# Mistiming of thought and perception predicts delusionality

Adam Bear[a,1], Rebecca G. Fortgang[a], Michael V. Bronstein[a], and Tyrone D. Cannon[a,1]

[a]Department of Psychology, Yale University, New Haven, CT 06520

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**The timing of thoughts and perceptions plays an essential role in belief formation. Just as people can experience in-the-moment perceptual illusions, however, they can also be deceived about how events unfold in time. Here, we consider how a particular type of temporal distortion, in which the apparent future influences "earlier" events in conscious awareness, might affect people's most fundamental beliefs about themselves and the world. Making use of a task that has been shown to elicit such reversals in the temporal experience of prediction and observation, we find that people who are more prone to think that they predicted an event that they actually already observed are also more likely to report holding delusion-like beliefs. Moreover, this relationship appears to be specific to how people experience prediction and is not explained by domain-general deficits in temporal discrimination. These findings may help uncover low-level perceptual mechanisms underlying delusional belief or schizotypy more broadly and may ultimately prove useful as a tool for identifying those at risk for psychotic illness.**

consciousness | perception | delusionality | schizophrenia | postdiction

Imagine that, as you leave your house, a few raindrops fall on your skin. You may have the thought that you should go grab your umbrella. Such an observation is completely ordinary and unlikely to encourage any odd beliefs about how the world works. However, a minor alteration to the order in which this perception and thought arise might produce a dramatically different outcome. Mistakenly thinking that you knew to grab your umbrella before you felt raindrops might inspire the belief that you have an exceptional ability to predict the weather or even that you are clairvoyant. More generally, someone who systematically misperceives herself as successfully predicting an event like the weather could come to hold exaggerated or even delusional beliefs about her knowledge or agency.

We explore whether such a relationship exists by building on a recent "postdiction" (1) paradigm, which found that people frequently mistake their predictions for events that have already happened (2). In one such experiment, participants were presented with a set of white circles on a screen and were asked to choose which circle they thought would change color. After an experimentally manipulated delay, one of these circles turned red, and participants indicated whether they had accurately predicted which circle would be the one to change color or whether they had chosen the wrong circle. Alternatively, they could respond that they did not have time to make a prediction before they noticed this event occur. If participants gave one of these first two responses, they reportedly believed that they finished making their prediction before the event that they were predicting occurred (just as someone might believe they finished predicting whether it was going to rain before the weather changed). Participants reported an unrealistically high rate of accurate predictions. The circle that was selected to change color on a given trial was completely random, yet participants claimed to have predicted this impossible-to-predict event at levels that were well above chance. Crucially, this bias was primarily observed when the time available to make a prediction was brief (a delay of roughly 250 ms or less). This suggests that the effect was driven by unconscious processing of the red circle while the decision was still in progress, rather than a general response bias or motivation to report making an accurate prediction, which could be observed after any amount of time.

In the present study, we investigated whether the extent to which people experience this illusory reversal of thought and perception predicts their self-reported likelihood of holding certain delusional ideas in other, broader contexts. We hypothesized that if people frequently confuse a feeling of anticipation of an event with the mere observation of an event that has already occurred, they could develop unusual views about their ability to control their environment. This might particularly help explain the presence of delusions that they (or others) have magical abilities to control objects or others' thoughts through supernatural forces, to predict or foretell the future, or to read minds before words are spoken. It might also help explain the sense that new, unrelated events and information confirm preexisting delusional beliefs, as a notion that one has predicted or foretold an event may contribute to its perceived salience and relevance. This effect might therefore also be pertinent to the maintenance of delusional beliefs.

Although delusional beliefs represent a prominent symptom of schizophrenia and other psychotic disorders, psychosis is distributed across a continuum; delusions and delusion-like beliefs are also present in the general population (3). For this reason, we chose to explore whether confusion about the relative timing of thought and perception might relate to delusion-like ideation in a nonclinical sample recruited via Amazon's Mechanical Turk. This strategy allowed us to collect data from a relatively large ($n$ = 1,013) sample of participants and to observe the relationship between postdiction and delusion-like beliefs as a scaled variable, rather than probing for group differences and enmeshing delusions with a network of other psychotic symptoms. [Participants

## Significance

**The nature and origin of delusional belief in illnesses like schizophrenia has been an active topic of research for decades. Yet relatively less work has been devoted to relating this high-level phenomenon to lower-level perceptual mechanisms. We consider whether an illusory reversal in the perception of when a prediction and observation occur in time predicts the presence of delusion-like ideation. We find evidence for such a relationship, suggesting that specific perceptual deficits in how people experience the timing of their thoughts might be a contributor to delusionality. Detecting these perceptual abnormalities early on may therefore prove fruitful for understanding, diagnosing, and treating certain forms of mental illness.**

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[1]To whom correspondence may be addressed. Email: adam.bear@yale.edu or tyrone.cannon@yale.edu.

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were tested in two separate collections, the second of which was preregistered through AsPredicted.org. However, because there were no statistically significant differences between these two samples in our three main dependent measures (*Supporting Information*), we collapse the two samples for all analyses reported in the main text to give the best possible estimates of the effects. In *Supporting Information*, however, we report the successful replication of our main analysis in the preregistered sample on its own.]

Participants completed a prediction task similar to the one described above (2). In this task, five empty squares appeared in random locations on a screen, and participants predicted which of these squares would light up red. They then indicated whether they had made a correct prediction, an incorrect prediction, or no prediction (if they did not have time to finish before one of the squares lit up). We manipulated the amount of time participants were given to make their prediction before one of the squares was randomly selected to turn red (Fig. 1*A*).

In the above task, participants' judgments of timing hinged on integration of an externally generated event (a square turning red, perceived visually) and an internally generated event (making a decision). Participants also completed a control task (in counterbalanced order with this prediction task) that measured their general ability to discriminate two external (visual) events in time. The task was similar in appearance to the prediction task, but instead of making a prediction, participants indicated whether a square flashing red was preceded or followed by the screen blinking (going blank for a brief moment). We randomly selected the order of these events and manipulated the delay between them (Fig. 1*B*).

