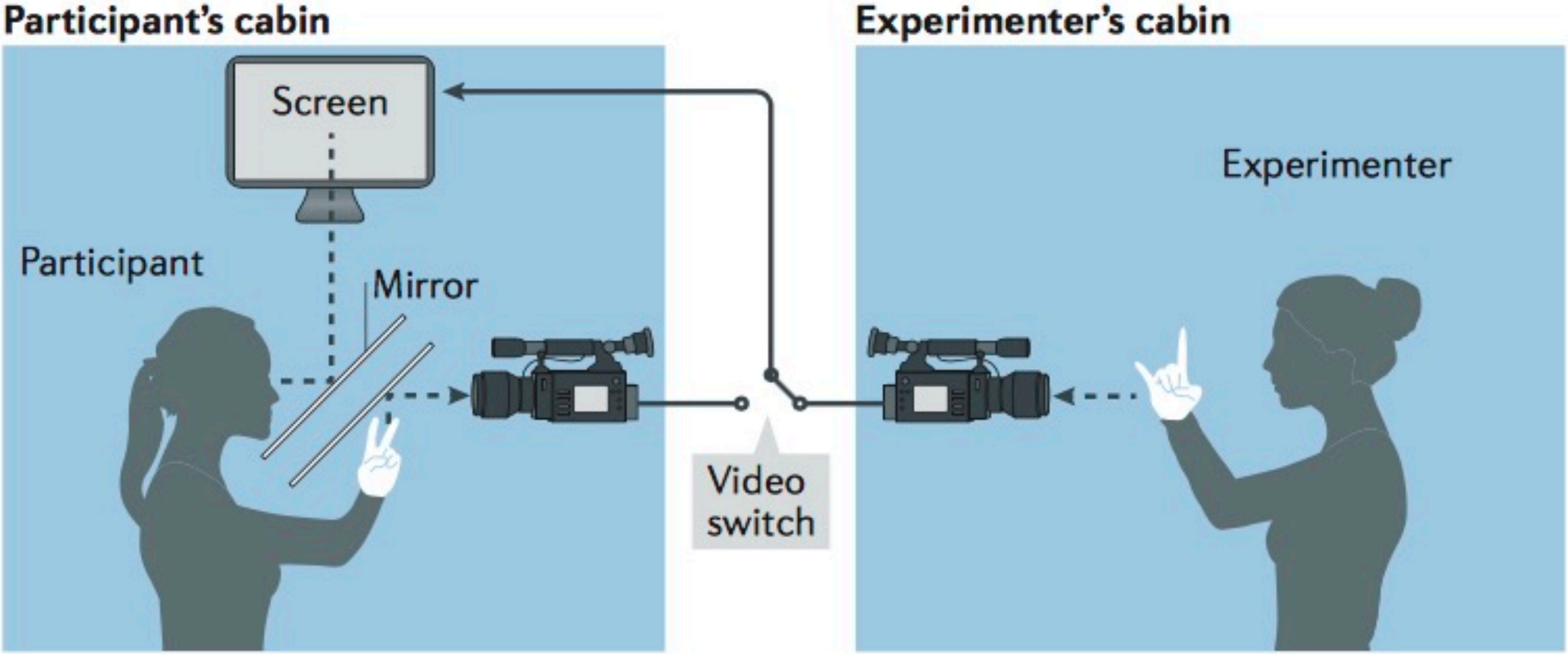

Figure 1 | **Explicit judgments of agency.** Action-recognition experiments can be used to examine explicit judgments of agency. In a typical example of this type of experiment, participants are asked to judge whether a video that they are watching shows their own hand movements or those of another person. Participants are asked to make a specific pattern of hand movement. A screen is connected to a video switch (controlled by the experimenter), allowing the participant to see either their own hand or the hand of an experimenter wearing an identical glove. The experimenter performs either the same hand movement as the subject or a different hand movement. If the participant reports that they are viewing their own hand action, they attribute authorship of the viewed action to themselves. Adapted from Sirigu, A., Daprati, E., Pradat-Diehl, P., Franck, N. & Jeannerod, M., Perception of self-generated movement following left parietal lesion, *Brain*, 1999, **122** (Pt 10), 1867–1874, by permission of Oxford University Press.

