Intentional binding as Bayesian cue combination: testing predictions with trait individual differences

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Abstract

We investigated differences in intentional binding in high and low hypnotisable groups to explore two questions relating to (i) trait differences in the availability of motor intentions to metacognitive processes and (ii) a proposed cue combination model of binding. An experience of involuntariness is central to hypnotic responding, and may arise from strategically being unaware of one's intentions. Trait differences in the ability to respond to hypnotic suggestion may reflect differing levels of access to motor intentions. Intentional binding refers to the subjective compression of the time between an action and its outcome, indicated by a forward shift in the judged time of an action toward its outcome (action binding) and the backward shift of an outcome toward a causal action (outcome binding). Intentional binding is sensitive to intentional action without requiring explicit reflection upon agency. One way of explaining the sensitivity of intentional binding is to see it as a simple case of multisensory cue combination in which awareness of intentions increases knowledge of the timing of actions. Here we present results consistent with such a mechanism. In a contingent presentation of action and outcome events, low hypnotisables had more precise timing judgements of actions and also showed weaker action binding than highs. These results support the theory that trait hypnotisability is related to access to information related to motor intentions, and that intentional binding reflects the Bayesian combination of cross-modal cues.

Keywords: Bayesian modelling; Hypnosis; Hypnotisability; Intentional binding; Sense of agency; Volition

Public significance statement

The sense of agency is the experience of authorship over one’s actions and their outcomes in the world (which may differ from actual authorship of action and outcomes). It is often measured using the intentional binding effect - a compressed time interval between an action and its outcome. However, the mechanism driving this effect is unknown. Here we present evidence that binding arises from the combination of action and outcome timing cues and propose a mechanism by which its relationship to agency and intention may be explained.

The cold control theory of hypnosis proposes that experiences of involuntariness for voluntary actions in response to suggestion reflect lack of awareness for intentions. We report differences consistent with this theory; highly hypnotisable people have more variable reports of the timing of an action than low hypnotisable people, which may reflect differences in access to unconscious intentions.

Introduction

The sense of agency is the experience we have of controlling our actions and their outcomes (Haggard & Chambon, 2012). The experience of agency supports attributions of responsibility, and therefore is of central importance to the structures that support social functioning (Moore, 2016; Haggard, 2017; Caspar, Cleeremans & Haggard, 2015). Current theoretical models propose that sense of agency is generated from the integration of multiple sources of information (e.g., internal motor cues and external contextual cues), with the relative influence of each source weighted by the precision of the information concerning each cue (Moore, Wegner & Haggard, 2009; Synofzik, Vosgerau & Lindner, 2009). Disruptions of the sense of agency occur in psychiatric disorders (e.g., in schizophrenia) and neurological disorders (e.g. corticobasal syndrome), and such disorders have been attributed to the malfunctioning of integration mechanisms (Moore & Fletcher, 2012).

Research on sense of agency can measure explicit judgements of agency, such as asking whether or to what degree a particular action or outcome is associated with an experience of agency (e.g., Wegner & Wheatley, 1999). Alternatively, implicit measures that require no reflection upon agency can be used, of which the intentional binding effect is the most commonly employed. Intentional binding refers to the compression of the perceived interval between the reported times of actions and their outcomes (Haggard, Clark & Kalogeras, 2002). The effect is generally considered an implicit measure of sense of agency because the magnitude of binding is reduced in unintended actions (for reviews see Moore & Obhi, 2012; Wolpe & Rowe, 2014). However, temporal binding of actions and outcomes also occurs in the timing of merely observed events, providing a causal relationship is inferred. In this light, intentional binding is perhaps best understood as the effect of information relating to an intention to perform an action (motor intention) on the magnitude of temporal binding over and above causal binding (Buehner, 2012, 2015). However, it is important to note that differences in intentional binding do not necessarily relate to intention or sense of agency (Suzuki et al, 2018).

Intentional binding can be measured by deriving intervals between the reported time of an action and outcome event from the difference in the reported time of action and outcome events when the outcome is contingent upon the action (contingent conditions) or when either event occurs in isolation (baseline conditions) (Haggard, Clark & Kalogeras, 2002). Measured in this way, intentional binding can be seen as consisting of two opposing shifts in the reported times between baseline and contingent conditions: a forward shift of action-timing judgements towards the time of the outcome event (action binding), and a backward shift of outcome-timing judgements towards the time of the action event (outcome binding). Binding may arise because of a prior belief that button presses and outcomes occur at almost the same time; thus, the estimate of the time of the one event carries information about the time of the other event, and, on this assumption, the timing estimates of each may be usefully combined. That is, temporal binding between an action and its outcome may arise from a *cue combination* mechanism in which the timing estimate reported for either action or outcome events is a precision weighted average of the two events (Kawabe, Roseboom & Nishida, 2013; Wolpe, Siebner & Rowe, 2013) (with a small offset given by prior belief; Ernst & Di Luca, 2011; Roach, Heron & McGraw, 2006). See Figure 1 for a visual representation of the influence of relative action/outcome precision on timing judgements and apparent temporal binding effects. Such a mechanism predicts that a relatively high precision of timing judgements of either event will have opposing effects on action and outcome binding components. For example, if precision of action event timing judgements is relatively low (Figure 1, middle row), in the contingent condition (in which the action causes the outcome) timing judgements of action and outcome events will be drawn towards the time at which the outcome occurs, leading to a relatively small magnitude of the shift in perceived timing of the outcome toward the time of action occurrence (outcome binding) and a relatively large magnitude of the shift in perceived time of the action towards the time of outcome presentation (action binding). Conversely, relatively high precision of action event timings in contingent conditions (Figure 1, bottom row) will result in both action and outcome event timing judgements which are drawn towards to the actual time of action, so that the magnitude of action binding will be relatively small and that of outcome binding relatively large. Therefore, any individual differences in the availability of information that affects the relative precision of action timing judgements (e.g., motor intentions) should be reflected in intentional binding with opposing effects on action and outcome binding (Lush & Dienes, 2018). Here we propose a theory about how precision weighting influences temporal estimates; how those temporal estimates relate to agency is an additional question. For example, awareness of intentions is associated with a sense of agency; if awareness of intentions increases action precision, it will decrease action binding. Thus, this theory is a different from (but related to) theories postulating that the sense of agency is a precision weighted combination of different cues to agency (Moore, Wegner & Haggard, 2009; Synofzik, Vosgerau & Lindner, 2009).

A non-pathological case of disruption to sense of agency occurs in response to hypnotic suggestion (Polito, Barnier & Woody, 2013). Successful hypnotic responding requires that the participant responds to an imaginative suggestion to form a non-veridical experience of the world or the self. The experience of involuntariness (the classical suggestion effect of hypnosis; Weitzenhoffer, 1980) is the central feature of such responding. For example, in a hypnotic context (following a hypnotic induction) a successful response to an imaginative suggestion to experience one’s arm lifting as though tied to an invisible balloon can result in the subject raising their arm. While participants must have voluntarily raised their arm, they report experiencing the action as involuntary. Such responding is not rare - over 70 % of the population typically respond successfully to a suggestion to perform a motor action ('ideomotor suggestion') of this type (Magalhães de Saldanha da Gama, Davy & Cleeremans, 2012).