After completing these two tasks, participants were administered the 21-item Peters et al. (4) Delusions Inventory (PDI), which measures a general proneness to a broad array of delusion-like ideation (e.g., paranoia, magical thinking, reference). Although our main hypothesis focused on the relationship between performance on the prediction task and the presence of specific forms of delusions, the interitem correlation for items on the PDI is high, suggesting that the questions all tap in to a single underlying construct of delusionality (4). Therefore, we conducted our primary analyses using the PDI total score to maximize variance on this underlying trait.

## Results

Postdiction in the prediction task—thinking that you made an unbiased prediction that was actually biased by the "future" event of a square turning red—was assessed by exploring participants' rate of claiming to have made an accurate prediction (among trials in which participants thought that they completed their prediction before the square turned red) as a function of the time they were given to make this prediction. Because there were five squares to choose from on each trial, "honest" predictions, which are unbiased by the appearance of the red square, should be correct ~20% of the time. Of course, a number of factors could inflate this percentage: participants could have a general response bias to say they predicted the red square when they did not (e.g., because they were lying), or they might respond randomly on some trials because they are inattentive. In contrast, the model we focus on here hypothesizes that there should be a time-dependent bias in the rate of reported successful prediction, with shorter trials leading to higher reported accuracy, because there is a limited window of time in which unconscious processes like subliminal attention capture can influence a prediction before the outcome of this prediction enters conscious awareness. In other words, on shorter trials, participants' predictions should be more likely to be in progress when a square turns red, which could bias this prediction before the participant becomes consciously aware of the color change (leading to an illusory reversal of the timing of the prediction and the predicted event in conscious awareness). On longer trials, in contrast, the prediction is likely to have already been completed and encoded into working memory before the red square is even unconsciously processed.

Thus, our key analyses focus on a negative time-dependent relationship between the reported accuracy of prediction and the delay before a square turned red. Specifically, because any boost in accuracy observed for these short time delays should quickly diminish and asymptote to chance levels (or chance levels plus or minus some baseline response bias), we modeled delay on a logarithmic scale. We combined results from the two different orders in which the participants could have done the prediction task (before or after the control temporal discrimination task) because there was no significant main effect of task order, $b = 0.016$, $z = 0.49$, $P = 0.624$, or interaction of task order and log of delay, $b = -0.012$, $z = -1.71$, $P = 0.086$, on prediction accuracy. Results from a multilevel logistic model (see *Methods* for details of modeling procedure) with participant treated as a random (intercept-only) variable confirmed the presence of a robust relationship between the probability of reporting an accurate prediction (excluding "didn't have time" trials, in which no prediction was reported to have made been made) and the log of delay (in milliseconds), $b = -0.048$, $z = -8.50$, $P < 0.001$ [model $\chi^2$ (1) = 72.17, $P < 0.001$; Fig. 2*A*], replicating previous work (2). (In all analyses involving

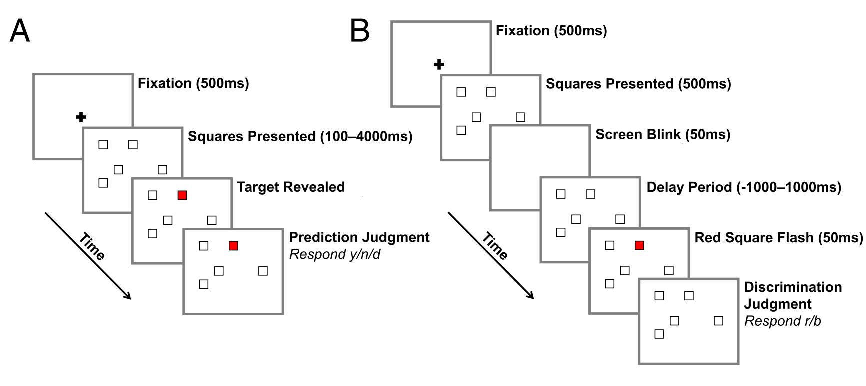


**Fig. 1.** Experimental procedure. Participants completed a prediction task and a temporal discrimination task in counterbalanced order. (*A*) Procedure for prediction task. After fixation, five squares were presented in random locations on the screen, and participants were tasked with predicting which one would light up red before the target was revealed after a variable delay. Participants then indicated whether they had predicted the target (y), had predicted a different square (n), or did not have time to complete a prediction before the target appeared (d). (*B*) Procedure for temporal discrimination task. After fixation, five squares were presented in random locations on the screen, and two events followed: the screen blinked, and one of the squares flashed red. The event that occurred first was randomized, and the delay between the two events was varied. Participants indicated whether they thought the red flash (r) or blink (b) occurred first.

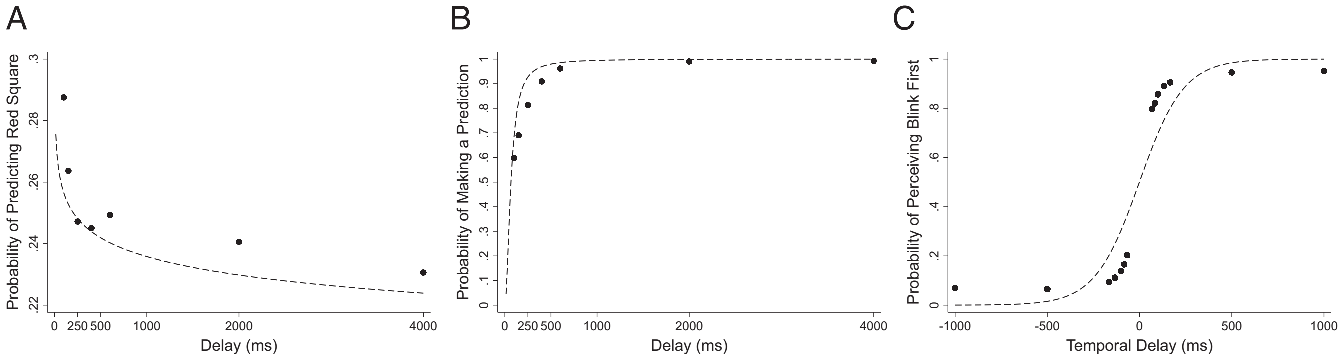


**Fig. 2.** Overall results from prediction and temporal discrimination tasks. Dots show mean responses by delay, and dotted lines show model fixed effects for participants' (*A*) probability of reporting that they predicted the red square (among trials in which participants claimed to have completed their prediction), (*B*) probability of completing a prediction in the postdiction task, and (*C*) probability of thinking that the blink occurred before the red flash in the temporal discrimination task.

the prediction task, 19 participants who claimed in debriefing to have reported successful predictions when they did not actually make these predictions were excluded.) Moreover, the Akaike Information Criterion with finite-sample correction ($AIC_c$) for this model (128,134) was substantially lower than that for a null model without a delay term (128,204). The strength of evidence in favor of the more complex model can be quantified by calculating an evidence ratio based on the two models' Akaike weights (5). Support for this model was decisive (evidence ratio > $10^6$).

