). The experimental task was an altered Libet clock task as is conventionally used for assessing intentional binding (see also Antusch et al., 2019; 2020). Participants completed four randomized blocks (i.e., two baseline and two operant blocks). Each block consisted of 20 experimental trials and five practice trials, resulting in a total of 100 trials

per participant. Practice trials were indistinguishable from experimental trials but were discarded for the statistical analysis.

On each trial participants viewed a clock face that consisted of 40 grey dots, arranged in a circle from the center with a diameter of six cm. A black dot that moved at a speed of 2560 ms per rotation served as the clock hand. The initial position of the clock hand was determined randomly. Depending on the block, either one event (baseline blocks) or two successive events (operant blocks) occurred. On baseline blocks, participants either only pressed a key (baseline action) or heard a tone (baseline effect) while viewing the clock face and clock hand. In operant blocks, participants first pressed a key, which was followed by the paired tone 250 ms later. On all trials involving an action (all except for the baseline tone block), a visual brief message was presented in the center of the screen for 3000 ms before the clock face was presented. This message indicated which key (x or n) participants should press on a given trial, thus restricting participants in their choice of action options (Schwarz et al., 2019). Left and right key presses were distributed equally across trials (i.e., ten trials per key and block). Participants were instructed to wait with pressing the key until the clock hand had completed one full rotation. Thus, timing of action selection was free. In baseline effect trials, one of the tones was played at a randomly determined moment during the second rotation of the clock hand. Tones were distributed equally across trials (ten trials per tone).

The clock hand rotated further for 1000 ms after the last event before she disappeared. Subsequently, the mouse cursor and a prompt appeared in the center of the clock face. Participants' task was to indicate when the key press (baseline action and operant action trials) or the tone had occurred (baseline effect and operant effect trials). Participants gave their judgments by clicking on one of the dots of the clock face with the mouse cursor. Then, a new trial started. The inter-trial interval was equal to 1000 ms. See Fig. 1 for a visualization of an operant trial.

At the end of the experiment, participants provided their demographics, were thanked for their participation, reimbursed and debriefed.

2.2. Data analysis plan

Prior to the main analysis, temporal judgments more than one quarter (± 640 ms) away from the actual temporal onset were excluded from data analysis (0.43% of all trials; Aarts et al., 2012). Furthermore, judgments on trials in which participants pressed the wrong key or pressed a key multiple times were excluded (0.69% of all trials). Overall, the amount of trials excluded based on these criteria was small (1.02% of trials).

Based on the temporal judgments, mean estimates per block and participant were calculated. Subsequently, using these mean estimates, separate temporal shift scores for the action and the tone shift were calculated by subtracting the mean estimates of baseline trials from the mean estimates of operant trials (action shift = mean estimate in operant action trials – mean estimate in baseline action trials; tone shift = mean estimate in operant tone trials – mean estimate in baseline tone trials). Finally, overall binding scores were computed by subtracting the tone shift from the action shift (i.e., overall score = action shift – tone shift). Positive overall binding scores thus indicated temporal compression of the interval between action and effect (temporal binding) while negative scores were indicative of temporal repulsion. We hypothesized that intentional binding would emerge in a multiple forced action context (i.e., similar to the default condition of intentional binding research). To test this hypothesis, we subjected the overall binding scores to a one-tailed one-sample *t*-test against 0.

3. Results

The overall binding score ($M = 64.58$, $SD = 72$) was subjected to a one-tailed one sample *t*-test against zero. The results revealed a strong overall binding effect, $t(28) = 4.83$, $p < .001$, $d = 0.9$, 95% CI [0.46, 1.32]. Separate shifts for the key press and the tone are visualized in Fig. 2.

3.1. Experiment 2

In the first experiment, we tested a new task in our laboratory to assess the strength of intentional binding in a multiple action task where participants are forced to press one of two keys, and established that perceptual compression of the temporal interval between action and effect clearly emerged. Being ensured about the validity of our task, we set up a follow-up experiment aimed to replicate the findings obtained in the study of Schwarz et al. (2019). Specifically, participants had either partial autonomy (forced choice, free

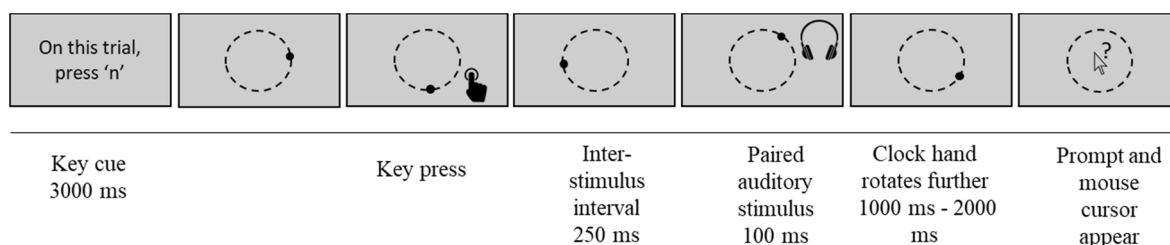


Fig. 1. Visualizations of an operant trial. The trial depicts a right key press (i.e., participants had to press the n-key).

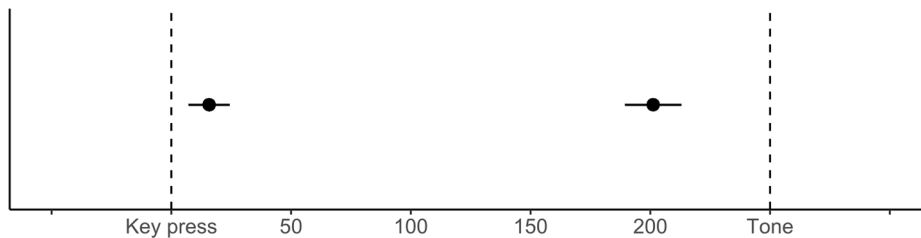


Fig. 2. Separate action and effect shifts in Experiment 1.

timing) or full autonomy (free choice and free timing) in action selection. Schwarz et al. (2019) found no difference between these two conditions on intentional binding, thus supporting a null effect. Accordingly, we anticipated no difference between partial and full autonomy on intentional binding. Because of the expected null effect, we tested our hypothesis using both, frequentist statistics and Bayesian, statistics.