The cold control theory of hypnosis argues that the experience of involuntariness in hypnotic suggestion arises from the strategic unawareness of intentions (Dienes, 2012). Successful response to a hypnotic suggestion requires two, separate, intentions. First, the intention to respond hypnotically at all (White, 1941), which may be conscious (but not need be), and second the specific intention used for a specific suggestion, e.g. "arm rise!", which must be unconscious for the experience to be hypnotic. While to some authors 'strategic' is ipso facto 'conscious' (e.g. Jacoby, Lindsay, & Toth, 1992), there is evidence that strategic control can be implemented without being aware of relevant mental states (e.g. Dienes et al, 1995; Lau & Passingham, 2007; Norman et al 2019; Van Gal et al, 2010). On this basis, a highly hypnotisable could consciously try to have a hypnotic experience, but not know how they achieved it – for example, because the intention implementing the strategy was itself unconscious.

Therefore, a successful response to a hypnotic suggestion involves performing an intentional act but, through being unaware of the intention, experiencing the act as unintentional. That is, hypnotic responding involves reflecting upon whether or not an act is intentional and is therefore essentially a metacognitive phenomenon. There is evidence that the experience of involuntariness over motor actions in successful response to an imaginative suggestion of involuntariness (within a hypnotic context) is related to a reduction of action intention related information in timing judgements: Specifically, a post-hypnotically induced experience of involuntariness is accompanied by (a) judgements of action timing that are closer to the time of action than normal action judgments (Haggard, Cartledge, Dafydd & Oakley, 2004); (b) an increase in the variability of action timing judgements and (c) a reduction in the outcome binding component of intentional binding (Lush et al, 2017; for a review of time judgements in hypnosis and hypnotisability see Lush & Dienes, 2019). Intentions of which one is aware rather than unaware may have properties more accessible to further processing (e.g., Cleeremans & Jimenez, 2002); for example, conscious intentions plausibly afford greater precision in the estimation of the timing of intentional actions.

Hypnotisability can be measured by response to suggestion on standardised scales following hypnotic induction (hypnosis screening; for reviews see Laurence, Beaulieu-Prévost & Du Chéné, 2008; Woody & Barnier, 2008; Terhune & Cardena, 2016). Measured in this way, hypnotisability can be considered a relatively stable trait, with strong test-retest reliability over a 25-year period (Piccione, Hilgard & Zimbardo, 1989). Typically, participants are divided into low hypnotisable (e.g., the lowest 10% of scores) and high hypnotisable groups (e.g., the highest 10% of scores) based on their recorded responses to a hypnosis screening. According to cold control theory, individual differences in trait hypnotisability should reflect individual differences in the ability to generate and maintain inaccurate metacognition of intentions (we employ the term metacognition in a broad sense to describe a cognitive process which is directed at or 'about' another cognitive process). Recent evidence supports the theory that an ability to generate and sustain an experience of involuntariness reflects a trait for relatively low access to intentions; thus, high hypnotisables report later awareness of motor intentions than medium or low hypnotisables (Lush, Naish & Dienes, 2016). Furthermore, they are less sensitive to disruptions of control when forming judgements of agency in a task designed to measure metacognition of sense of agency (Terhune & Hedman, 2017).

Here we investigate the relationship between trait hypnotisability and intentional binding to investigate both predicted trait differences in metacognition of intentions and predictions arising from a cue combination model of intentional binding. We predict that lower metacognitive access to intentions in high hypnotisables will be reflected in decreased within-participant precision of action timing judgements and consequently reduced outcome binding and increased action binding relative to low hypnotisables. Because we do not expect high and low hypnotisables to differ in the precision of outcome judgements, we also predict that action judgements will account for more of the total precision across both types of judgement in lows than in highs. Finally, in accordance with a cue combination mechanism for binding, we predict that the percentage of total precision which accounts for action binding should be negatively related to action binding and positively related to outcome binding.

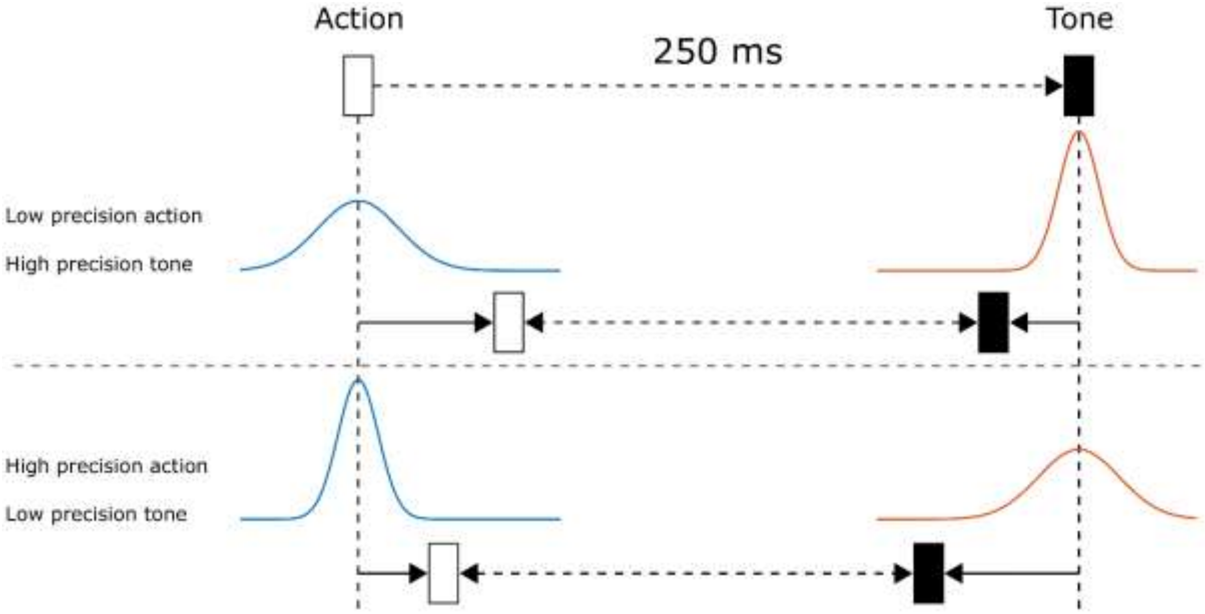

Figure 1. Predictions of a cue combination model of intentional binding. The top row shows actual timing of action and outcome events. The bottom two rows show, schematically, judged time of action and outcome events (white and black blocks, respectively) when action or outcome precision (indicated by width of curves) are relatively high. When precision of action event timing judgements is relatively low, action binding is relatively high (middle row). When precision of action event timing judgements is relatively high, action binding is relatively low (bottom row).

Method

Participants

In total, there were 70 participants (35 highly hypnotisable and 35 low hypnotisable). Fifty-seven participants were recruited following screening on the Sussex Waterloo Scale of Hypnotisability (SWASH; Lush, Moga, McLatchie & Dienes, 2018). Of these, 28 participants were highly hypnotisable (5 males and 23 females, mean age = 19.3 years, *SD* = 1.9) and 30 were low hypnotisable (2 males and 28 females, mean age = 20.5 years, *SD* = 5.3). Thirteen participants were recruited (in an earlier year) following screening on the Waterloo-Stanford Group Scale of Hypnotisability (WSGC; Bowers, 1993). Of these, 7 participants were highly hypnotisable (2 males and 5 females, mean age = 20.3 *SD* = 1.8) and 6 were low hypnotisable (2 males and 4 females, mean age = 21.5, *SD* = 2.8).