Critically, we examined whether the strength of this relationship was moderated by participants' reported delusionality (PDI total score; see *Supporting Information* for individual subscale results). Would the bias in accurate prediction observed at short delays be exaggerated in people more prone to delusion-like ideation? To examine this question, we expanded the logistic model reported above to include a term for delusionality and, more essentially, the interaction between delusionality and the log of delay. Because the distribution of PDI scores was right-skewed, we log-transformed these values (adding 1 to the original scores to map 0 scores to 0 on the log scale). Both independent variables were mean-centered to facilitate interpretation. The hypothesized interaction was observed: in addition to being generally more likely to report accurate predictions, $b = 0.041$, $z = 3.18$, $P = 0.001$, participants who scored higher on the PDI exhibited a more negative relationship between delay and reported accuracy of their predictions, $b = -0.013$, $z = -2.94$, $P = 0.003$ [model $\chi^2$ (3) = 89.98, $P < 0.001$]. (Though we preregistered this particular analysis strategy with an intercept-only random effect for participant, the PDI × delay interaction remains significant, $b = -0.013$, $z = -2.23$, $p = 0.026$, in a more complex random-effects model that includes a random slope for delay.) That is, higher delusionality was associated with a larger postdictive bias in prediction (Fig. 3*A*). A comparison of the two $AIC_c$ values for a model with (128,120) and without (128,127) this interaction term justifies the added model complexity (evidence ratio = 27). Moreover, this relationship remained unchanged, $b = -0.013$, $z = -2.94$, $P = 0.003$, in a model that includes controls for participants' sex (whether they were male), $b = -0.036$, $z = -1.11$, $P = 0.265$; age, $b = -0.0050$, $z = -3.25$, $P = 0.001$; religiosity, $b = 0.014$, $z = 2.70$, $P = 0.007$; and self-reported confidence in their predictions, $b = -0.92$, $z = -1.22$, $P = 0.224$.

In an attempt to explain this association between delusionality and postdiction in the prediction task, we examined whether it related to a general deficit in temporal perception. That is, we considered whether individuals with more delusion-like ideation are simply poorer at discriminating any two events in time, and therefore, when they make their predictions close in time to the appearance of the stimulus that they are predicting, they are more liable to mistakenly think that the stimulus occurred after they finished their prediction even when it did not. The potential contribution of a domain-general timing deficit to the association between delusions and performance on our prediction task in this manner might be expected given evidence that individuals with delusions display cerebellum-mediated deficits in timing (6–8). To examine this possibility, we assessed whether there was a relationship between performance on our control task, which measured temporal discrimination of two visual events, and (log-scaled)

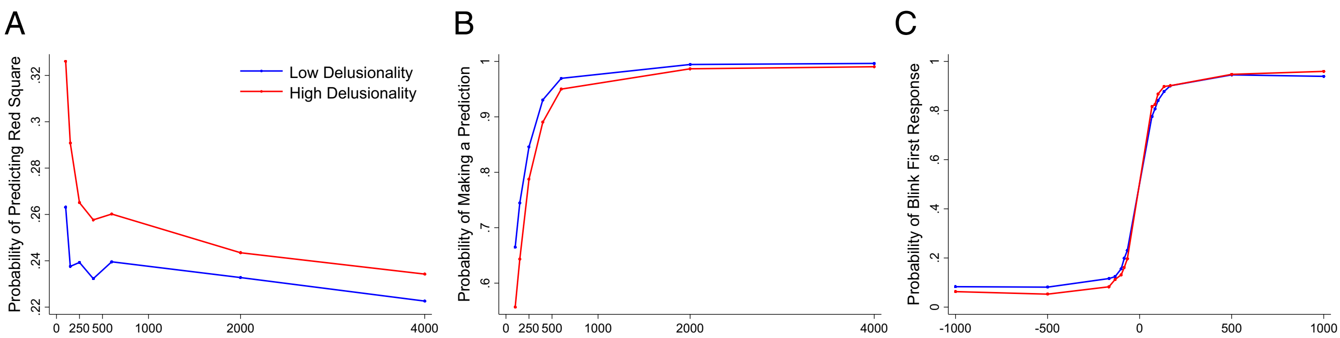


**Fig. 3.** Results by delusionality on prediction and temporal discrimination tasks. Bottom quartile (blue line) and top quartile (red line) delusional participants on (*A*) probability of reporting that they predicted the red square (among trials in which participants claimed to have completed their prediction), (*B*) probability of completing a prediction, and (*C*) probability of thinking that the blink occurred before the red flash in the temporal discrimination task. Results were divided by quartile for illustrative purposes only; all analyses reported in the main text treat delusionality as a continuous variable.

delusionality. Discrimination performance for each participant was calculated using the signal detection measure $d'$ (with values of 0 and 1 converted to 0.01 and 0.99, respectively). Surprisingly, participants endorsing more delusion-like ideation were not worse at temporal discrimination and, in fact, showed slightly improved performance on this task, $r(964) = 0.11$, $P = 0.001$ (Fig. 3*C*). Moreover, when including participants' temporal discrimination performance ($d'$) as a covariate in the model reported above, which assesses prediction performance as a function of delay and delusionality in the prediction task, the impact of delusionality on the relationship between delay and accurate prediction observed above was maintained, $b = -0.013$, $z = -2.73$, $P = 0.006$. (Because the temporal gap in this task was varied parametrically, a more appropriate analysis strategy would be to model the sensitivity of a psychometric function for each participant's data. Unfortunately, because of the limited and noisy data that several subjects contributed, fitting such a model was not possible, so we stick with the simpler measure of $d'$.)