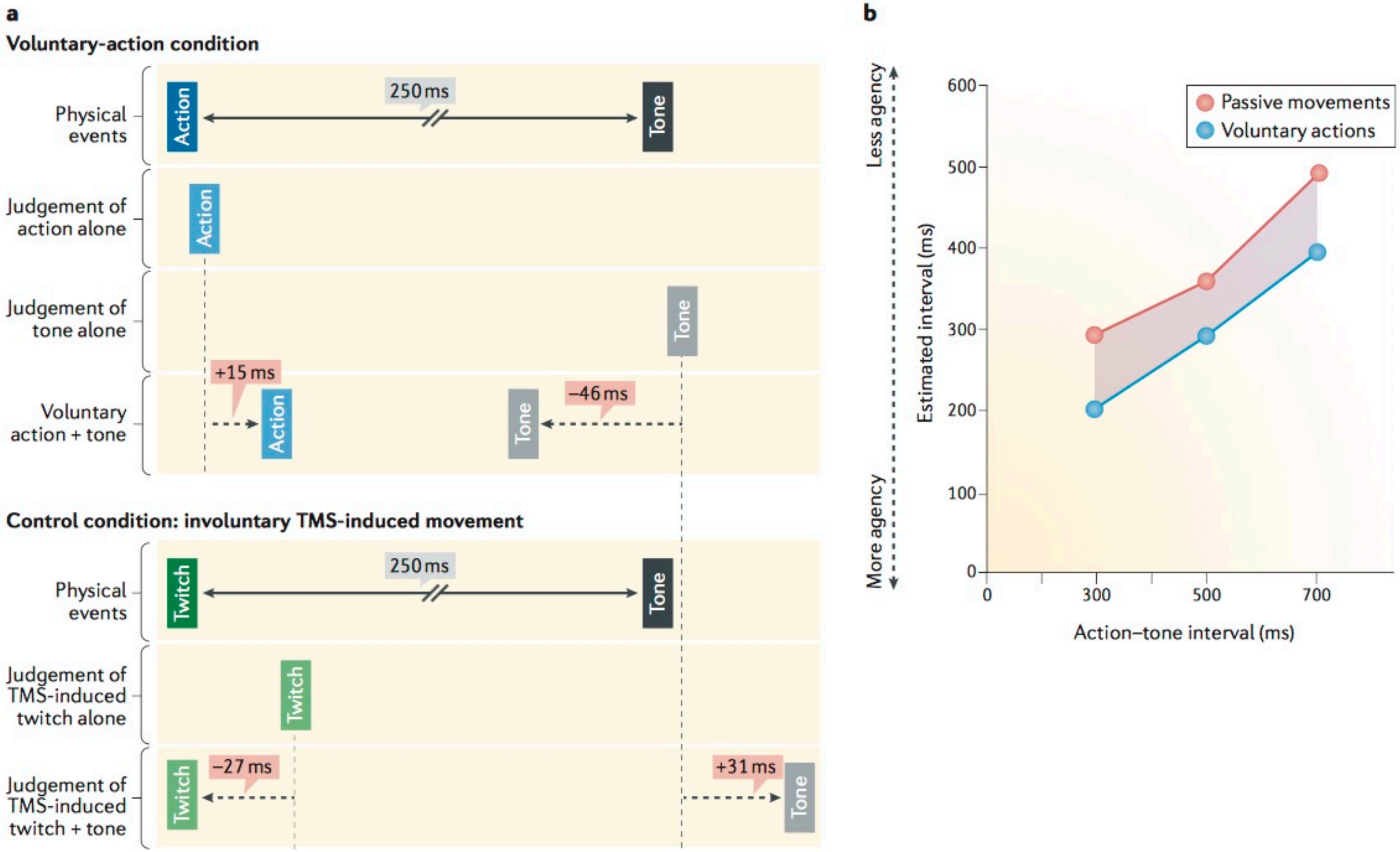

Figure 2 | **Measuring sense of agency implicitly. a** | The schematic shows how the intentional binding task can provide an implicit measurement of sense of agency[45]. In this task, participants view a small rotating clock hand. They make a self-paced button-press action, which triggers a tone 250 ms later (physical events indicated by the dark blue and grey boxes). Thus, participants are expected to experience a sense of agency over the tone. They report the time at which they pressed the button or at which they heard the tone, in separate blocks of trials. First, the participants are asked to estimate the clock time at which they made the action or heard the tone in separate baseline conditions in which only the action or only the tone occurs (estimates indicated by the light blue and grey boxes). Next, in the experimental conditions, the participants themselves cause the tone by their own action and judge either the time of the action or the time of the tone. In this case, the perceived times of the action and tone shift closer to each other (indicated by the dashed arrows, not drawn to scale), relative to the baseline conditions. This produces an intentional binding effect. Replacing the intentional action with a physically similar but involuntary movement (a twitch evoked