For WSGC screened participants, high hypnotisables were selected for scores of 8 or above (which was the top 3.5% of the 202 screened) out of a maximum of 12 (*M* = 9.1, *SD* = .9) and low hypnotisables for scores of 1 or 0 (*M* = .7, *SD* = .5). WSGC screened low hypnotisable participants were selected for scores of 1 or below (6% of the sample). For SWASH-screened participants, combined subjective and objective hypnotisability scores (the simple mean of the objective and subjective scores, each scaled out of a maximum of 10) were used to identify high and low hypnotisable participants. There was a minimum cut-off of 5.5 (which was the top 10% of 418 screened) for the highly hypnotisable group (*M* = 6.5, *SD* = .8). The low hypnotisable group (*M* = 1.3, *SD* = .6) scored 2 or below (16% of SWASH scores lie below 2).

Ethical approval was received from the University of Sussex ethical committee and informed consent was obtained. Participants received cash payment of £7 or course credits.

As in Lush et al (2017), participants were recruited for the duration of four academic years (1 year for WSGC screened participants and 3 years of SWASH screening), until there were no more responses.

Procedure (Adapted From Lush, Parkinson & Dienes, 2016 and Lush et al, 2017)

No power analysis was conducted. We included Bayes factors so that there would be an assessment of the sensitivity of the data to distinguish H0 and H1. Once the data are in, power has no relevance to how sensitive the data are, because power is a property of decision rule in the long run; conversely, Bayes factors indicate the sensitivity of the very data collected to distinguish H1 and H0.

See Figure 2 for a pictorial representation of the task. Visual stimuli were displayed at 100 Hz on a 21-in. CRT monitor and auditory stimuli were presented via Sennheiser headphones. For each trial, a clock face was presented, marked at thirty-degree intervals and subtended a visual angle of five degrees. A static dot, subtending at 0.2°, appeared at a pseudo-randomised position and began rotating around the clock 250 ms later (at 2560 ms per revolution). Participants were seated at a viewing distance of approximately 60 cm. A computer keyboard was used to record actions (button presses).

There were four trial types, presented in separate blocks. In contingent trials the button caused the tone and participants reported either the time of the action (contingent action judgements) or the time of the tone (contingent tone judgements). In baseline trials the button did not cause a tone and participants reported either the time of the button press (baseline action judgements) or the time of a tone (baseline tone judgements). Therefore participants pressed the button in each type of trial except in baseline tone trials. The four different types of judgement are used to generate the binding measures. Action binding (the shift of judged action timing towards the time of the outcome tone) is calculated from the difference between baseline action judgements and contingent action judgements. Outcome binding (the shift of judged outcome timing towards the time of action) is calculated by the difference between baseline tone judgements and contingent tone judgements.

Text instructions as to which event to report (action or tone, see below) were delivered on screen at the beginning of each block and before each trial. In contingent trials, pressing a key triggered a 1000 Hz, 100 ms duration pure tone after a 250 ms delay. Participants were asked to look at a fixation cross in the centre of the clock and to wait for at least one revolution before pressing the button at a time of their choosing. The trial was restarted if the action occurred before one full revolution or after six revolutions. Participants were asked not to plan ahead or to aim for a particular point on the clock and to report either the action or the tone (to give contingent action or contingent tone judgements). Baseline action trials were the same as contingent action trials except the button did not trigger a tone. In baseline tone trials, the tone was triggered pseudo-randomly between 2.5 s and 7 s following one revolution of the clock.

Following the tone (or action on baseline action trials), the dot continued moving for a pseudo-randomised period of time between 1200 ms and 2370 ms. The clock was then removed from the screen for a pseudorandomised time interval (500 ms to 1280 ms). When the clock reappeared, participants were able to control the position of the dot with a mouse. Moving the mouse forward (toward the screen) caused the dot to move in a clockwise direction around the clock face and the reverse mouse movement (away from the screen) caused the dot to move counter-clockwise around the clock face. Participants were asked to move the dot to the position it had occupied at the time of the judged event (action or tone) and to press the mouse button to record their judgement.

Each block consisted of 40 repetitions of one trial type and blocks were separated by 30 s rest periods. The four blocks were presented in counterbalanced order. Before the session began, all participants were trained with four practice trials in the baseline tone condition and four in the baseline action condition so that they could become familiarised with the reporting procedure. All Stimuli were generated with Matlab running Psychtoolbox v3 (Kleiner et al., 2007)

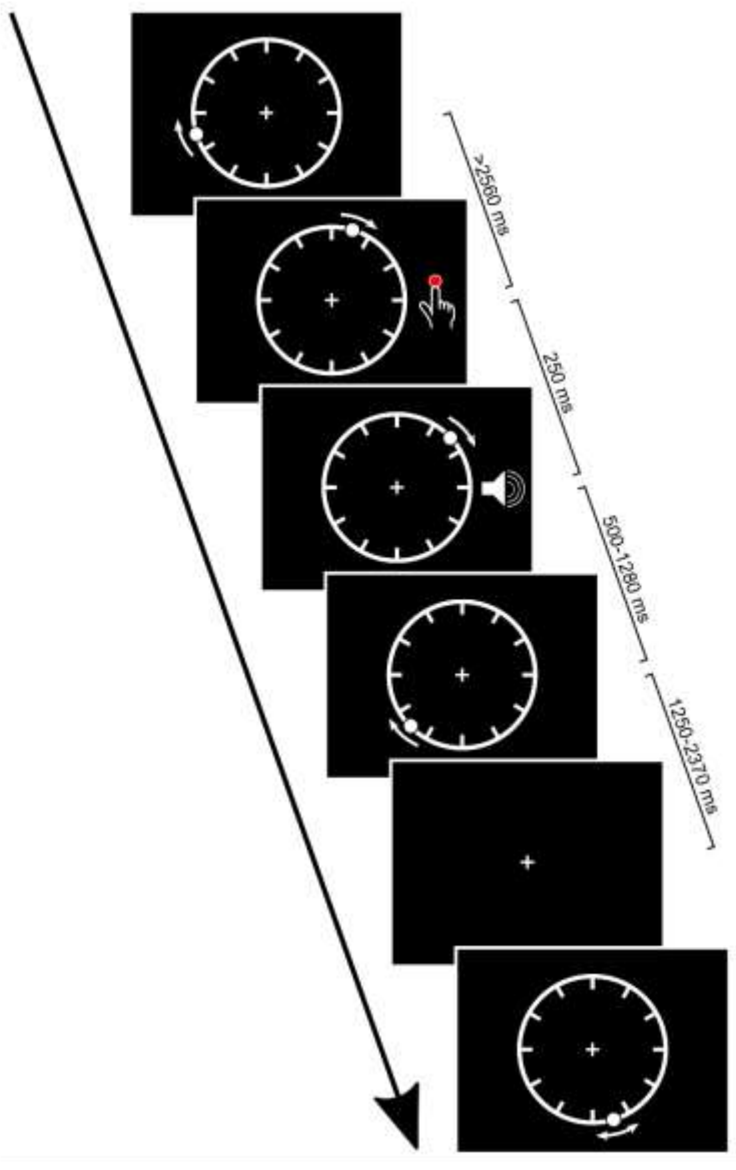

Figure 2. Participants judged the time at which they pressed a button or heard a tone by reporting the position of a rapidly moving dot on clock face at the time the event occurred.