Although general temporal discrimination could not account for the enhanced postdictive bias observed in more delusional participants, it is possible that the speed with which participants specifically made their predictions could. The relevance of this factor is supported by the association between reduced processing speed and the psychosis spectrum, such that processing speed is known to be reduced both in schizophrenia and related disorders (9) as well as in individuals with subclinical psychotic experiences (10). In theory, slower predictions should be more prone to postdictive influence for the same reason that having less time to make a prediction enhances this effect: the prediction must still be in progress for the future stimulus to subliminally bias it, and this is more likely to be the case if the prediction is completed later in time. However, the amount of time that it takes people to reach their decision about what they predicted may also correlate with how conservative a threshold they use to decide when they have made up their mind [e.g., as implemented in an accumulator model (11)]. Hence, slower predictions may index slower decision speed or demand for greater accumulated evidence before finalizing one's decision (although the latter seems unlikely for reasons explained below). Furthermore, the present study did not measure the absolute amount of time it took participants to make their predictions, but tracked a relative judgment about whether the predictions were completed before or after a square lit up red. So, even holding constant the effects of participants' baseline choice speed and conservativeness when making their predictions, there could be heterogeneity in the relative speeds at which information about one's prediction vs. information from visual perception reach awareness. One explanation for postdiction in the present study (discussed below with regard to corollary discharge models) stipulates that it is this relative timing difference that accounts for people's mistaken belief that they completed their predictions before they actually did. Specifically, the perceptual information that a square has changed color may reach awareness later than the information that one has completed a prediction, leading to an erroneous reversal of the perceived timing of the prediction and predicted event. On this account of people's timing judgments, then, people who are more likely to think that they finished their predictions before a square turned red should (all else equal) be more susceptible to postdictive effects on prediction, because they show the greatest mismatch in how they experience the timing of the prediction vs. the square changing color.

For all of these reasons, participants' rates of reporting that they completed their predictions before the color change warrants further examination, with the caveat that the present study only measured a relative judgment about when the prediction was completed vis-à-vis the color change. These relative judgments may therefore track a number of different timing- and prediction-related variables, which may vary independently. Nevertheless, we can test whether these judgments bear any kind of relationship to how much the postdictive effect was observed in different participants. In a multilevel logistic model (with participant treated as a random variable), we first examined participants' probability of reporting that they had time to make a prediction (indicating either that they predicted the red square or that they predicted a different square before a red square lit up) as a function of the log of delay and delusionality (log of PDI). Unsurprisingly, people were more likely to report making a prediction when the delay was longer, $b = 1.93$, $z = 114.82$, $P < 0.001$ [model $\chi^2$ (3) = 13,519.71, $P < 0.001$] (Fig. 2*B*). More interestingly, higher delusionality was associated with a lower overall probability of completing a choice, $b = -0.30$, $z = -5.23$, $P < 0.001$. This was qualified by a significant delay-by-delusionality interaction, indicating that more delusional participants were less likely to report completing their predictions, particularly at shorter delays, $b = -0.057$, $z = -3.92$, $P < 0.001$ (Fig. 3*B*).

These results suggest that more delusion-prone people take longer to reach their decisions (which, as discussed above, could be explained by a number of different factors). However, this association between delusionality and prediction time may simply be orthogonal to the association with postdiction, or it may be a mediating mechanism. To help address this question, we calculated each participant's overall probability of reporting that they made a prediction before a square lit up red (1 − the probability of giving a didn't have time response) and entered this as a covariate in the multilevel logistic model reported earlier, which regressed prediction accuracy (probability of "yes" predictions among responses in which participants claimed to have made a prediction) on the log of delay, the log of the PDI, and their interaction. Including this covariate, $b = 0.10$, $z = 0.93$, $P = 0.352$, did not eliminate the critical observed interaction between delusionality and delay, $b = -0.013$, $z = -2.93$, $P = 0.003$, suggesting that slower prediction speed does not explain why more delusion-prone individuals showed more postdiction. Indeed, in general, participants were far more likely to show postdiction when they reported making more predictions: when regressing prediction accuracy on log of delay and probability of making a prediction, there was a significant negative interaction between probability of making a prediction and log of delay, $b = -0.30$, $z = -6.52$, $P < 0.001$. So the people who feel like they can make predictions most quickly are typically more likely to confuse the timing of their prediction and the outcome of that prediction, perhaps because they are less conservative in how they make their predictions or because they have selective delays in perceptual processing. But despite the fact that more delusion-prone people reported making fewer predictions, they also showed more of this postdictive confusion.

## Discussion

We find that people who more often confuse the timing of their predictions with an observed outcome are more prone to report delusion-like thoughts and experiences. This association is not driven by domain-general deficits in timing-discrimination ability, and it is unlikely to be explained by the increased time taken by delusion-prone people to make their predictions. In fact, we find that, in general, those who report earlier predictions (relative to the timing of the outcome they are predicting) more commonly show a postdictive bias in these predictions.

There are a number of potential explanations for this unique relationship, which could be explored in future work. One notable, but ultimately unlikely, possibility follows from evidence that individuals who are more prone to delusions (e.g., those with schizophrenia) may have impaired internal monitoring of errors (12) and may fail to respond to violations of their predictions as strongly as healthy controls (13). Given that the current task involves self-monitoring of predictions, it is natural to hypothesize that these abnormalities may help explain why more delusion-prone participants attained unrealistically high accuracy in their reported predictions. Specifically, they may have more often failed to register that their initial prediction did not match the location of the subsequently appearing red square and, in turn, have mistakenly reported being correct. This would result in an overall elevation of reportedly correct predictions in the delusion-prone group, as observed in this study. But it is not obvious why such deficits would lead to particularly high reported accuracy on faster trials, especially given that the tasks that typically measure prediction error are administered at considerably longer time scales. Perhaps prediction signals are particularly weak on these shorter trials, which makes them more susceptible to bias. Detecting these error signals with techniques that can capture the time course and intensity of these signals (e.g., EEG) is therefore an important consideration for follow-up work. Nevertheless, prediction error and self-monitoring deficits alone seem unlikely to account for the substantial time-dependent differences that we observe.