4. Methods

4.1. Participants and design

Thirty-nine (29 females) volunteers with a mean age of 24 years ($M = 23.56$, $SD = 4.29$) participated in this study in exchange for course credit or a financial reimbursement. All participants provided written informed consent.

A 2 (target: key press vs. tone) \times 2 (type of trial: baseline vs. operant) \times 2 (autonomy: partial autonomy vs. full autonomy) within-subjects design was used.

4.2. Procedure

Participants were seated in front of a computer screen in a separate cubicle. After written informed consent was obtained, participants put on the headphones and began with the experiment. All instructions were provided on screen. The experiment was programmed in Eprime 2.0.

Learning phase. The experiment began with the same learning phase as in Experiment 1.

Experimental trials (altered Libet clock trials). Participants completed two within-subject conditions in counterbalanced order: the *partial autonomy* condition (resembling Experiment 1) and the *full autonomy* condition. Each condition consisted of the same four randomized blocks (baseline action, baseline effect, operant action and operant effect). Each block consisted of 25 trials (20 experimental plus five practice trials), resulting in 200 trials in total. The general set-up of trials and the parameters of the clock were identical to Experiment 1, differences are outlined below.

Different to Experiment 1, in the partial autonomy condition, when participants pressed a different key than the instructed key, the trial was aborted prematurely, and they received error feedback stating that they had pressed the wrong key to enforce the instructions. In the full autonomy condition, participants could freely choose which key to press and when to press it. Instead of receiving a cue which key to press on a trial, they read a reminder that they could press either of the keys. They were asked to try pressing each key equally often. A setup of a partial and full autonomy trial is depicted in Fig. 3.

4.3. Data analysis plan

As before, prior to the main analysis temporal judgments that were more than one quarter (± 640 ms) away from the actual temporal onset were excluded from data analysis (Aarts et al., 2012). Furthermore, also trials on which more than one key press was registered were excluded. Overall, the amount of trials excluded based on these criteria was small and very similar to the first experiment (1.52% of trials).

Subsequently, mean estimates per block and separate temporal shift scores for the action and the tone were calculated. Shift scores in both conditions were calculated using the same formula as in Experiment 1. Finally, overall binding scores for the separate conditions and for both conditions together were computed by subtracting the tone shift from the action shift (i.e., overall score = action shift - tone shift). Positive overall binding scores thus indicated temporal compression of the interval between action and effect (temporal binding) while negative scores were indicative of temporal repulsion.

After data preparation, we examined whether order of condition affected the intentional binding effects of the partial and full autonomy conditions. Next, for the sake of comparison with findings of Experiment 1, we assessed whether overall binding scores as well as the binding scores in the respective conditions were significantly different from zero. To that end, we conducted three one-tailed one-sample *t*-tests. We first tested the overall binding score against 0 with a one-tailed one-sample *t*-test to test whether intentional binding emerged in general and regardless of conditions. Then, to test whether binding occurred in binding score per condition against 0. Finally, we tested the main hypothesis with a two-tailed paired samples *t*-test and report whether temporal binding was different in the partial and full autonomy conditions. Additionally, to illustrate the strength of the evidence for the H_0 and to

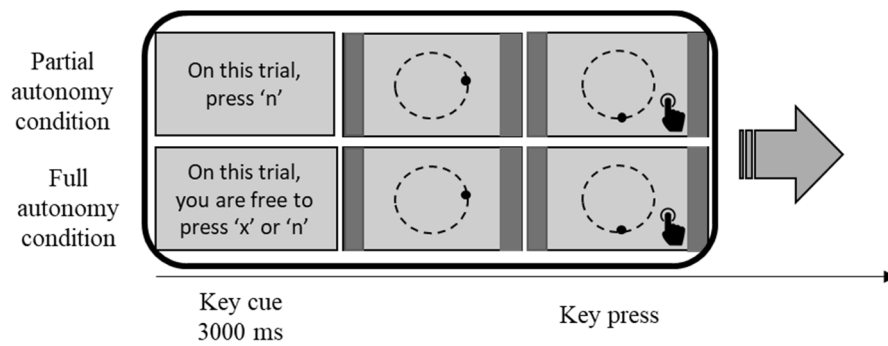


Fig. 3. Operant trials in the partial and full autonomy condition. The arrow indicates that the trial in the full autonomy condition proceeded identical to the partial autonomy condition.

confirm the frequentist analyses, equivalent Bayesian analyses were performed. A Bayesian paired samples *t*-test was conducted using JASP (JASP Team, 2019). As we had no knowledge about a possible prior distribution and the expected strength of the evidence, we chose to use the default Cauchy prior equal to 0.707. See Supplementary Materials for the robustness check.

5. Results

Influence of order. To rule out that the order in which participants completed the two within-subject conditions significantly influenced their temporal perception, we conducted a repeated measures ANOVA on the overall binding scores using choice condition as a within-subject factor and order as a between-subject factor. The results revealed no significant effects: main effect of choice condition, $F(1,37) = 0.059$, $p = .809$, $\eta^2 = 0.00$, 95% CI [0.00, 0.06] and interaction between choice condition and order, $F(1,37) = 1.374$, $p = .249$, $\eta^2 = 0.04$, 95% CI [0.00, 0.20].

Overall binding. The one-tailed *t*-test on the overall binding score revealed a significant temporal binding effect ($M = 70.08$, $SD = 108.83$), $t(38) = 4.021$, $p < .001$, $d = 0.64$, 95% CI [0.29, 0.99].

Binding in the separate conditions. To test if temporal binding emerged in both conditions, two separate one-tailed one-sample *t*-tests were conducted. Results revealed significant temporal binding in both conditions: partial autonomy condition ($M = 68.76$, $SD = 115.96$), $t(38) = 3.703$, $p < .001$, $d = 0.59$, 95% CI [0.25, 0.93] and full autonomy condition ($M = 71.39$, $SD = 114.95$), $t(38) = 3.878$, $p < .001$, $d = 0.62$, 95% CI [0.27, 0.96]. See Fig. 4 for a visualization of the separate shifts for the key press and the tone in the separate conditions.