by transcranial magnetic stimulation (TMS) of the motor cortex) has the opposite effect (dark and light green boxes indicate the time of the actual twitch versus the estimated times of the twitch). Thus, sense of agency can be measured implicitly and quantitatively using the magnitude of perceptual shifts in action and tone timing. **b** | In an interval-estimation paradigm, participants give an absolute verbal estimate of the delay (in ms) between a key-press action and a tone that follows after a short but somewhat variable delay. Lower estimated delays correspond to a greater sense of agency[93]. Thus, estimates are shorter for a voluntary key press than they are in a control condition in which the finger is passively pushed onto the response key. The actual intervals between key press and tone are randomized but are always shorter than 1 second to prevent counting. Part **b** is adapted with permission from REF. 38, Elsevier.

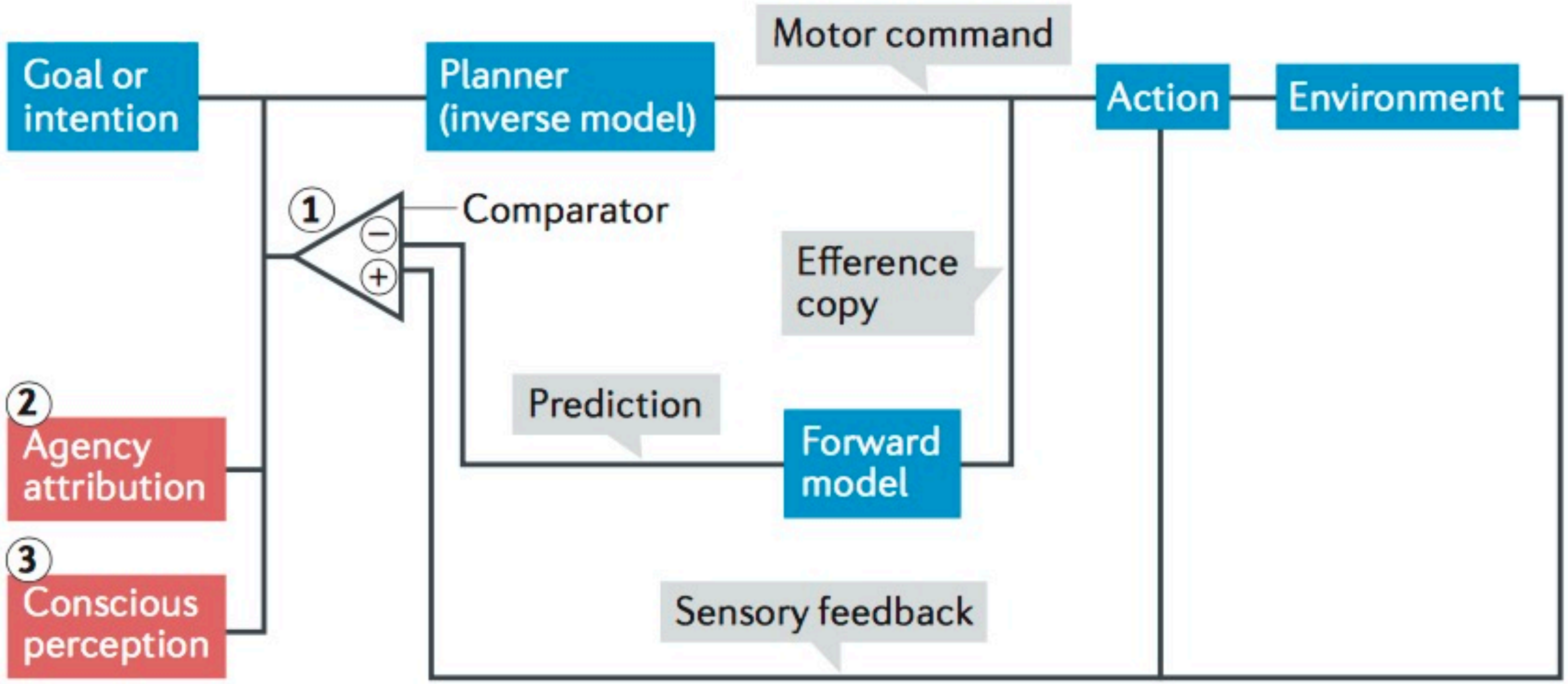

Figure 3 | **The comparator model for neural control of action and agency.** In the comparator model of action control, an action begins with an intention or desired goal state. An inverse model computes the motor command that is required to achieve the goal state (or at least to approach it) and generates the motor command that will drive the action. A