There is also considerable evidence that people prone to delusions jump to conclusions when reasoning (14, 15), at least in the context of binary choice tasks like the one used here (16). It has been proposed that this tendency can be explained by supposing that these individuals more readily rely on weak evidence to reach a decision (17). Consistent with this notion, when answering trivia questions schizophrenia patients were more willing than healthy controls to decide that one of the answers was correct despite assigning relatively low subjective probability to their chosen answer (18).

In *Supporting Information*, we consider whether liberal acceptance of this sort could, on its own, explain the time-dependent bias observed in our prediction task, without the red square covertly influencing participants' decisions. Using a simple accumulator model, we show that this is unlikely: lowering choosers' subjective threshold for reaching a decision does not increase their probability of reporting a successful prediction (Fig. S1). Moreover, no matter the decision threshold, choosers are not more likely to report successful predictions when they have less time to make a decision.

Of course, it is possible that liberal acceptance or prediction error deficits may exacerbate other factors that contribute to the biases we observe. We consider two such factors here, which both involve the red square implicitly entering and corrupting the decision process. First, confusion regarding the source of information might lead to confusion about whether one correctly predicted which square would change color. Over the course of a trial in this task, squares are rendered more task-relevant for at least two reasons: one internal (the participant's prediction pertains to them) and one external (they change color). Confusing these internal and external sources of information might lead individuals to feel that they predicted the color change correctly when, in fact, they merely observed it. Indeed, delusion-prone individuals may have particular difficulty monitoring these confusions due to their increased confidence in errors and decreased confidence in correct responses (19). Consistent with this explanation, individuals with schizophrenia have been shown to struggle with reality monitoring—that is, distinguishing internal thoughts from external perceptions (20–22). This account does not necessarily explain why delusion-prone individuals primarily showed an enhanced bias to think they predicted the red square on faster trials. However, it is plausible that this confusion would be most likely to arise on exactly these trials because the prediction would be more likely to be in progress (not yet completed and encoded into memory) when the target appeared, which may make discriminating the source of information regarding the task-relevance of any given square more difficult. Future work could test whether the effects we observe in the current study relate to source memory impairments.

An additional line of work has explored how delusions of control, which lead those afflicted to believe that their actions are being controlled by external agents, can be explained by timing deficits in predictive mechanisms. According to corollary discharge models (23–25), the brain stores a copy of its motor commands and compares these instructions to sensory feedback it receives after behavior is initiated. When this predictive model and sensory feedback match, the brain is able to infer that behavior was self-initiated, explaining experiences of self-willing actions and individuals' inability to tickle themselves (26). However, this self-monitoring system may be disrupted in those with passivity symptoms, leading to a discrepancy between prediction and sensory feedback even when behavior is self-generated.

In support of this theory, people can successfully tickle themselves if the sensory feedback they receive from a robotic hand is delayed relative to the initiation of their action and therefore does not perfectly match up with the brain's predictions (26). In other words, a delay in perceptual information reaching awareness may underlie delusions of control. Indeed, both behavioral (27) and neurophysiological (6, 8) work suggests that temporal deficiencies of this sort are common in schizophrenia, which may further help explain the enhanced postdictive effect among more delusional individuals in the present study. In particular, an exaggerated bias to think that one has made an accurate prediction on faster trials could be explained by the appearance of the target covertly biasing prediction before the participant becomes aware of the target. Greater perceptual processing delays could make individuals vulnerable to this effect for a longer period.

Given that disturbances in temporal cognition are common even in schizophrenia spectrum disorders (7), it was surprising to find that the more delusion-prone participants in our nonclinical sample performed no worse (and, in fact, slightly better) on our temporal discrimination task than those with fewer delusions. It is possible that the more delusional participants in our sample were simply more motivated or attentive while doing the discrimination task. Even if our participants did take longer to become aware of sensory stimuli, however, this would not necessarily impair their performance on the temporal discrimination task. Because this task requires discriminating two visual events, any delay applicable to both of these events would cancel out when the participant needed to make a discrimination judgment. In contrast, if the processing delay is specific to perceptual information and does not affect how quickly someone becomes aware of their internally generated prediction, this perception-specific delay could introduce a systematic bias for people to think they have made predictions earlier in time than they actually have, relative to what they are perceiving. This could, in turn, generate the observed illusion in which somebody thinks they have made a prediction about an event that has already occurred. The fact that the more delusion-prone participants in our sample were generally less likely to think they completed their predictions before the color change may speak against this hypothesis. However, for reasons explained above, this measure is confounded with several other timing-related variables, which may covary with this particular deficit. In particular, more delusion-prone individuals may tend to make slower predictions overall (explaining their fewer reported predictions in the experiment) while also experiencing perception-specific delays in information reaching conscious awareness. Future work could, therefore, more carefully explore the specificity of the temporal deficits in delusion-prone individuals to test whether this is a plausible mechanism for the effects observed in the current study.

Our findings here may relate to the phenomenon of intentional binding (28), whereby the timing of an intentional action (e.g., a button press) and its associated sensory consequences (e.g., a tone) are compressed in conscious awareness. Like the confusion of prediction and perception we describe, intentional binding is a partly postdictive phenomenon, with the perceived timing of one's action depending on whether a tone is subsequently played. Intriguingly, intentional binding appears to be disrupted in patients with schizophrenia, partially due to an enhanced postdictive shift in the perceived timing of one's action forward in time when this action is followed by a tone (29). Although the present findings cannot be explained by a similar forward shift in time, as they involve purely mental prediction rather than intentional motor action, the mechanisms underlying the postdictive influences observed in both paradigms may be related. Offering a possible synthesis of these illusions is therefore an important consideration for future study.

The current findings may have practical implications, as well. Future work could administer our task to clinical populations (e.g., delusional individuals with schizophrenia) or even explore whether postdictive timing errors emerge before delusions arise (i.e., during the prodromal phase of illness) and correlate with previously reported neurological and cognitive markers of psychosis. If this work were to yield positive results, it would suggest that the task used here may be useful in identifying those at risk for psychosis. The potential promise of this task in this regard is enhanced by its extreme ease to administer, with the option of being run online in a matter of minutes. (Indeed, for diagnosis purposes, it is perhaps even possible to run only short-delay trials, where the difference in self-reported accuracy on the prediction task is greatest.) This possibility is noteworthy given that early detection of psychosis and subsequent intervention improves illness course substantially (30) and given that several potentially effective interventions for at-risk (i.e., prodromal) individuals exist (31).