Difference between conditions. A paired-samples *t*-test was conducted to assess the difference between partial and full autonomy conditions. The analyses showed that the difference between the partial autonomy condition ($M = 68.76$, $SD = 115.96$) and the full autonomy condition ($M = 71.39$, $SD = 114.95$) was not statistically significant, $t(38) = -0.212$, $p = .833$, two-tailed, $d_z = -0.03$, 95% CI [-0.23, 0.19].²

Finally, Bayesian paired-samples *t*-test revealed a BF_{01} equal to 5.627, 95% CrI [-0.33, 0.27], indicating moderate evidence for the null hypothesis.

6. Discussion

In Experiment 2, we tested how having participants freely select and time their action versus forcing them which action to execute but letting them freely decide on the timing affects intentional binding. Overall, we replicated the intentional binding effect found in Experiment 1. However, our results did not show an increase binding when participants were fully free in their choice over action selection and action timing. This null effect replicates earlier work (Schwarz et al., 2019), and was supported by frequentist tests and Bayesian tests. While our task differs from the task used by Schwarz et al. on a few features (e.g., different keys, different tones, different Libet clock), the absence of a difference appears rather robust. Apparently, then, having partial or full autonomy over action selection does not matter for peoples' sense of agency and the temporal perception between their actions and effects associated with them.

6.1. Experiment 3

So far, in the first two experiments action timing was free. Participants were able to enact their intended action at a self-chosen

² We inspected the data to see whether participants pressed the left or right key equally in the full autonomy condition (see Supplemental Materials). Only a few participants showed an inclination to (freely) press the same key more than 80% of the time. Excluding these participants did not change the results: The difference between partial autonomy ($M = 51.07$, $SD = 104.05$) and full autonomy ($M = 58.99$, $SD = 110.66$) was not significant, $t(33) = -0.584$, $p = .563$, two-tailed, $d_z = -0.10$, 95% CI [-0.32, 0.18].

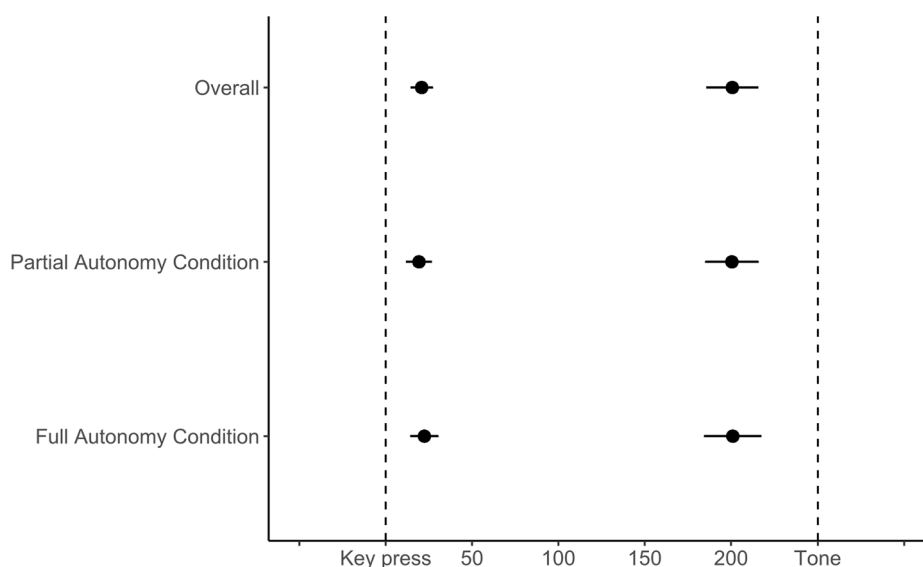


Fig. 4. Separate action and effect shifts collapsed over conditions and for the individual conditions in Experiment 2.

moment during the second rotation of the Libet clock. Note that such a self-chosen moment of action selection is typical in intentional binding studies (e.g., Haggard et al., 2002; Moore & Haggard, 2008; Ruess, Thomaschke, & Kiesel, 2017), suggesting that participants normally have at least partial autonomy. In Experiment 3 we therefore challenged participants' personal autonomy further by forcing them to press a specific key at a specified moment, namely when they encounter a cue on the screen. This way, autonomy over action selection is absent, as the type *and* moment of action execution is fully delegated to the environment. If personal autonomy is important for the sense of agency, then having no autonomy at all should reduce intentional binding compared to the conventional condition of partial autonomy in intentional binding research.

6.2. Methods

6.2.1. Participants and design

Forty-one (30 females) volunteers with a mean age of 21 years ($M = 21.46$, $SD = 2.7$) participated in this study in exchange for course credit or a financial reward. All participants provided written informed consent.

A 2 (target: key press vs. tone) \times 2 (type of trial: baseline vs. operant) \times 2 (autonomy: partial autonomy vs. no autonomy) within-subjects design was used.

6.2.2. Procedure

Participants were seated in front of a computer screen in a separate cubicle. After providing written informed consent, they put on the headphones and began with the experiment. All instructions were provided on screen. The experiment was programmed in Eprime 2.0.

Learning phase. The experiment began with the same general learning phase as was used in Experiments 1 and 2.

Experimental trials (altered Libet clock trials). Participants completed two counterbalanced within-subjects conditions: a *partial autonomy* condition (same as in Experiments 1 and 2) and a *no autonomy* condition. Each condition comprised the same four randomized blocks of 25 trials each (20 experimental and five practice trials). Trials and parameters of the clock resembled those in Experiments 1 and 2, and differences are outlined below.

In contrast to the first two experiments, we integrated the visual cue for action timing in the two vertical grey columns on the left and right side of the computer screen. Thus, in the new *no autonomy* condition, participants were not only instructed which key to press but also when exactly to press, namely at the moment that they saw the timing cue. The timing cue consisted of one of the vertical columns on the left or right side of the screen flashing up in white for 100 ms. The location of the cue (left or right) coincided with the instructed key (i.e., the left column flashed-up when the x-key should be pressed and vice versa for the n-key). Participants were instructed to press the key as soon as possible after the presentation of the cue. If participants pressed the wrong key or pressed before the presentation of the visual cue, the trial was aborted and they received error feedback.