Action and outcome events were presented either alone (baseline conditions) or the action caused the tone to occur 250 ms after the button press (contingent conditions).

Measures

Within-participant SD of timing judgements provides a measure of precision in estimating the time of an event. If binding reflects the combination of cues according to the precision afforded to actions or their outcomes, any differences in intentional binding should be accompanied by differences in this measure. In terms of cue combination theory, it is the interaction between high vs low hypnotisables by outcome vs action timing precision that should determine changes in intentional binding between groups.

Mean judgement errors were calculated for each group on each trial type. Individual judgements more than 3.5 SD from the mean for each participant on each judgement type were excluded before mean judgement errors were calculated for each participant. Thirty-four judgements were excluded by this method (2.1 % of all trials). The adjusted mean errors for action and tone conditions were then subtracted from their respective contingent conditions to calculate action and outcome binding. If binding reflects cue combination, an interaction between high vs low hypnotisables by action and outcome timing precision should be reflected in an interaction between high and low hypnotisables and action vs outcome binding (because precision of action timing should influence the magnitude of action and outcome binding in opposing directions).

The relative precision of contingent action and outcome judgements was calculated from the proportion of precision (the inverse of within-participant squared SD) in both contingent action and outcome judgements accounted for by each judgement type (action or outcome). A cue combination theory of intentional binding predicts that binding should shift in proportion to precision. When precision of action timing judgements is relatively high, action binding magnitude should be smaller, and outcome binding magnitude greater, than when precision of action timing judgements is relatively low. Therefore the relative precision (inverse variance) of action timing judgements should correlate negatively with action binding and positively with outcome binding.

Data Analyses

Bayes factors (*B*) were used to assess strength of evidence (Wagenmakers Verhagen Ly Matzke Steingroever Rouder & Morey, 2017). Unlike null-hypothesis significance testing, Bayes factors have the advantage of distinguishing sensitive evidence for H_0 from insensitive evidence (which is little or no evidence for or against a hypothesis). A *B* of above 3 indicates substantial (or better: moderate) evidence for the alternative over the null hypothesis and below 1/3 substantial (/moderate) evidence for the null over the alternative hypothesis. *B*s between 3 and 1/3 indicate data insensitivity in distinguishing null and alternative hypotheses (Dienes, 2014; Jeffreys, 1939; Lee & Wagenmakers, 2013). Here, $B_{H(0, x)}$ = refers to a Bayes factor in which the predictions of H1 were modelled as half-normal distribution with an SD of x (Dienes 2014); the half-normal can be used when a theory makes a directional prediction where x scales the size of effect that could be expected (so x can be chosen from e.g. relevant past studies; or it can be set to half of a plausible maximum effect).

We now describe how we modelled H1 for each of our tests. The expected scale of effect, x, cannot be set by the actual difference being tested but must be derived otherwise. Other aspects of the same data may constrain plausible values of the effect (e.g. the size of an effect overall may constrain how much that effect could be expected to be modified) (Dienes, 2014). In the present study, in all cases a result significant at the 5% level corresponded to a B > 3, and vice versa, with the model of H1 we used (cf. Jeffreys, 1939, p. 359, for this rough but not guaranteed correspondence between B and p; if the obtained effect is roughly the size expected on a half-Normal model of H1 the correspondence typically obtains, Dienes, 2014. But there is no monotonic relation between p values and Bayes factors.).

Testing differences in binding.

Kranick et al. (2013) provide an estimate of the sort of difference in intentional binding that could be found between different groups using conversion disorder patients vs matched controls (conversion disorder involves voluntary-like movements experienced as non-volitional; and relevant for us, people with conversion disorder are relatively highly hypnotisable; Roelofs et al, 2002); in their study, the difference between groups in tone binding was on the order of magnitude of about half the effect found in control participants. Bayes factors for group differences in each measure were therefore calculated using a half-normal distribution with SD based on half the average of action and outcome binding in all participants.

Testing differences in precision.

Bayes factors for within-participant SD of timing judgement group contrasts were calculated using a half-normal based on the expected change in variance accompanying a 50% change in binding. On the theory that binding arises from the precision-weighted combination of outcome and action time estimates, the percentage change in binding would equal the percentage change in the relative precision, i.e. of the estimated variance. The change in SD is proportional to the square root of the change in variance. Thus, a 50% increase in variance amounts to the standard deviation increasing by approximately 20% of the average within-participant SD across all conditions (16 ms).

Testing relation between binding and precision.

Assuming equal weighting of each source, for 100% relative precision of action judgements, outcome binding would be 250 ms and for 0% relative precision of action judgements action binding would be 250 ms. The maximum range of the precision scale is 100%. If there was no influence on action or outcome binding other than precision, and precision acted as strongly as it theoretically could (assuming a prior that action and outcome occur at the same time), the slope of binding change against precision would be 250 ms/100 = 2.5 ms. This slope is a maximum slope though because it presumes no noise in measurement or in mechanism (and the prior just stated). Therefore, a Bayes factor for regressing relative precision of action judgements on shift of contingent action timing from baseline was calculated using a half-normal distribution with mean SD of half the maximum possible raw slope (1.25 ms per unit percent change in relative precision).

Testing differences in proportion of total precision.

For the test of the difference between high and low hypnotisables in the proportion of total precision accounted for by action judgements, cold control theory predicts that highs should have less precision than lows (given highs tend to be less aware of intentions to act). Thus, whatever action timing precision highly hypnotisables have, if low hypnotisables have greater precision, the maximum difference between highs and lows in proportion of precision accounted for by action judgments is set by how far from 1 that proportion is for highs. Thus, we can model H1 with a half-normal using an SD of half the precision of how close highs are to 1 (i.e. half the plausible maximum value). Thus, an SD of .275 was used, based on the half the difference between the proportion of total precision accounted for by action judgements in highs (predicted to be least precise in judging actions) and 1, in our data.

To indicate the robustness of Bayesian conclusions, for each *B*, a robustness region is reported, giving the range of scales that qualitatively support a given conclusion (i.e.

evidence as insensitive, or as supporting H0, or as supporting H1), notated as: RR [x1, x2] where x1 is the smallest SD that supports the conclusion and x2 is the largest.

Data are available at https://osf.io/vuk67/

Results

Timing Judgements

First, we examined participant's judged time of action and outcome events in baseline and contingent conditions. Figure 3a shows high hypnotisables' time judgements of events compared to the actual time of event for baseline condition action, *M* = 11.7 ms (*SD* = 45.6), and outcome, *M* = -10.2 ms (*SD* = 60.8), and contingent condition action, *M* = 50.57 ms (*SD* = 55.8) and outcome, *M* = -68.34 ms (*SD* = 90.4). Figure 3b shows low hypnotisables' time judgements of events compared to the actual time of event for baseline condition action, *M* = -7.0 ms (*SD* = 48.4), and outcome, *M* = -12.8 ms (*SD* = 52.6), and contingent condition action, *M* = 15.5 ms (*SD* = 50.1) and outcome, *M* = -93.5 ms (*SD* = 73.8).