Finally, although we focus on the relationship between postdictive timing errors and delusion-like belief because delusions are most clearly theoretically connected to our task, the work is positioned at the intersection between perceptual and cognitive processes and may also relate to perceptual aberrations. Although frequently treated as entirely distinct, processes governing abnormalities in perception and belief likely interrelate and may even be explained by a single factor (32). Tendency toward mistiming in cognitive and perceptual information may therefore represent a mechanism involved in these two components of positive symptomatology.

In conclusion, the work discussed here uncovers a robust relationship between people's tendency to overascribe predictive ability to themselves and to exhibit delusion-like ideation and experiences. Although more work is needed to assess the mechanisms underlying this relationship and its clinical utility, the present study provides further demonstration of how low-level features of the mind connect up to people's most fundamental beliefs about reality.

## Methods

A detailed description of the experiment is provided in *Supporting Information*. All procedures were approved by the Yale University Institutional Review Board. Participants gave their informed consent after reading a description of the study, with expected length and payment, in Amazon's Mechanical Turk. They could withdraw their consent at any time by exiting the survey. All data will be made available upon request.

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# Supporting Information

## Bear et al. 10.1073/pnas.1711383114

### SI Methods

The experiment was administered through the Qualtrics platform, and the tasks were written in JavaScript, which was embedded within the Qualtrics study.

**Participants.** Participants were recruited in two batches online, using Amazon's Mechanical Turk. A total of 366 participants (169 female; 36.0 y old) initially completed the study, and then an additional 700 participants were recruited for a second sample, which was included as part of preregistered replication attempt of our main hypothesis (preregistered on aspredicted.org). Although efforts were taken to prevent participants from taking the experiment more than once or from acquiring a completion code on Mechanical Turk without completing the study, several such people were identified and eliminated from further analysis. Our resulting second sample therefore consisted of 647 unique participants (325 female; 35.4 y old), yielding 1,013 participants in total.

**Prediction Task.** On 140 trials, participants were presented with a fixation cross [a 30-pixel (px) +] for 500 ms, following by five empty squares. They were tasked to "pick (in your head) a single square that you think will turn red" before one of the squares was randomly selected to turn red. To limit the amount that participants could plan their predictions in advance, the position of these five squares was randomly chosen on each trial from a set of possible locations of a 5 × 5 grid, centered on the position of the previously shown fixation cross. However, to force participants to attend outside of the place of fixation, a square was never presented directly where the fixation cross had been presented (meaning there were only 24 possible locations from which the squares could appear). Each square had 50 × 50 px dimensions, and the 5 × 5 grid of possible locations spanned a region that was 330 × 330 px (leaving 20 px spacing between each possible square location).

We experimentally varied the delay between the initial presentation of the empty squares and the moment at which one of these squares was selected to turn red. There were seven possible delays: 100, 150, 250, 400, 600, 2,000, and 4,000 ms. (Note, however, that these delays are only approximations, because the experiment was run online, and therefore the exact timing of stimulus presentation was sensitive to the particular frame rate, processing speed, etc. of each participant's computer and monitor.) Each of the seven possible delays was used on 20 trials, presented randomly across the 140-trial sequence.

After a square turned red on a given trial, participants indicated whether they had predicted that square would turn red ("y" key for "yes"), whether they had predicted that a different square would turn red ("n" key for "no"), or whether they did not have time to make a prediction before one of the squares turned red ("d" key for "did not have time"). After giving their response, participants were then prompted to press the enter key whenever they were ready to begin the next trial.

Before the task began, participants were given detailed instructions about how to perform the task (see below for exact wording). In particular, to avoid encouraging participants to report that they made a prediction before a square turned red even on the extremely fast trials in which this was difficult, the instructions emphasized that, although participants should try to make their predictions as quickly as possible, "it's completely understandable and expected that you won't always have a chance to complete your guess in time, even if this is the case on most or all trials." To avoid excessive preparation of one's prediction before the trial began, participants were also instructed to "try to make your guess right when the empty squares appear and no earlier."

Participants needed to answer three comprehension questions correctly to proceed. Those who made a mistake were given one more chance to read the instructions and answer these questions correctly; and if they failed to answer one of the questions correctly a second time, they were booted from the study.

Participants who passed comprehension completed seven practice trials before the main task, consisting of a single trial of each of the seven possible delays, presented in random order.

**Temporal Discrimination Task.** This task again consisted of 140 trials and was visually similar to the prediction task, but asked participants to perceptually judge which of two events occurred first. As before, a fixation cross appeared for 500 ms, followed by five empty squares presented in randomly selected locations from the same 5 × 5 grid described above. However, these squares always remained on the screen for 500 ms until one of two possible events occurred. Either the screen blinked (went completely blank) for 50 ms, or one of the squares was randomly selected to flicker red for 50 ms. (Note that, unlike in the prediction task, this square only temporarily turned red before becoming empty again to preserve symmetry between the length of this event and the screen blink.) Then, after an experimentally manipulated delay in which the empty squares remained again on the screen, the opposite event occurred for 50 ms (i.e., if a blink had occurred first, a red flicker occurred, and vice versa). Participants indicated whether the blink came first ("b" key) or the red flashed first ("r" key).

There were seven possible (approximate) delays between these two events: 66.66, 83.33, 100.00, 133.33, 166.67, 500.00, and 1,000.00 ms. Each of the seven possible delays was used on 20 trials, presented randomly across the 140-trial sequence. Additionally, on each trial, either the blink or the red flicker was randomly selected to occur first. Thus, there were 14 conditions in total.

As in the prediction task, participants read instructions and completed seven practice trials of each delay condition, presented in random order, before starting the main task.

**Subclinical Delusion Questionnaire.** Participants' delusionality (i.e., the amount of delusion-like ideation they experienced) was tested using the 21-item version of the PDI (4).

**Multilevel Analysis.** All multilevel logistic regressions were fit using the *melogit* command in STATA 13.1 with default settings. All variables except the categorical participant identification (ID) were modeled as fixed effects. Participant ID was treated as an intercept-only random effect. More information on STATA's procedure for fitting this class of model is available at www.stata.com/manuals13/memelogit.pdf.

