Neuropsychologia 133 (2019) 107156

Contents lists available at ScienceDirect

Neuropsychologia

journal homepage: www.elsevier.com/locate/neuropsychologia

Free Wally: Where motor intentions meet reason and consequence

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ARTICLE INFO

Keywords:
Consciousness
EEG
ERD
Free will
Motor intention
Readiness potential

ABSTRACT

To investigate the neural preparation and awareness of an intention to act, neuroscientists typically examine spontaneous movements: self-paced flexions of the hand or foot. However, these movements may not present a straightforward case of intended action as they are performed in absence of reasons to act and without the evaluation of action consequences. Therefore, a common criticism of these studies is that they lack ecological validity, because the results do not generalize to the more societally relevant deliberate actions that we perform in daily life. We agree that research on intended action should include reason-based deliberate actions in order to be more relevant for debates about human agency and free will. Therefore, we have developed a computer game called “Free Wally”, which invites players to perform deliberate actions to achieve a goal. Free Wally provides a controlled environment for studying deliberate intended action, by presenting information for deciding *whether* or not to act, *what* action to perform and *when* to perform it, incorporating all basic components of an ecologically valid intended act. As a first step to validate our setup, we compare this game to a second computer game that measures spontaneous actions in a traditional way. While playing either game, the timing of the experienced intentions to act is measured using a real-time probing method. Moreover, the neural preparation for action is measured in terms of the (lateralized) readiness potential and alpha/beta event-related desynchronization across the motor cortex. No differences were found between the games in these last stages of action preparation, suggesting that the Free Wally game can be used to study intended action. However, differences in earlier stages during intention formation are to be expected. With Free Wally as a tool, we hope to encourage further research into the formation and content of ecologically valid motor intentions.

1. Introduction

Research on the relation between the neural preparation and subjective experience of an intention to act focuses mostly on one type of action: spontaneous movement. Specifically, self-paced wrist extensions, finger flexions or button presses (for an overview: see Saigle et al., 2018). Although some studies investigate spontaneous decisions rather than movements (e.g. Bode et al., 2013; Soon et al., 2013), it is the general element of spontaneity that seems most important for actions to be considered free (Deutschländer et al., 2017; Haggard, 2019). However, it is also the element of spontaneity that makes these actions most trivial (Banks and Pockett, 2007). Imagine you are a participant in a Libet-type experiment (Libet et al., 1983). You are instructed to perform a self-paced wrist extension whenever you feel the intention to do so. As soon as you notice an intention to move, you are asked to remember and report the configuration of a clock that is in front of you. As you may notice, this task feels quite artificial. There are no apparent reasons to perform the action, other than to follow the experimental instructions. Moreover, action performance has no noticeable effect on the environment, nor does it involve any consequences that can be evaluated and experienced by the actor or others. When asking for the motivations behind such acts, one receives no further explanations other than ‘I just wanted to’ or simply a shrug. This is not the type of action about which societally relevant questions regarding responsibility, accountability, or even free will, will be raised (Nachev and Hacker, 2014; Mecacci and Haselager, 2015).

The spontaneous actions measured by neuroscience research are not the most straightforward cases of intended action. Besides the lack of reasons and consequences, it is questionable whether these actions would be preceded by a consciously experienced intention in daily life. Therefore, the reported intention onsets in Libet-type experiments may relate more to the onset of an *urge* than an intention to act (Mele, 2010; Roskies, 2011). For these reasons, neuroscience experiments on intended action have often been criticized about whether their results will hold for the more complex and deliberate actions that we may perform in daily life (Radder and Meynen, 2013; Saigle et al., 2018).