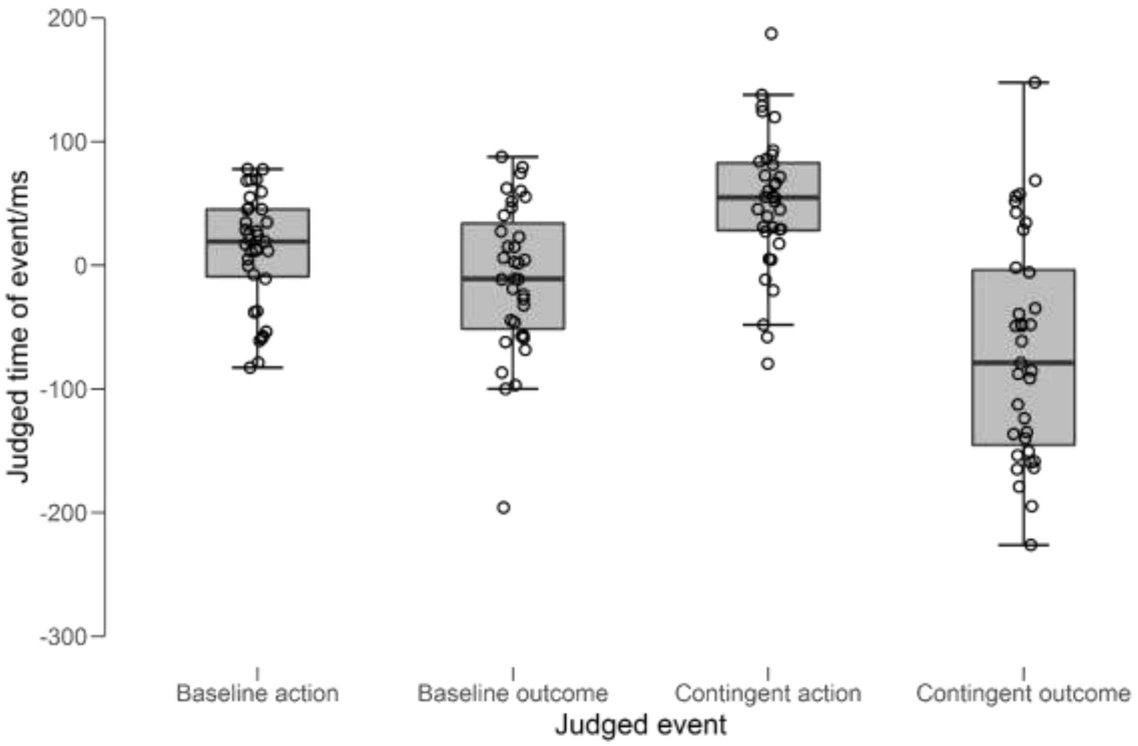

Figure 3a. Judged time of events (action or outcome, subtracted from actual time of event) by condition (Baseline or Contingent) for the high hypnotisable group.

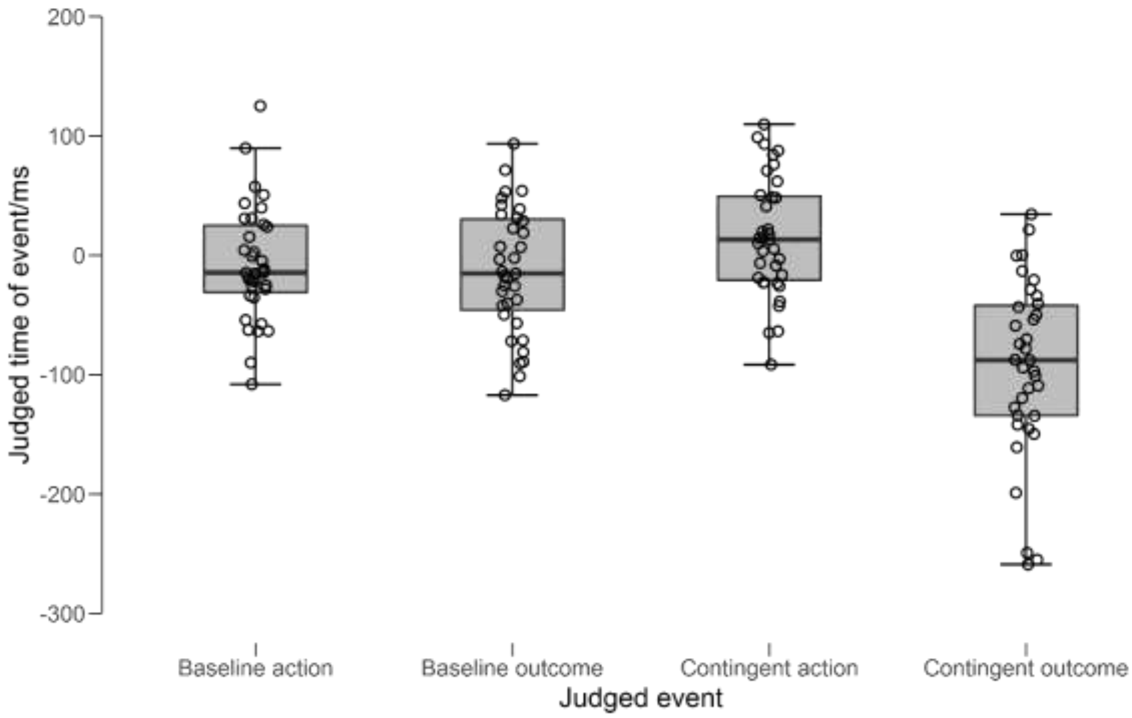

Figure 3b. Judged time of events (action or outcome, subtracted from actual time of event) by condition (Baseline or Contingent) for the low hypnotisable group.

Baseline Within-participant SD of Event Judgements

First, we tested the prediction that highly hypnotisable participants would have less precise (more variable) reports of baseline action event timing judgements than lows. We make no prediction for differences in precision of tone judgement timing. There was no evidence either way for an interaction, $F(1, 68) = 2.06$, $p = .156$, $\eta^2p = .029$, $B_{H[0, 16]} = 1.60$, RR [0, 105] (see Figure 4). As predicted, planned simple effects comparisons showed that high hypnotisables had greater SDs for baseline action timing judgements (M =78.4, SD = 28.2) than low hypnotisables (M = 60.3 ms, SD = 21.9), $t(68) = 3.01$, p =.004, d = .72**,** $B_{H[0, 16]} = 37.81$, RR = [3, 380]. However, there was also evidence for highs having higher baseline tone judgement SD (M = 90.4ms, SD = 22.4) than lows (M = 81.0 ms, SD = 15.0

ms), *t*(1,59.39) = 2.05, *p* = .045, Glass's Δ = .42. $B_{H[0, 16]}$ = 3.74, RR [4, 245], which was not predicted one way or the other. This may be attributable to generally lower metacognition in highs, which we discuss below.