### Prediction Task Instructions

In this part of the experiment, you will be rapidly presented with a "+" sign, followed by a set of 5 empty squares, appearing in various locations on the screen. After a short delay, one of these squares will turn red.

When the + sign appears on the screen, orient your attention to this plus. Then, as soon as the empty squares appear, your task is to pick (in your head) a single square that you think will turn red.

Once one of these squares turns red, you will be asked to report whether or not you had guessed the square that in fact turned red. Use the N key to indicate that you guessed a square that did NOT light up red and the Y key to indicate that you successfully guessed the square that DID end up turning red (we'll remind you of these keys on the main experimental page).

Note that you will not be able to give your response (and the keyboard will not be responsive) until a square lights up red.

Often times, a square will turn red very soon after the empty squares appear, so it's important that you try your hardest to make your guess as quickly as possible. But it's completely understandable and expected that you won't always have a chance to complete your guess in time, even if this is the case on most or all trials. If you do end up failing to complete a guess before one of the squares turns red, simply indicate this by pressing the D key (we'll again remind you of this key on the main experimental page in case you forget).

It's important for our research that you're honest about whether you completed your guess before one of the squares turned red. Please do not "cheat" and claim that you guessed a red square if you only made your "guess" after you saw a square change color. There's no bonus for guessing correctly (guessing the red squares) or penalty for guessing incorrectly (missing the red squares), so if you're unsure about whether you completed your guess in time, simply press D.

It's also important that, whenever possible, you try to make your guess right when the empty squares appear and no earlier. Let the guess "come" to you spontaneously and automatically, without deliberating or strategizing ahead of time. Indeed, the experiment is designed to be completed at a fast pace without having you carefully think through your guesses.

### Prediction Task Comprehension Questions

Participants needed to complete all three of the following questions to proceed to the prediction task. If they made a mistake, they were given the opportunity to read the instructions one more time and try again. If they made an error again, they were paid a small amount and not allowed to continue to the task. Answer choices were presented in randomized order.

*i*) When should you pick a square in your head that you think will light up red?

- When the empty squares initially appear on the screen. [Correct answer.]
- As soon as one of the empty squares turns red.
- Before the + sign appears on the screen.

*ii*) How should you make your guess of a square that will light up red?

- By thinking carefully about which square will light up red.
- By spontaneously letting your guess come to you. [Correct answer.]
- By pressing a random key on the keyboard.

*iii*) What should you do if you don't have a chance to finish making a guess before one of the squares lights up red?

- Report that you guessed a red square (by pressing Y).
- Report that you didn't guess a red square (by pressing N).
- Report that you didn't have time to make a guess (by pressing D). [Correct answer.]

### Temporal Discrimination Task Instructions

In this part of the experiment, you will be rapidly presented with a + sign, followed by a set of 5 empty squares, appearing in various locations on the screen. Then, two events will follow: (*i*) a "blink" of the screen (where the entire screen disappears for a fraction of a second and then reappears); and (*ii*) one of the five squares flashing red. These two events will happen in one of two orders: either the blink will occur before a square flashes red OR a square will flash red before the blink occurs.

Your task is to identify which occurred first — the red square lighting up or the blink of the screen. Use the R key to indicate that the red square lit up first and the B key to indicate that the blink occurred first (we will remind you of these keys on the main experimental page).

You may find this task difficult at times. If you're unsure of which of these events occurred first, please give your best guess. Also, note that you should not assume that the different orders of events will happen with equal likelihood; it may be the case that one kind of order happens much more often than the other.

### Preregistered Results

Our official preregistration is available at https://aspredicted.org/blind.php/?x=wz2c3n.

First, we report the results of our primary analysis in the preregistered sample, after excluding didn't have time responses and the responses of participants who admitted to misreporting their prediction success (as specified in the preregistration report). The resulting sample had $n = 634$ participants. Critically, we examined in a multilevel logistic regression whether the probability of reporting successful prediction as a function of time delay negatively interacted with participants' (log-scaled) PDI total score. The hypothesized interaction was observed: in addition to being generally more likely to report accurate predictions, $b = 0.049$, $z = 2.92$, $P = 0.004$, participants who scored higher on the PDI exhibited a more negative relationship between delay and reported accuracy of their predictions, $b = -0.012$, $z = -2.14$, $P = 0.032$ [model $\chi^2$ (3) = 75.73, $P < 0.001$]. (Note that the $P$ value reported here and elsewhere comes from a two-tailed test. Because we had a preregistered directional hypothesis, a one-tailed test would also be appropriate, resulting in $P = 0.016$.)

We also discuss several secondary/exploratory analyses in the preregistration. One such analysis was to restrict the above regression to participants with nonzero scores on the PDI (resulting in an $n = 576$). After this restriction, the hypothesized interaction no longer reached statistical significance $b = -0.015$, $z = -1.53$, $P = 0.125$; however, it was similar in effect size, suggesting that the lack of significance may have simply been due to insufficient power to detect an effect in this subsample of participants.

We also considered replacing the PDI total score with the answers to just the two yes/no grandiosity items in the PDI (resulting in a grandiosity variable that could take on the values of 0, 1, or 2). Using this variable in place of the PDI total score resulted in an interaction effect that was statistically significant, $b = -0.023$, $z = -2.59$, $P = 0.010$. Follow-up work could explore whether the postdiction effect selectively impacts grandiose delusions or whether this result is simply explained by the fact that this class of delusions is correlated with other questions in the PDI.

Lastly, we examined whether we would continue to get the hypothesized interaction when including the (log-scaled) number of errors on the temporal discrimination task as a covariate in the above model. When including this covariate, our hypothesized interaction between delay and PDI total score remained unchanged, $b = -0.012$, $z = -2.15$, $P = 0.032$.

We also mention the inclusion of a new exploratory measure—the Brief Core Schema Scales—in our preregistered sample (33). These scales comprise four measures: positive-self, positive-other, negative-self, and negative-other, which were log-scaled for interpretation. Positive-other was negatively correlated with (log-scaled) PDI total score, $r = -0.15$, $P = 0.002$; negative-self was positively correlated with PDI scores, $r = 0.33$, $P < 0.001$; and negative-other was positively correlated with PDI scores, $r = 0.40$, $P < 0.001$. There was no significant relationship between positive-self and PDI scores, $r = -0.05$, $P = 0.237$.