As before, on operant trials the key press was followed by the paired tone at 250 ms. The clock hand then kept rotating for a random time interval between 1000 and 2000 ms before disappearing. Finally, participants estimated the temporal onset of either the key press or the tone and a new trial began. See Fig. 5 for a visualization of operant trials in the two conditions.

6.2.3. Data analysis plan

Like in the preceding experiments, excessive temporal judgments were excluded from the main analysis (0.20% of all trials).

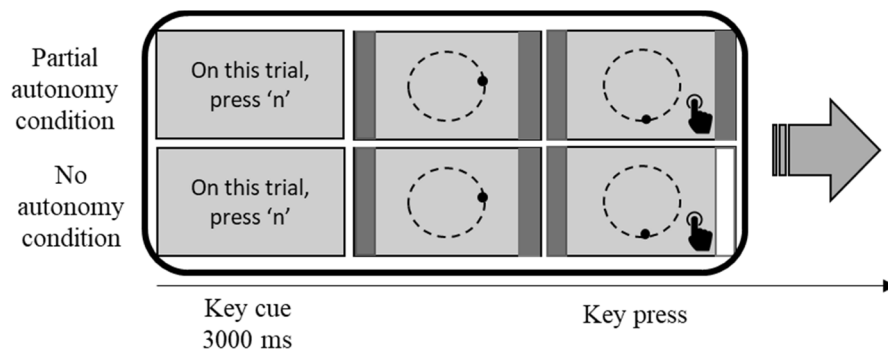


Fig. 5. Visualization of an operant trial in the partial autonomy condition and no autonomy condition. The timing cue of in the no autonomy condition is presented in white as part of the vertical column. The arrow indicates that the trials in both conditions proceeded in identical manner.

Moreover, trials on which participants pressed the wrong key or reacted too fast (before the presentation of the cue) or too slow (more than three standard deviations away from their mean reaction time) to the visual cue in the forced condition, were set to missing and excluded from data analysis (0.99% of all trials). The data of one participant who reacted slower (more than three standard deviations away from the group mean) than the average of the sample was entirely excluded from analysis. Mean estimates per block, separate temporal shift scores for the action and the tone, binding scores in the two within-subject conditions as well as overall binding scores were calculated using the same formulas as in Experiments 1 and 2.

Next, we performed a few checks. First, we examined whether order of condition affected the intentional binding effects of the partial and full autonomy conditions.³ We then tested whether the overall binding scores as well as the binding scores in the respective conditions were significantly different from zero. We therefore conducted three one-tailed one-sample *t*-tests. Finally, we tested whether temporal binding was different in the control partially instructed and the fully restricted condition with a two-tailed paired samples *t*-test. To assess the strength of the evidence, an equivalent Bayesian paired-samples *t*-test was conducted using JASP (JASP Team, 2019). We again used a Cauchy prior equal to 0.707. A robustness check is reported in the Supplementary Materials.

7. Results

Influence of order. To rule out that the order in which participants completed the two within-subject conditions significantly influenced their temporal perception, we conducted a repeated measures ANOVA on the overall binding scores using choice condition as a within-subject factor and order as a between-subject factor. The results revealed no significant effects. Neither the main effect of choice condition, $F(1, 38) = 0.277, p = .602, \eta^2 = 0.01, 95\% \text{ CI } [0.00, 0.13]$ nor the main effect of order, $F(1, 38) = 0.028, p = .869, \eta^2 = 0.00, 95\% \text{ CI } [0.00, 0.03]$ nor the interaction between choice condition and order, $F(1, 38) = 1.392, p = .245, \eta^2 = 0.04, 95\% \text{ CI } [0.00, 0.20]$, was significant.

Overall binding. To test whether participants showed an overall intentional binding effect (regardless of condition), we subjected the overall binding score to a one-tailed *t*-test against zero. Results revealed that the overall temporal binding of about 55 ms ($M = 54.64, SD = 83.41$) was highly significant, $t(39) = 4.143, p < .001, d = 0.66, 95\% \text{ CI } [0.31, 0.99]$.

Binding in the separate conditions. To test if temporal binding emerged in both conditions, two separate one-tailed one-sample *t*-tests were conducted. Results revealed significant temporal binding in both conditions: partial autonomy condition ($M = 49.63, SD = 99.27, t(39) = 3.162, p = .0015, d = 0.5, 95\% \text{ CI } [0.17, 0.83]$) and no autonomy condition ($M = 59.66, SD = 127.04, t(39) = 2.970, p = .0025, d = 0.47, 95\% \text{ CI } [0.14, 0.79]$). See Fig. 6 for a visualization of the separate shifts for the key press and the tone in the separate conditions.

Difference between conditions. A paired-samples *t*-test was conducted to assess the statistical significance of the difference between the extent of temporal binding in the within-subject conditions. The results suggested that the difference of roughly 10 ms ($M = 10.03, SD = 155.42$) between the conditions was not statistically significant, $t(39) = -0.408, p = .685, \text{ two-tailed}, dz = -0.06, 95\% \text{ CI } [-0.51, 0.36]$. A parallel Bayesian paired samples *t*-test was conducted to assess the strength of the evidence. The analysis revealed a BF_{01} equal to 5.42, 95% CrI $[-0.36, 0.24]$, indicating moderate evidence for the null hypothesis.

8. Discussion

In Experiment 3, we aimed to test whether further reduction of personal autonomy would decrease intentional binding. Therefore,

³ In the no autonomy condition we checked the speed of responding to the timing cue to ensure that participants did not wait too long but indeed pressed the key upon seeing the cue. For each participant we averaged response times across the three blocks that required participants to press an instructed key. On average, participants reacted to the cue in under 600 ms ($M = 578.55$), indicating that they responded fairly fast to the timing cue in the Libet clock set-up. There were no differences on reaction times between the three blocks, $F(2, 38) = 0.449, p = .642, \eta^2 = 0.02, 95\% \text{ CI } [0.00, 0.14]$.