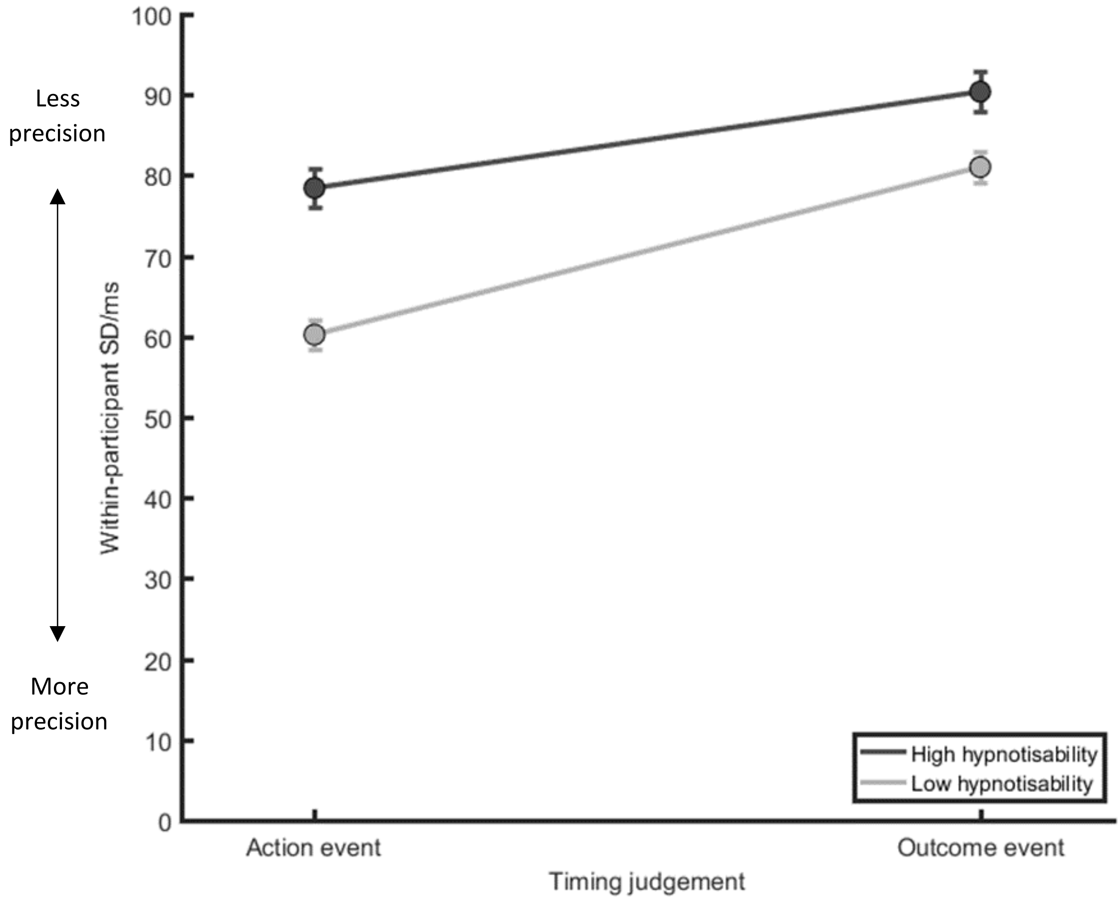

Figure 4. Interaction between high and low hypnotisability and judged event on *baseline* condition within-participant standard deviations of timing judgements (error bars show within participant SE).

Action and outcome binding

Next, we tested the prediction that, as a result of having relatively lower access to motor intentions, high hypnotisables would have increased action binding and decreased outcome binding. There was evidence for an interaction between group and type of event judged (action or outcome) on timing judgement shift from baseline, $F(1,68) = 4.22$, $p = .044$, $\eta^2p = .058$, $B_{H(0, 25)} = 4.38$, RR [14, 91]. Figure 5 shows the action and outcome binding measures for each group. *t*-tests were used to test planned comparisons between groups. There was evidence that highly hypnotisable participants showed greater action binding (M = 38.9 ms, SD = 37.5) than low hypnotisables (M = 22.5 ms, SD = 27.9), $t(68) = 2.07$, $p = .042$, $d = .49$, $B_{H(0, 25)} = 4.13$, RR [6, 39]. There was no evidence as to whether low hypnotisables showed greater outcome binding (M = -80.7 ms, SD = 66.1) than high hypnotisables (M = -58.2 ms, SD = 77.4), $t(68) = 1.31$, $p = .195$, $d = .31$, $B_{H(0, 25)} = 1.74$, RR [0, 240].

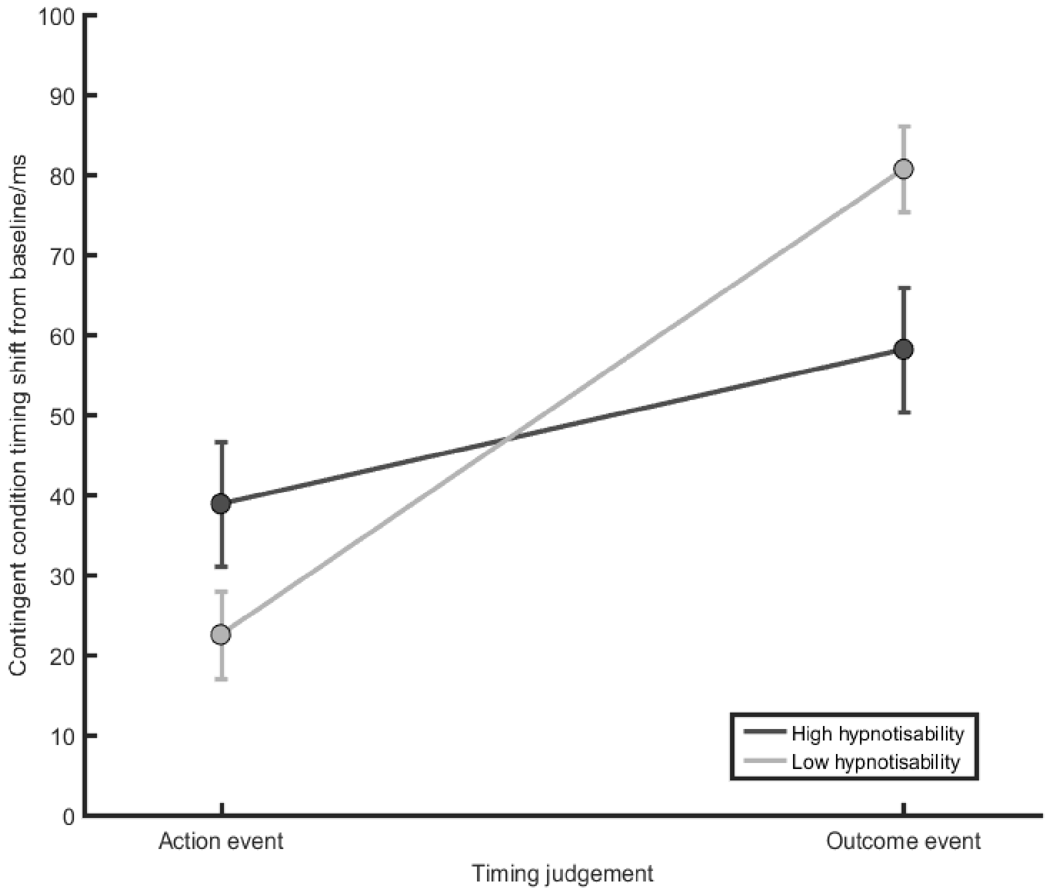

Figure 5. Interaction between high and low hypnotisability and judged event on contingent condition timing shift from baseline (i.e., magnitude of binding)