Substituting each of these measures in place of the PDI in our main regression analysis found a significant positive interaction between positive-self and delay, $b = 0.021$, $z = 2.12$, $P = 0.034$; a significant positive interaction between positive-other and delay, $b = 0.021$, $z = 2.61$, $P = 0.009$; a significant negative interaction between negative-other and delay, $b = -0.013$, $z = -2.02$, $P = 0.043$; and no significant interaction between negative-self and delay, $b = -0.012$, $z = -1.52$, $P = 0.128$.

However, including each of these measures as covariates in the original model with the PDI and its interaction with time delay did not undermine the previously observed positive main effect of PDI scores, $b = 0.042$, $z = 2.30$, $P = 0.022$, or the negative PDI × time delay interaction, $b = -0.012$, $z = -2.13$, $P = 0.033$.

## PDI Subscale Results

The PDI (4) contains three subscales indexing how much each of the delusion-like beliefs is distressing, preoccupying, and believed to be true ("conviction"). Each of these questions is answered on a 1–5 scale, contingent on the participant answering yes to the yes/no question of whether they have the belief. (Note that the responses to these three subscale questions are included in the PDI total score.)

Below, we report model results from each of these subscales separately. Just like the model with log of PDI total score reported in the main text, each of our models was a multilevel logistic model, with participant treated as a random variable. Each of the PDI subscales was log-scored and mean-centered, along with the time delay. We consider both main effects and the PDI subscale × time delay interaction.

**Distress Subscale.** There was both a positive main effect of (log) PDI distress, $b = 0.050$, $z = 3.01$, $P = 0.003$, and negative interaction with (log) time delay, $b = -0.018$, $z = -3.14$, $P = 0.002$ [model $\chi^2$ (3) = 90.20, $P < 0.001$].

**Preoccupation Subscale.** There was both a positive main effect of (log) PDI preoccupation, $b = 0.070$, $z = 4.20$, $P < 0.001$, and negative interaction with (log) time delay, $b = -0.018$, $z = -3.08$, $P = 0.002$ [model $\chi^2$ (3) = 98.12, $P < 0.001$].

**Conviction Subscale.** There was both a positive main effect of (log) PDI conviction, $b = 0.050$, $z = 3.12$, $P = 0.002$, and negative interaction with (log) time delay, $b = -0.016$, $z = -2.81$, $P = 0.005$ [model $\chi^2$ (3) = 88.94, $P < 0.001$].

In sum, the results from the individual PDI subscales are consistent with those reported in the main text for the PDI total score.

## Computational Model of Prediction Task

To model prediction decisions in our task that would not be postdictively influenced by the appearance of the red square, we consider a simple accumulator, in which a decision is made when the chooser's confidence in one of the five options crosses some threshold $t$, where $0.2 < t \leq 1$.

Choosers begin their decision with equal confidence in each option (0.2, or 1/5, in this case), and then confidence in each option fluctuates from random drift. At all times, the chooser's confidence in each of the options sums to 1. At each time step, confidence in one of the options that is not already 0 is randomly selected to drop by 0.01, and another option is randomly selected from the remaining options to gain 0.01 confidence. This process continues until confidence in one of the options equals or exceeds $t$ or until some maximum number of time steps is reached (representing the time delay before one of the squares turns red in our task). If the maximum number of time steps is reached before confidence in any option crosses $t$, a didn't have time response is recorded. Otherwise, we randomly select a "correct" option from the set of five options and compare it to the chooser's predicted option (the option whose confidence crossed $t$). If the predicted option and correct option match, the decision is recorded as correct; otherwise, the decision is recorded as incorrect.

We simulated 100,000 decisions for three different decision thresholds ($t$ = 0.3, 0.5, or 0.7) and five different maximum decision times (250, 500, 1,000, 2,000, or 4,000 time steps). Importantly, we do not assume that the time steps in the model bear any obvious quantitative relationship to the millisecond time delays used in our task. However, we tried to pick a broad range of times to assess whether the proportion of correct responses varies at all as a function of time, and, just as in our empirical data, we find time delays in which a substantial proportion of simulated predictions are not completed in time.

As shown in Fig. S1*A*, we find no systematic relationship among probability of correct prediction and decision threshold, maximum decision time, or their interaction. (Note that for $t$ = 0.7, the 250 maximum decision time data point is missing because there were no completed predictions for these parameter values.) This is confirmed by logistic regression: the probability of making a correct prediction in this simulated data set (among completed decisions; $n$ = 767,928) was not significantly affected by decision threshold, $b = 0.012$, $z = 0.22$, $P = 0.829$; maximum decision time, $b < -0.001$, $z = -0.58$, $P = 0.559$; or their interaction, $b < 0.001$, $z = 0.29$, $P = 0.768$. The same is true if we use the log of maximum decision time (all $ps > 0.774$).

Thus, it seems that liberal acceptance for translating confidence into decisions alone cannot explain a time-dependent pattern in the probability of successfully predicting the red square.

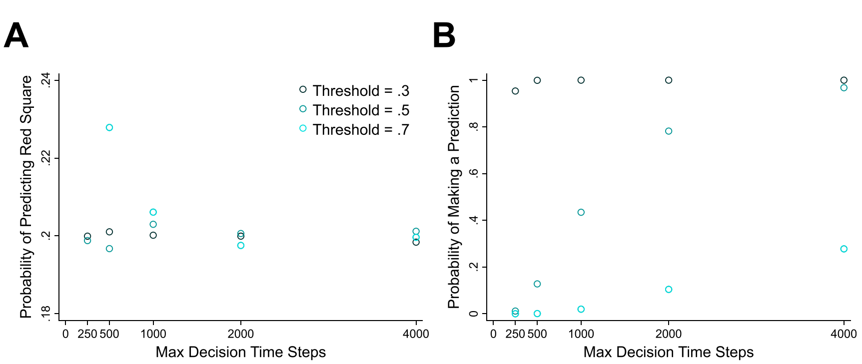


**Fig. S1.** Simulated results of prediction task by decision threshold. (*A*) Probability of reporting a correct prediction of the red square (among trials in which choosers completed their prediction) and (*B*) probability of completing a prediction.