forward model uses a copy of the current motor command (known as an efference copy) to predict the probable sensory consequences of the command[56]. This prediction is compared with sensory feedback signals that provide information about the ongoing action and about its effects on the external environment. The result of the comparison can be used in three ways: to adjust the current motor command (**1**); to attribute agency for actions and environmental events (**2**) (if the comparator gives a result of zero then the event is caused by one's own action); and to attenuate predictable, self-produced sensations (**3**).

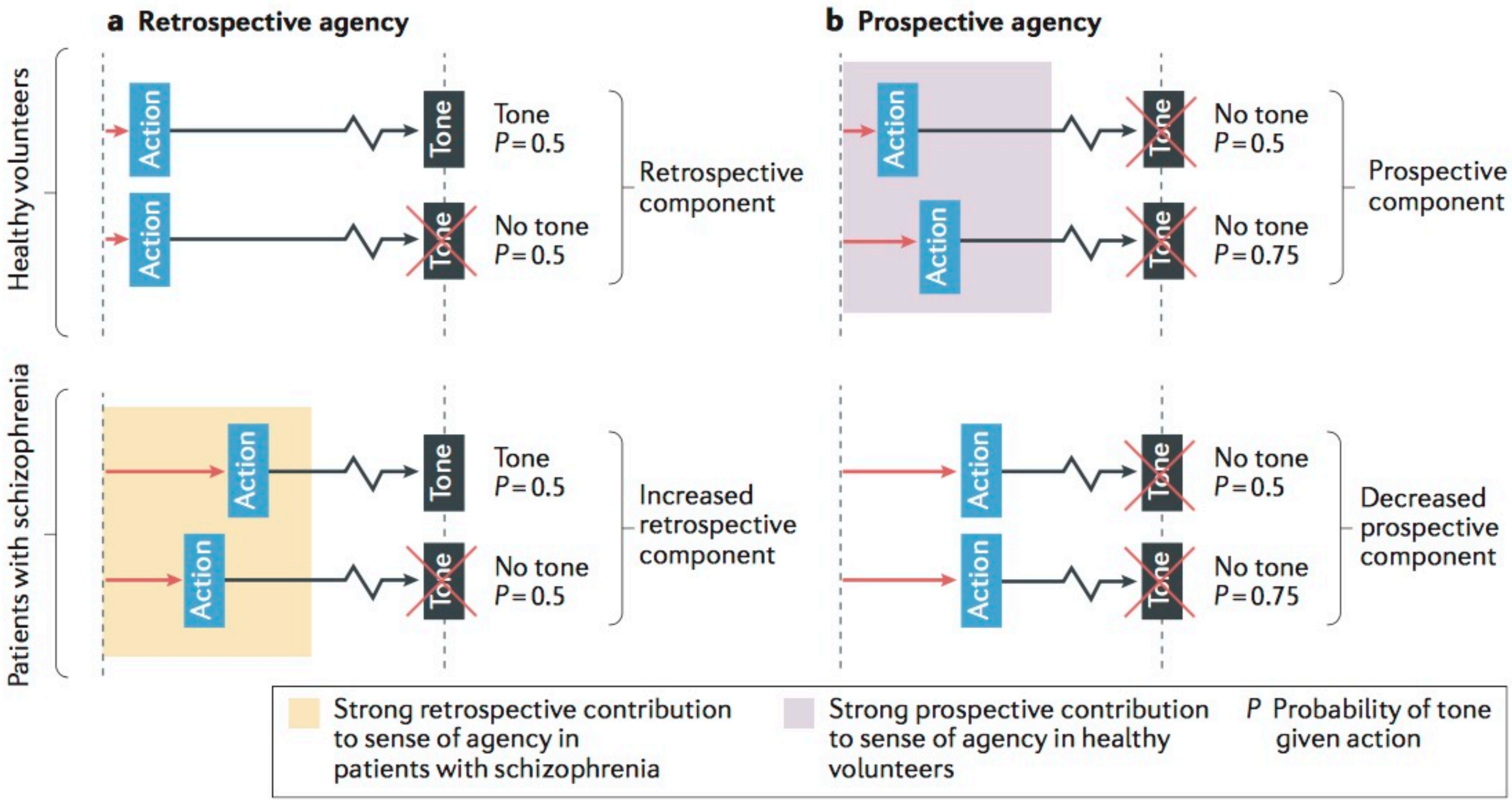

Figure 4 | **Prospective and retrospective agency.** The schematics illustrate the results of an experiment that used the intentional binding effect to distinguish between prospective and retrospective components of the sense of agency. **a** | Voluntary actions were followed by tones in 50% of trials (trials chosen at random). In healthy volunteers, the perceived time of the action (blue rectangles) was shifted towards the tone (red arrows, not drawn to scale) and independent of whether the tone occurred or not. In patients with schizophrenia, the perceived time of the action showed a general shift towards the time of the tone (grey rectangles), perhaps indicating poor attention to time. Crucially, the perceived time of action was shifted more in trials in which the tone actually occurred than in trials in which it was omitted. Thus, for the patients with schizophrenia, the tone triggered a retrospective reconstruction of the experience of the action. **b** | To assess prospective components of sense of agency, the perceived time of action was compared between two blocks of trials, which differed in the probability that the action would cause a tone. Only the trials in which no tone actually occurred are shown. In healthy volunteers, the perceived time of action showed stronger shifts when a tone was highly likely to occur than when the tone was less likely to occur. Thus, the strength of predictions about the tone influenced the experience of action. This prospective aspect of sense of agency was absent in patients with schizophrenia. These results suggested that the sense of agency in healthy volunteers is based on predictions that use knowledge about action–outcome relations, whereas the sense of agency in patients with schizophrenia is based on retrospective reconstruction. Adapted from Voss, M. *et al.*, Altered awareness of action in schizophrenia: a specific deficit in predicting action consequences, *Brain*, 2010, **133**, 3104–3112, by permission of Oxford University Press.