Relative precision

Finally, we tested predictions relating to the proportion of total precision accounted for by action judgements. As predicted, a greater proportion of total precision for contingent judgments was accounted for by action judgements in lows (M = .64, SD = .16) than in highs (M = .54, SD = .13), $t(68) = 2.76$, $p = .007$, $d = .67$, $B_{H(0, .18)} = 14.59$, RR = [.016, 1]. Because a cue combination mechanism may underlie binding in both groups, data from high and low hypnotisables were combined for the following analyses (though note that these analyses at least partly reflect group differences[1]). A cue combination mechanism of binding predicts that the percentage of total precision arising from action judgements should be negatively related to action binding and positively related to outcome binding. Results were consistent with the first prediction, *b* = -.59 ms (*SE* = .26), *t*(68) = 2.23, *p* = .029, $B_{H(0, 1.25)}$ = 4.74, RR = [.16, 2.15]. However, there was no evidence for or against the predicted positive relationship between relative precision of action judgements and outcome binding, *b* = .52 ms (*SE* = .58), *t*(68) = .900, *p* = .371, $B_{H(0, 1.25)}$ = 1.11, RR [0, 5.30]. The beta for the combined evidence from both regressions (in their predicted directions) was .58 ms (*SE* = .24) 95% CI [.11, 1.04], $B_{H(0, 1.25)}$ = 6.25, RR [.14, 2.88]. Therefore, there was evidence for a cue combination mechanism for action binding, but no evidence for or against cue combination in outcome binding.

1 A meta-analysis of regression slopes based only on within-group differences was also conducted, *b* = .50 ms (*SE* = .24), *t*(68) = 2.08, *p* = .041, $B_{H(0, 1.25)}$ = 2.99, RR [.12, 1.25]

Discussion

We tested high and low hypnotisable participants in an intentional binding task in order to investigate two separate questions relating to (i) trait differences in metacognitive access to motor intentions and (ii) the predictions of a cue combination model of intentional binding. First, there is evidence that the ability to respond to imaginative suggestions in the context of hypnosis is inversely related to metacognitive access to motor intentions (Lush, Naish & Dienes, 2016; Terhune & Hedman, 2017). We hypothesized that reduced access to such information would result in differences in the precision of action timing judgements between highly hypnotisable and low hypnotisable participants. The results supported this hypothesis: compared to low hypnotisables, highs' judgements of the timing of intentional actions were more variable, and action timing judgements accounted for less of the total precision of all timing judgements for highs than for lows. Second, if intentional binding is a case of multi-modal cue combination, differences in the precision of action judgements should influence action and outcome binding in opposite directions. Specifically, greater precision of action timing judgements should result in reduced action binding (a smaller shift in perceived time of action toward the time of outcome event) and increased outcome binding (a larger shift in perceived time of outcome toward the action event), as the action cue should have a greater influence over timing judgements when action and outcome events are presented together (see Figure 1 for schematic depiction). For action binding, this prediction was met; low hypnotisables showed reduced action binding when compared to high hypnotisables. There was no sensitive evidence either for or against the hypothesis that lows would show more outcome binding than highs. When data from both groups was combined, there was evidence consistent with the theory that the relative precision of action judgements influences action and outcome binding in opposite directions. Taken together, these results are consistent with both a cue combination model of intentional binding and of a relationship between trait differences in hypnotisability and metacognition of intentions. Figure 6 shows a simplified representation of the change in action binding associated with increased precision of action in low compared to high hypnotisables.

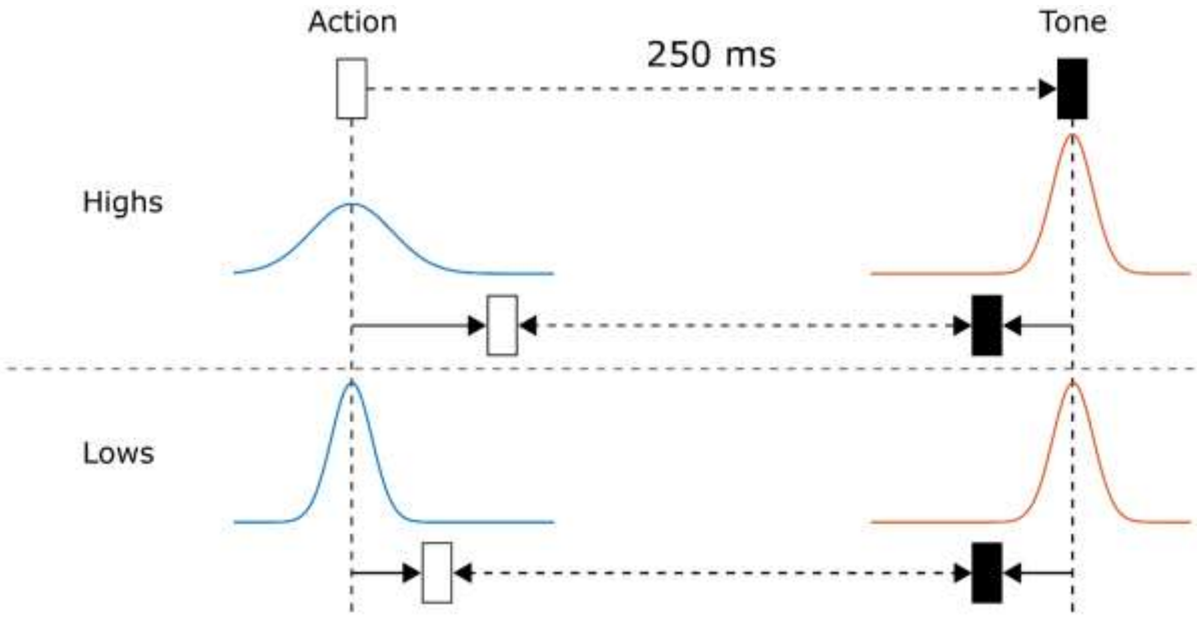

Figure 6. A simplified representation of study results. Consistent with predictions, low hypnotisables showed more precise action judgements and weaker action binding than high hypnotisables. The data were insensitive for outcome binding.

There is existing experimental evidence for a cue combination mechanism supporting action binding. Wolpe, Siebner & Rowe (2013) manipulated the variability of outcome judgements by masking the outcome tone with constant white noise and varying the level of tone intensity and found that action binding decreased when outcome judgements were relatively imprecise. The authors also reported a non-significant analysis for an influence of variability on outcome binding and argue on this basis for a dual process account of binding. In this account, action binding is driven by cue combination but outcome binding occurs when the threshold for perception of an action outcome is crossed more rapidly due to a sensorimotor pre-representation of the outcome (Waszak et al, 2012). However, (and unlike Bayes factors) null hypothesis significance tests do not provide evidence for the null hypothesis (see Dienes, 2014). The results presented by Wolpe et al do not, therefore, provide evidence against a cue combination mechanism in outcome binding. Indeed, to our knowledge, there is no reported evidence against a cue combination model of outcome binding. Therefore, and because a single process model is more parsimonious than a dual process model, we work to the assumption that a single process accounts for both action and outcome binding.