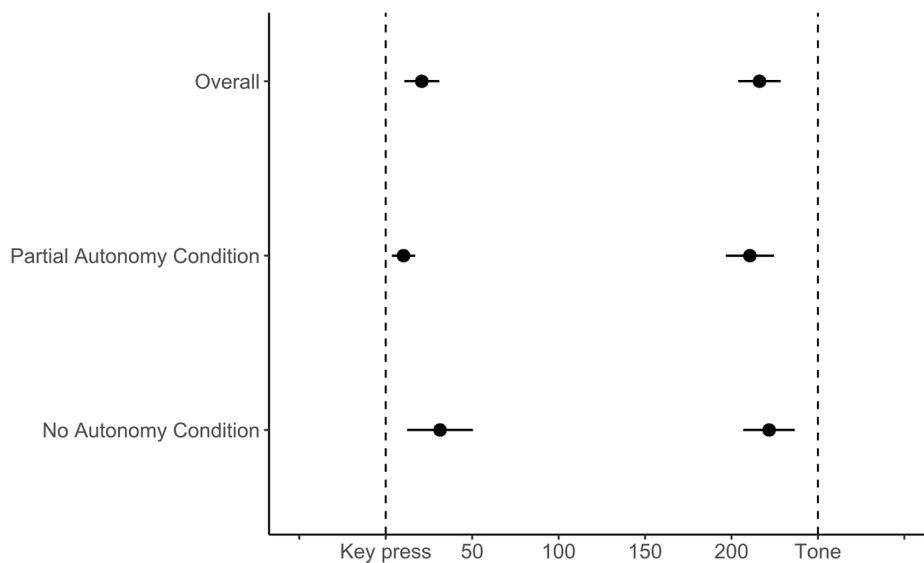


Fig. 6. Separate action and effect shifts collapsed over conditions and for the individual conditions in Experiment 3.

participants were not only instructed to press a specific key (like in the partial autonomy condition), but they also had to press at a designated moment in time, i.e. immediately when seeing an action timing cue. Both conditions of partial and no autonomy produced intentional binding effect and the strength of the effect did not differ. This null effect was corroborated by frequentist tests and Bayesian tests, suggesting that the absence of difference is likely not due to a Type 2 error. Thus, our findings suggest that even assigning the timing of action selection by the environment does not undermine the sense of agency, an effect that seems peculiar in light of the presumed importance of action choice and timing in research on personal autonomy and voluntary action. For a complete overview of the separate overall binding scores in each experiment and condition, please see Fig. 7.

Before concluding that personal autonomy does not affect the sense of agency over producing effects by own actions, as measured by the intentional binding task, we assured that the different objective (full, partial vs. no) autonomy conditions also install different psychological states in line with our manipulations. To this end, we conducted an additional study. We tested the operant blocks of the three respective conditions used in Experiments 1–3 (full, partial and no autonomy) and asked participants to report their subjective

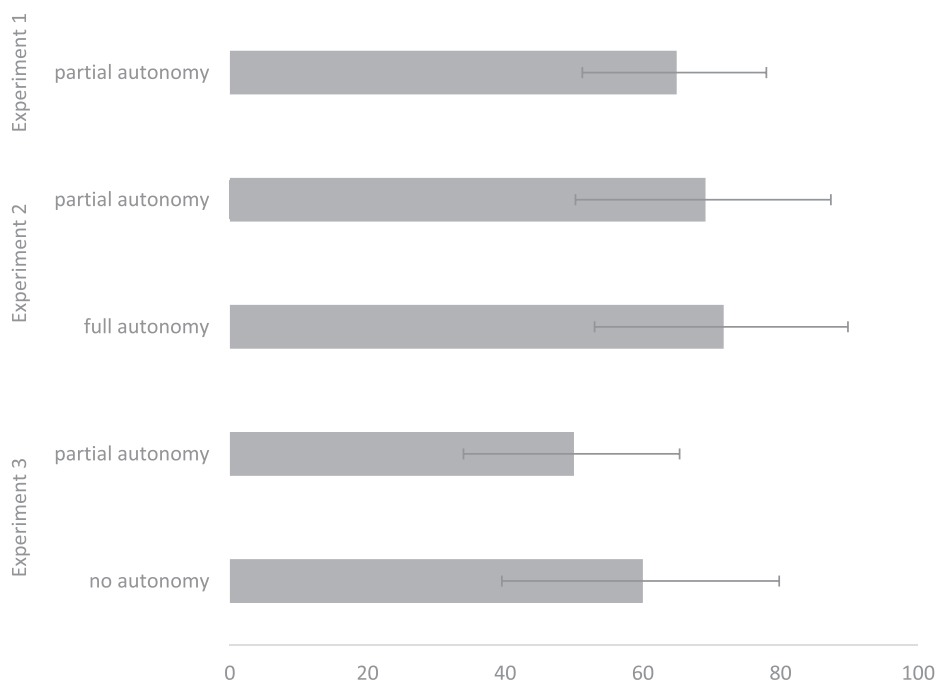


Fig. 7. Overall binding scores in ms per condition for Experiments 1–3. Error bars represent the individual standard errors.

experiences of autonomy in each condition. It may be expected that subjective experiences of autonomy over producing effects by own actions decrease when moving from full to partial and to no autonomy.

9. Experiment 4 : Extra check on the relation between objective and experienced autonomy

9.1. Methods

9.1.1. Participants and design

27⁴ (20 females) volunteers with a mean age of 24 years ($M = 23.89$, $SD = 3.95$) took part in the experiment in exchange for monetary reimbursement. The experiment used a 3 (condition: control vs. free vs. forced) $\times 3$ (autonomy parameter: control vs. choice vs. intentionality) within-subjects design.