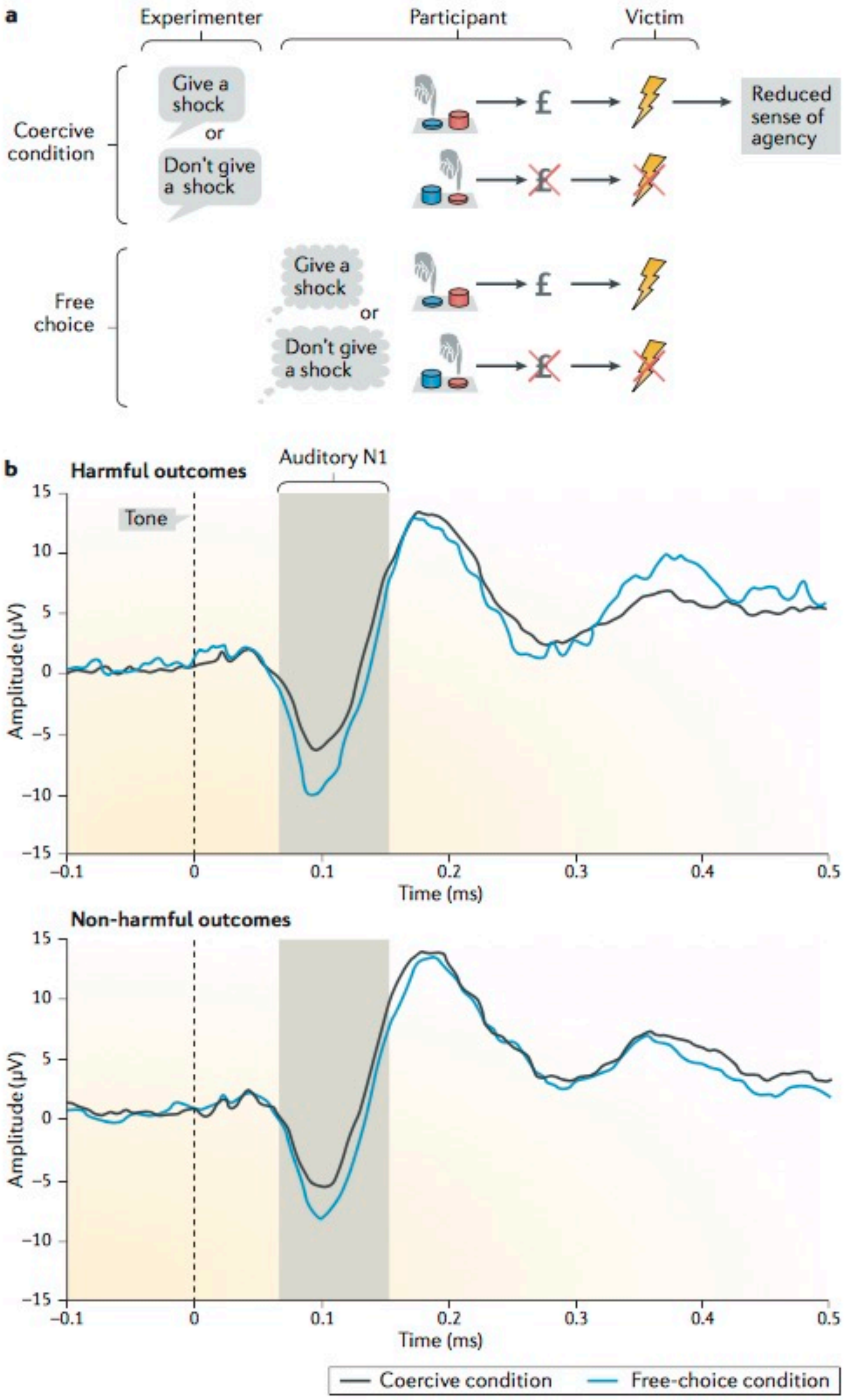

Figure 5 | **Coercion reduces sense of agency. a** | The schematic illustrates an experiment testing the effects of coercion on sense of agency[92]. The participant was asked to estimate the time interval between a button press and a tone. In the coercive condition, the experimenter told the agent which key they had to press before each trial. One key would deliver a painful electric shock to a 'victim' at the same time as the tone and also bring the agent a financial reward. Another key delivered no shock to the victim and earned the agent no money. In a free-choice condition, the agent could choose between the same two keys, and the experimenter gave no instructions. The agent's estimates of intervals between action and tone were significantly greater when they were coerced into giving the victim a shock than when they freely chose to do so, suggesting a reduced sense of agency under coercion. **b** | Event-related potentials (ERPs) evoked by the tone are shown. Coercive instructions reduced the amplitude of auditory N1 component of the ERP, suggesting that the neural processing of action outcomes was reduced in the coercive condition compared with a free-choice condition. This effect was seen both when the action lead to a painful shock and when it did not. Part **b** is reproduced with permission from REF. 92.