In previous studies (Kawabe, Roseboom & Nishida, 2013; Wolpe, Haggard, Siebner & Rowe, 2013) a Bayesian cue combination model has been proposed in which it is assumed that cross-modal sensory information arises from a single source. However, intentional binding experiments employ sizeable delays between action and outcome (typically 250 ms) and it is known that the sensitivity of multi-sensory integration to information regarding the relatedness of sensory signals increases with discrepancies between perceptual estimates (e.g., Bresciani et al, 2005). Such discrepancies have been previously addressed in other sensory domains by the addition of a prior which quantifies an expected delay between components and the degree of belief in the relatedness of the sensory signals (Ernst, 2007; Ernst & Di Luca, 2011; Roach, Heron & McGraw, 2006) or through modelling of multisensory causal inference (Körding et al 2007; Shams & Beierholm, 2010; Kayser, C. & Shams, 2015). Modelling of intentional binding via Bayesian cue combination requires the addition of such a prior (Lush, Roseboom, Seth, Cleeremans & Dienes, 2018); for example, reflecting beliefs regarding causality between action and outcome to which intentional binding is known to be sensitive (Buehner, 2012, 2015), and specifying the expected interval between action and outcome. A model of this sort may describe a process by which trait differences in the salience-driven precision of motor intentions relate to the ability to experience an intentional action as unintentional. It may also be extended to cases in which the salience of an intention is altered by induced beliefs; for example differences in intentional binding relating to the belief that one is not the cause of an action (Desantis, Roussel & Waszak, 2011) or is not responsible for action (Caspar, Cleeremans & Haggard, 2015).

According to dissociated experience theories of hypnotic responding, the experience of involuntariness in hypnotic responding occurs when monitoring systems become dissociated from cognitive control systems (for a review, see Woody & Sadler, 2008). According to higher order thought (HOT) theories of consciousness, conscious experiences are essentially metacognitive; a particular mental state only becomes conscious when there is a higher order mental state directed at it (Rosenthal, 2000). The cold control theory of hypnosis recasts dissociated experience within the framework of HOT theory, arguing that the experience of hypnotic involuntariness arises from the production and maintenance of inaccurate HOTs directed at unconscious first order intentions (Dienes, 2007; 2012). Therefore, a successful response to a hypnotic suggestion involves performing an intentional act but, through an inaccurate HOT of intending, experiencing the act as unintentional. Increased within-participant variance of action timing judgements in high hypnotisables relative to low hypnotisables is consistent with the theory that trait hypnotisability reflects differences in metacognitive access to intentions (Dienes et al, 2016; Lush, Naish & Dienes, 2016). High hypnotisables may show greater variance in action timing judgements because they have less access to information related to motor intentions when forming HOTs of intending. Consistent with this, highs show more variable action judgement timing (and decreased outcome binding) following a post-hypnotic suggestion for the experience of involuntariness over actions (Lush et al, 2017). There is also evidence that TMS of dorsolateral prefrontal cortex (dlPFC) increases hypnotisability (Dienes & Hutton, 2013). The dlPFC has been proposed to support HOTs (Lau & Rosenthal, 2011; Passingham & Wise, 2012) (including HOTs of intending, Lau, Rogers, Haggard & Passingham, 2004); hence the increase in hypnotic responding may be attributable to the disruption of HOTs of intending. If dlPFC supports HOTs relevant to the precision of action timing judgements, disruption of dlPFC should lead to an increase in action timing variability, reduced action binding and increased outcome binding (depending on how it affects the precision of outcome timing judgment).

The sense of agency is disrupted in certain neurological and psychological disorders, and the results presented here may inform studies of such disorders. For example, there is evidence for differences in action binding in disorders of agency. In corticobasal syndrome (for which disorders of agency are diagnostic), patients show greater action binding than controls and the magnitude of action binding is positively related to variability of action time judgements (Wolpe et al, 2014b). In this study, because the patient group showed abnormalities in a brain area considered important for motor intentions (the preSMA), these results may be attributable to differences in access to motor intentions. Additionally, Voss et al (2010) report greater action binding in schizophrenic patients than in controls (although no evidence for a difference in action timing variability was reported for this study).

It has been argued that the sense of agency arises from the integration of multiple sources of information, with the influence of each source weighted by precision (Moore, Wegner & Haggard, 2009, Synofzik, Vosgerau & Lindner, 2009). Therefore, hypnotic responding may arise from the relatively high weighting of hypnosis-related beliefs and the relatively low weighting of motor information. Note that precision weighting in the generation of sense of agency is here not to be confused with precision weighting in event timing in the intentional binding effect. Furthermore, according to cue integration models of sense of agency, the relationship between intentional binding and sense of agency is not straightforward. For example, having relatively weak outcome binding does not mean that highs differ in their sense of agency from lows because when information from one source is weak, other information will be weighted more highly (Moore & Fletcher, 2012).

Cold control theory requires only that metacognitive differences related to intentions should be reflected in trait hypnotisability. However, it is possible that high and low hypnotisables differ in domain-general metacognition. In the baseline conditions we report increased variability of timing judgements for both an auditory tone and an intentional action in high hypnotisables. Future studies could employ established measures of metacognition to explore this possibility (e.g., see Fleming & Lau, 2014; Barrett, Dienes & Seth, 2013).

Here we have focused on action binding and outcome binding as separate components of intentional binding. However, intentional binding studies often report an overall binding measure rather than the individual action and binding components. For studies that employ direct interval estimation (Engbert, Wohlschläger & Haggard, 2008) or delay estimation (Kawabe, Roseboom & Nishida, 2013; Wen, Yamashita & Asama, 2017), these two components cannot be discriminated. If a cue combination mechanism drives binding, then a particular overall measure of intentional binding could arise from various combinations of action and outcome binding shifts; indeed, as a change in precision in one component only would make outcome and action binding change in opposite directions, a single measure of total binding could hide important patterns. It should also be noted that while, as we have argued here, changes in precision of information about action might drive such differences in binding, temporal shifts from baseline to contingent timing judgements will also be driven by the precision of information regarding the outcome event (e.g., Wolpe, Haggard, Siebner & Rowe, 2013). Future work on intentional binding should therefore report a measure of precision of timing judgements and separate action and outcome shifts wherever possible.

As high and low hypnotisables are both special groups, it has been argued that medium hypnotisables should be included as a control group in hypnosis studies, to distinguish between the possibilities that the difference is attributable to highs or lows alone (Kirsch, 2011). The present study was based on evidence for a linear relationship between hypnotisability and metacognition of intentions (Dienes et al, 2016; Lush, Naish & Dienes, 2016), and the inclusion of low hypnotisables maximized the predicted potential differences. However, future studies are required to rule out the possibility that the relationships between trait hypnotisability and variance of action judgements or components of binding are non-linear.

In summary, we report reduced precision of action timing judgements and increased action binding in high compared to low hypnotisables. These results are consistent with a cue combination model of both components of intentional binding and with the theory that hypnotisability is related to differences in the availability of information relating to an intention to perform an action.

Author Contributions

P.L., Z.D. and W.R. developed the study concept. P.L. and Z.D. designed the study. P.L. collected experimental data and P.L and R.B.S performed data collection for participant screening. P.L. and Z.D. selected analytical procedures and P.L conducted analyses. P.L. drafted the manuscript, and A. K. S., W.R., A.C. and Z.D. provided critical revisions.

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