9.1.2. Procedure

The task started with the general learning phase (Experiments 1–3). Next, participants completed two blocks: the operant action and the operant effect Libet clock trials, counterbalanced in order. Thus, each trial comprised a key press and a resulting tone. Because we were interested in the psychological experience of producing effects by one's own actions and not temporal perception, the experiment did not use baseline blocks. Each of the two operant blocks comprised three sub-blocks, also counterbalanced in order. The three sub-blocks corresponded to the three types of conditions: full, partial and no autonomy. Participants completed six trials in the operant action block and the operant effect block, resulting in a total of 36 trials (12 for each of the three autonomy conditions).

Like in Experiments 1–3, in each trial participants saw the clock face framed by two grey columns on the left and right of the screen. The trial then proceeded, depending on the condition (full, partial or no autonomy). At the end of each trial, participants answered three questions about their experience of autonomy: They indicated how much control (9-point Likert scale; 1 - *no control*, 9 - *a lot of control*), how much choice (9-point Likert scale; 1 - *no choice*, 9 - *a lot of choice*) and how much intentionality (9-point Likert scale; 1 - *not at all*, 9 - *a lot*) they experienced on a given trial. In sum, each item was measured 12 times in each condition.

At the end, participants filled in their demographics, were thanked and reimbursed for their participation.

9.1.3. Data analysis plan

Per condition, for each participant we averaged the 12 control, 12 choice and 12 intentionality items, separately. We then averaged the means for the three items into a measure of subjectively experienced autonomy for each condition (internal consistency – Cronbach's alpha – was 0.82, 0.84 and 0.92 for the full, partial and no autonomy conditions, respectively. Subsequently, the subjective measure of autonomy was subjected to a repeated measures ANOVA with condition (full, partial, or no autonomy) as within-subject variables. Pairwise comparisons were analysed to establish which conditions differed from each other.

10. Results and discussion

The repeated measures ANOVA revealed a significant main effect of condition, $F(2, 25) = 23.849$, $p < .001$, $\eta^2 = 0.91$, 95% CI [0.24, 0.94]. Pairwise comparisons showed that the subjectively experienced autonomy in the full autonomy condition ($M = 7.76$, $SD = 1.15$) was significantly higher than in the partial autonomy condition ($M = 7.03$, $SD = 1.24$), $p < .001$, and in the no autonomy condition ($M = 4.82$, $SD = 2.14$), $p < .001$.

These findings show that the objective situation of full autonomy was experienced as having relatively strong autonomy, while the objective situation of no autonomy substantially weakened the conscious experience of personal autonomy. Partial autonomy fell in between. Observing these differences is important as they clearly indicate that the autonomy conditions installed different psychological states. That is, having no autonomy led to weaker feelings of control, choice and intentionality, compared to having full or partial autonomy. Importantly, there is ample research showing that humans are deeply concerned with conditions of autonomy, and especially with the sheer lack of autonomy (e.g., Deci & Ryan, 2002). Taken these findings together, then, suggest that our participants cared about having full or no autonomy, even in our rather neutral experimental set up involving simple actions and tones.

11. General discussion

The present study aimed to address the relationship between personal autonomy and the sense of agency over causing one's actions and their effects in the external world. Specifically, we examined whether and how objective conditions of personal autonomy that undermine a person's intention affect intentional binding when the selection and timing of goal-directed action is forced or free. We thus compared conditions of no autonomy (forced action selection and timing), partial autonomy (forced action selection and free timing) and full autonomy (free action selection and timing). Our findings indicate that intentional binding was equally strong in all three conditions, suggesting that personal autonomy is unrelated to the sense of agency. Importantly, the three autonomy conditions clearly differed on subjectively experienced personal autonomy, showing that our participants were aware of and concerned about the autonomy restrictions implemented in the task. These findings concur with recent work by Schwarz et al. (2019), who showed that full

⁴ We originally aimed for a sample of 30 participants, however, the data of three participants was lost due to technical problems.

and partial autonomy significantly differed on explicit measures of control, but not intentional binding as assessed with the Libet clock. The present study extends this work by showing that no autonomy does reduce the conscious experience control further without affecting intentional binding.

Our findings seem to contradict other research on forced and free action selection and timing. [Wenke and colleagues \(2009\)](#), for example, found reduced intentional binding when participants had partial autonomy compared to no or full autonomy. They offered a metacognitive account to explain these effects, according to which individuals establish a more fluent experience of behavior when actions result from a single (versus different) mode of selection. While this account seems plausible, a closer look at the experimental procedure suggests a crucial difference with our procedure. Specifically, in the no autonomy condition participants were instructed to select one key response over the other, but were instructed to press the key somewhere in the second rotation. In other words, participants were forced to press the key in a specified time window but had to wait and then press the key at a preferred moment in time. Accordingly, action timing in this condition could be construed as free rather than forced, resembling our partial autonomy condition that is typical for most intentional binding research (e.g., [Haggard et al., 2002](#); [Moore & Haggard, 2008](#); [Ruess et al., 2017](#)). Furthermore, when action selection was forced and timing was free (identical to our partial autonomy condition), [Wenke and colleagues](#) found less binding compared to when having full autonomy of action selection and timing, which differs from our results. As such, our findings concur with those of [Schwarz et al. \(2019\)](#), who did not find differences in intentional binding between partial and full autonomy. These puzzling findings raise the question whether autonomy is relevant for the sense of agency.

To answer this question, we might need to consider the study of personal autonomy in the context of the bigger picture of intentional binding research. First, it is important to note that the forced timing component in our no autonomy condition was operationalized as an environment-controlled action that leaves not much room for free timing, as participants had to immediately respond to a timing cue. Whereas this externally induced action timing did not affect intentional binding, other studies seem to do. For example, initial research on intentional binding comparing free action timing with involuntary action induced by TMS, demonstrated that taking autonomy away from the individual also eradicates the sense of agency, resulting in temporal repulsion instead of binding. In line with this, we found additional evidence for repulsion effects when participants received action-related sensory input (tactile stimulation on the finger that will cause a predicted effect), ruling out the possibility to internally select and execute the action ([Antusch et al., under review](#)). Slightly different results are reported for the actual execution of actions that are externally induced by pressing the finger of a participant on a key to cause an effect ([Borhani et al., 2017](#); [Dogge et al., 2012](#)). Temporal binding in these situations is significantly decreased, and effects are much smaller than when the action is voluntary. In short, externally triggered actions seem to abolish or even reverse binding, indicating that such behaviors are not accompanied by the sense of agency. Why, then, did our condition in which action timing was externally triggered fail to reduce the sense of agency?