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https://doi.org/10.1016/j.neuropsychologia.2019.107156
Received 12 March 2019; Received in revised form 29 July 2019; Accepted 2 August 2019
Available online 05 August 2019
0028-3932/

1.1. Requirements for deliberate intended action

In order to study deliberate intended action in an ecologically valid way, we suggest the following aspects should be represented in an experiment:

1. A *goal*: something you want to achieve. Your actions are an attempt to reach that goal.
2. A *strategy*: the course of action by which you can achieve your goal.
3. Some type of *deliberation*: inference based on relevant stimuli, leading up to a decision to act. We consider actions to be free when there are reasons for acting, but these reasons do not compel one to do anything in particular (Mecacci and Haselager, 2015).
4. An *intention*: being or becoming committed to an act. In daily life, intended actions usually involve three components: we need to decide *what* we want to do, *when* we want to do it and *whether* or not we still want or can do it when the time comes (Brass and Haggard, 2008).
5. An *action*: e.g. an intended movement. Immediate actions are performed as soon as the intention to act arises. With planned actions, there is some time between the intention to act and the action performance.
6. A certain *outcome*: the change in the environment caused by the action.
7. The *consequences* of the achieved outcome: the impact of the outcome. Certain outcomes can lead to consequences that could evoke an evaluative or emotional experience, such as a sense of achievement or failure, or pride or shame.

Each of these aspects can involve a sense of responsibility. For instance, a person is responsible for setting their own goal and for selecting, evaluating and executing a strategy to achieve that goal. We believe that these elements are required for experiments measuring deliberate intended actions to be considered ecologically valid and therefore societally relevant. One needs to perform experiments including these factors to validate that they do not invalidate the conclusions of less ecologically valid experiments.

1.2. Free Wally

We have implemented each of these elements in a computer game called "Free Wally". Free Wally allows players to perform intended actions to achieve a goal: free a whale that is held captive on top of a hill. Stimuli provide reasons to act and actions have consequences, increasing the ecological validity of the measured actions. The game offers a choice of *what* action to perform, *when* to perform it and *whether* to execute it, incorporating all components of an intention (Brass and Haggard, 2008). Although external stimuli play a role in the development of an intention to move, commitment to an intention is based primarily on the player's own initiative. This type of intention involves the availability of options to the player about what to do, and requires a decision (Mele, 2007). It is this type of intended action for which a person can explicitly formulate why they chose to behave a certain way, including evaluations of the intention, the act and its outcomes. Moreover, it is this type of action that we consider most important for our feeling of agency and free will (Roskies, 2011; Mecacci and Haselager, 2015).

Distinctive neural activities have been found predictive of, or correlated with, the *what, when* and *whether* components or *phases* (as argued in Verbaarschot et al., 2016) of intended action (Brass et al., 2013; Zapparoli et al., 2017). These distinct activities are usually identified by allowing the freedom to decide on only one out of three decisions, e.g. contrasting self-paced button presses of the right hand (fixed *whether* and *what,* free *when*) with spontaneous left and right hand button presses at a cued moment in time (fixed *whether* and *when*, free *what*) (Krieghoff et al., 2009; Hoffstaedter et al., 2012). The task that a participant needs to perform in this type of experiment is often quite artificial, e.g. intend to press a button with your right hand and at the last possible moment in time, veto your act (Brass and Haggard, 2007). In daily life, we usually decide on all three *what*, *when* and *whether* components prior to an intended act. Moreover, we do so based on reasons rather than acting of out of the blue. Importantly, we have the freedom to decide to do nothing: we are not required to act. This element is often missing in previous research, as participants are usually required to act on every single trial. Focusing only on one or two out of three phases of intending may lead to incomplete datasets that may fail to capture the full story behind an intended act. Moreover, although the neural correlates underlying these phases have received some attention, the potential differences in awareness of these phases has been left largely unexplored. With the exception of Soon et al. (2008), who investigated the timing of the awareness of the *what* and *when* phase separately, all studies seem to assume that there is only a general awareness of intending to act, ignoring potential differences in the timing of the subjective experience of the *what, when* and *whether* components. Linking the subjective experience of these components with the underlying neural correlates may increase our understanding of human motor cognition. Free Wally can be used as a tool to do so.

1.3. Measuring the timing of a conscious intention to act

To measure the subjective timing of the *what*, *when* or *whether* phases of intending to act, Free Wally adopts the probe method designed by Matsuhashi and Hallett (2008). While a participant is playing Free Wally, an auditory probe may be presented at a pseudo random moment in time. When at the moment a probe is presented, the player:

a. Experienced an intention to act; they should cancel (*veto*) their action and wait for the next trial to start
b. Did not experience an intention to act; they should *ignore* the beep and continue the game.