One plausible explanation pertains to the distinction between habits and goal-dependent behavior. Habits are conceptualized as responses to external cues that do not depend on the instigation of a goal. Habits are therefore difficult to change as the environment directly triggers them without the mediation of intentional control (e.g., [Aarts, Paulussen, & Schaalma, 1997](#); [Wood & Rünger, 2016](#)). Research on cognitive neuroscience indicates that a genuine habit is implemented by the sensorimotor striatum loop that corresponds to bottom-up action selection, while goal-dependent behavior is implemented by the cortico-basal ganglia loop that corresponds to deliberation and planning ([Yin & Knowlton, 2006](#)). In doing so, habits represent an instance of no autonomy, and it is plausible that the full absence of intentions in controlling action selection considerably weakens the sense of agency.

However, it is important to note that, in experimental research on human habits, researchers commonly employ task instructions that serve as goals to map stimuli to responses, and to provide context to the task. Therefore, what seems to look like a habit actually is a goal-directed action that is under intentional control ([Marien, Custers, & Aarts, 2019](#)). This may explain why we did not find an effect of no autonomy on intentional binding, because even when participants responded directly to external cues, the action was internally selected as part of the general goal of the task. These findings concur with a study by [Wang and colleagues \(2017\)](#). Combining the Simon-task with an intentional binding task, they instructed participants to press a left or right key to produce a tone. Key presses were triggered by auditory cues that were congruent or incongruent with the spatial location of the cue. Thus, action was more stimulus-based (in congruent trials) and intention-based (in incongruent trials). They found no differences on intentional binding. These findings indicate that while action selection and timing were stimulus-based, there was room to represent the sensory effects and to internally select the action to produce them. Finding binding in such a goal-directed behavior context suggests that endowing individuals with ‘minimal autonomy’, i.e. an agent’s ability to internally start up motor processes in response to a cue in order to achieve a goal at hand, is sufficient for agency experiences to emerge ([Dogge, Custers, & Aarts, 2019](#); [Passingham, Bengtsson, & Lau, 2010](#)). This fits well with the compatibilism view on free will and determinism (e.g., [Dennett, 2004](#); [Frankfurt, 1971](#); [Gallagher, 2000](#); [Korsgaard, 2009](#)), which emphasizes the opportunity for individuals to live in accordance with one’s personal goals and values as the key dimension of autonomy.

The analysis of the role of personal goals and values in the sense of agency may have implications for understanding when personal autonomy undermines the sense of agency. The effects of a lack of autonomy might be more profound when a person has to act against her own will. As we addressed above, this issue relates to the force of habit, in which a person intends to do A and then the environment triggers action B. However, acting against one’s will may also be part of a pervasive social context. Initial evidence for such attenuation of the sense of agency comes from [Takahata and colleagues \(2012\)](#). Their findings documented that when participants had no autonomy over their actions, binding decreased when the action-effect was punishing them (monetary loss) rather than rewarding them (monetary gain) or neutral. Remarkably, whereas participants could not anticipate the identity of the effect and had no autonomy over selecting their actions on any of the trials, there was no difference in binding for neutral and positive action-effects. This suggests that a lack of autonomy does not affect the sense of agency when action-effects are aligned with desirable goals (e.g., earning money) but only when desirable goals are violated (losing money).

Further insight showing that social pressure can act as a powerful situation to undermine the sense of agency comes from a recent study on coercion. Caspar and colleagues (2016) showed that intentional binding is weakened when participants have to punish another person. These findings give reason to suggest that the sense of agency diminished when undermining people's autonomy over selecting their action and forcing them to act against moral standards. Milgram (1974) coined this dramatic obedience effect as *agentic shift*, – the tendency to relinquish personal control to an external agent. Accordingly, whereas forcing people to select and time their action to achieve desirable goals leaves the sense of agency intact, forcing them to act against their goal challenges it. This interplay between autonomy over goals and actions with respect to the (implicit) sense of agency is somewhat speculative, and more research is needed to further examine how various levels and degrees of autonomy attenuate agentic experiences. Our findings may serve as a starting point for this, offering new insights that stimulus-based action selection does not suffice to reduce intentional binding as a proxy for the sense of agency and hence, to undermine people's belief to be the author of their own behavior.

Funding

No external funding was received.

Author contributions

S.A., R.C. and H.A. conceived the idea and planned the experiment. S.A. programmed the experiment, supervised data collection and analyzed the data. H.M. aided in programming. S.A. interpreted the data. S.A. drafted the manuscript, S.A. and H.A. wrote the final manuscript with input from all authors.

Acknowledgements

The authors thank Tara Tešanovic for her help in recruiting and testing participants for Experiment 2.

References

- Aarts, H., Bijleveld, E., Custers, R., Dogge, M., Deelder, M., Schutter, D., & van Haren, N. E. (2012). Positive priming and intentional binding: Eye-blink rate predicts reward information effects on the sense of agency. *Social Neuroscience*, 7(1), 105–112.
- Aarts, H., Paulussen, T., & Schaalma, H. (1997). Physical exercise habit: On the conceptualization and formation of habitual health behaviours. *Health Education Research*, 12(3), 363–374.
- Antusch, S., Custers, R., Marien, H., & Aarts, H. (2020). Intentionality and temporal binding: Do causality beliefs increase the perceived temporal attraction between events? *Consciousness and Cognition*, 77, Article 102835.
- Antusch, S., Custers, R., Marien, H., & Aarts, H. (under review). Sense of Agency in the Absence of Motor Movement: An Investigation into Temporal Binding of Tactile Sensations and Auditory Effects.
- Barlas, Z., & Obhi, S. (2013). Freedom, choice, and the sense of agency. *Frontiers in Human Neuroscience*, 7, 514.
- Borhani, K., Beck, B., & Haggard, P. (2017). Choosing, doing, and controlling: Implicit sense of agency over somatosensory events. *Psychological Science*, 28(7), 882–893.
- Brass, M., & Haggard, P. (2008). The what, when, whether model of intentional action. *The Neuroscientist*, 14(4), 319–325.
- Caspar, E. A., Christensen, J. F., Cleeremans, A., & Haggard, P. (2016). Coercion changes the sense of agency in the human brain. *Current Biology*, 26(5), 585–592.
- Caspar, E. A., Vuillaume, L., De Saldanha, Magalhães, da Gama, P. A., & Cleeremans, A. (2017). The influence of (dis) belief in free will on immoral behavior. *Frontiers in Psychology*, 8, 20.
- Damen, T. G., Van Baaren, R. B., Brass, M., Aarts, H., & Dijksterhuis, A. (2015). Put your plan into action: The influence of action plans on agency and responsibility. *Journal of Personality and Social Psychology*, 108(6), 850.
- Deci, E. L., & Ryan, R. M. (2002). Overview of self-determination theory: An organismic dialectical perspective. *Handbook of self-determination research*, 3–33.
- Dennett, D. C. (2004). *Freedom evolves*. Penguin UK.
- Dogge, M., Custers, R., & Aarts, H. (2019). Moving forward: On the limits of motor-based forward models. *Trends in Cognitive Sciences*, 23(9), 743–753.
- Dogge, M., Schaap, M., Custers, R., Wegner, D. M., & Aarts, H. (2012). When moving without volition: Implied self-causation enhances binding strength between involuntary actions and effects. *Consciousness and Cognition*, 21(1), 501–506.
- Frankfurt, H. (1971). Freedom of the Will and the Concept of a Person. *Journal of Philosophy*, 68.
- Gallagher, S. (2000). Philosophical conceptions of the self: Implications for cognitive science. *Trends in Cognitive Sciences*, 4(1), 14–21.
- Haggard, P., Clark, S., & Kalogeras, J. (2002). Voluntary action and conscious awareness. *Nature Neuroscience*, 5(4), 382–385.
- Korsgaard, C. M. (2009). *Self-constitution: Agency, identity, and integrity*. OUP Oxford.
- Iwatsuki, T., Shih, H. T., Abdollahipour, R., & Wulf, G. (2019). More bang for the buck: Autonomy support increases muscular efficiency. *Psychological Research Psychologische Forschung*, 1–7.
- JASP Team (2019). JASP (Version 0.10.2)[Computer software].
- Koestner, R. (2008). Reaching one's personal goals: A motivational perspective focused on autonomy. *Canadian Psychology/Psychologie Canadienne*, 49(1), 60.
- Marien, H., Custers, R., & Aarts, H. (2019). Studying Human Habits in Societal Context: Examining Support for a Basic Stimulus-Response Mechanism. *Current Directions in Psychological Science*, 28(6), 614–618.
- Milgram, S. (1974). *Obedience to authority: An experimental view*. New York, NY: Harper & Row.
- Moore, J., & Haggard, P. (2008). Awareness of action: Inference and prediction. *Consciousness and Cognition*, 17(1), 136–144.
- Moretto, G., Walsh, E., & Haggard, P. (2011). Experience of agency and sense of responsibility. *Consciousness and Cognition*, 20(4), 1847–1854.
- Passingham, R. E., Bengtsson, S. L., & Lau, H. C. (2010). Medial frontal cortex: From self-generated action to reflection on one's own performance. *Trends in Cognitive Sciences*, 14(1), 16–21.
- Pfister, R., Kiesel, A., & Hoffmann, J. (2011). Learning at any rate: Action–effect learning for stimulus-based actions. *Psychological Research Psychologische Forschung*, 75(1), 61–65.
- Ruess, M., Thomaschke, R., & Kiesel, A. (2017). The time course of intentional binding. *Attention, Perception, & Psychophysics*, 79(4), 1123–1131.
- Ryan, R. M., & Deci, E. L. (2006). Self-regulation and the problem of human autonomy: Does psychology need choice, self-determination, and will? *Journal of Personality*, 74(6), 1557–1586.
- Schwarz, K. A., Weller, L., Klaffehn, A. L., & Pfister, R. (2019). The effects of action choice on temporal binding, agency ratings, and their correlation. *Consciousness and Cognition*, 75, Article 102807.
- Synofzik, M., Vosgerau, G., & Newen, A. (2008). Beyond the comparator model: A multifactorial two-step account of agency. *Consciousness and Cognition*, 17(1), 219–239.
- Takahata, K., Takahashi, H., Maeda, T., Umeda, S., Suhara, T., Mimura, M., & Kato, M. (2012). It's not my fault: Postdictive modulation of intentional binding by monetary gains and losses. *PLoS ONE*, 7(12).

- Tanaka, T., & Kawabata, H. (2019). Sense of agency is modulated by interactions between action choice, outcome valence, and predictability. *Current Psychology*, 1–12.
- Tanaka, T., Matsumoto, T., Hayashi, S., Takagi, S., & Kawabata, H. (2019). What Makes Action and Outcome Temporally Close to Each Other: A Systematic Review and Meta-Analysis of Temporal Binding. *Timing & Time Perception*, 7(3), 189–218.
- Obhi, S. S., & Hall, P. (2011). Sense of agency and intentional binding in joint action. *Experimental Brain Research*, 211(3–4), 655.
- Wang, Y., Damen, T. G., & Aarts, H. (2017). Uncovering effects of self-control and stimulus-driven action selection on the sense of agency. *Consciousness and Cognition*, 55, 245–253.
- Wenke, D., Waszak, F., & Haggard, P. (2009). Action selection and action awareness. *Psychological Research PRPF*, 73(4), 602–612.
- Wood, W., & Rünger, D. (2016). Psychology of habit. *Annual Review of Psychology*, 67, 289–314.
- Yin, H. H., & Knowlton, B. J. (2006). The role of the basal ganglia in habit formation. *Nature Reviews Neuroscience*, 7(6), 464–476.
- Yoshie, M., & Haggard, P. (2013). Negative emotional outcomes attenuate sense of agency over voluntary actions. *Current Biology*, 23(20), 2028–2032.