Every time that a player did not intend to act during a trial, they are asked to confirm whether or not they vetoed their action in response to the probe that was presented during that trial. By looking at the timing of all probes that were ignored by a player and followed by an action, one can infer the time range relative to action onset during which a player experienced an intention to act: the distribution of ignored probes will show a gap prior to action onset. During this period, presented probes were followed by a veto response, indicating that the participant experienced an intention to act at that moment in time. Matsuhashi and Hallett used this strategy to investigate the subjective timing of the *when* phase of intending to act. However, one could easily adopt this strategy to measure the timing of the awareness of the *what* and *whether* phases. To investigate the *what* phase, the player would need to veto their action when a probe is presented at a time when they know *what* action they intend to perform. To investigate the *whether* phase, the player would be instructed to revert their decision to act or not act when a probe is presented at a time when they decided *whether* or not to act: i.e. the player should act when they decided not to act, or veto when they decided to act. After every action, the participant would be asked to confirm whether or not they reverted their *whether* decision due to a probe. Unlike Libet's clock method, the probe method is insensitive to potential post-hoc influences of action execution or consequence on the reported timing of an intention because all intention reports are collected prior to action onset (Verbaarschot et al., 2019).

1.4. Comparing spontaneous and deliberate actions

As a first step, we test Free Wally against another game called the "Object Game", which mimics the traditional designs of previous research and measures self-paced actions. The stimuli are made similar to Free Wally, in terms of their appearance and behavior, but lack any meaning: the actions are unreasoned and have no consequences. Therefore, the Object Game measures *spontaneous* actions: actions based on urges. In contrast, Free Wally measures *deliberate* actions: intended actions that are done for reasons and have consequences. To investigate whether the most frequently claimed results of previous research hold within the more ecological valid setting of our Free Wally game, we measure the timing of only the *when* phase of intending. In addition, we measure the (lateralized) readiness potential (Haggard and Eimer, 1999; Kornhuber and Deecke, 1965; Shibasaki and Hallett, 2006; Verbaarschot et al., 2015) and 8–30 Hz event-related desynchronization (ERD) (Pfurtscheller and Berghold, 1989) across the (pre)supplementary motor area. The readiness potential (RP) can start up to 2s prior to movement onset and consists of a slowly decreasing negative potential that is maximal over the vertex (i.e. Cz). Around 500 ms prior to movement onset, the RP is most negative on the contralateral side of the hand that is about to move. Similar to the RP, the 8–30 Hz ERD is visible up to 2s prior to movement onset and becomes more pronounced around 500 ms on the contralateral side to the hand that is about to move. Whereas the early part of the RP and 8–30 Hz ERD are thought to be predictive of *when* a person will move, the late parts also indicate *what* movement a person will perform (Pfurtscheller and Berghold, 1989; Shibasaki and Hallett, 2006).

The exact relationship between these brain signals and the experience of an intention to move or the performance of a movement remains unclear (Mele, 2010; Radder and Meynen, 2013). Both the (L)RP and 8–30 Hz ERD have been used to detect voluntary movement onset in real-time (e.g. Bai et al., 2011; Lew et al., 2012; Schultze-Kraft et al., 2016). However, although some predictions occur shortly (620–100 ms) prior to movement onset, many (around 45%) motor intentions are missed or are "predicted" after movement onset. This suggests that self-paced movements are at least not consistently preceded by a detectable (L)RP or 8–30 Hz ERD. Although these brain signals may not be sufficient or necessary for movement performance, they do seem to correlate to some degree with the experience of an intention to move. For example, the RP specifically precedes self-paced voluntary movement, but not involuntary or cued movement (Jahanshahi et al., 1995; Shibasaki and Hallett, 2006). Moreover, the RP increases with intentional engagement and decreases with mental indifference (Kornhuber and Deecke, 1965). Lastly, the RP is visible prior to a moment at which a person reports experiencing an intention to move, even in absence of movement performance (Verbaarschot et al., 2019). Investigating the (L)RP and 8–30 Hz ERD prior to spontaneous and deliberate intended movements may further increase our understanding of these signals in relation to the experience of an intention to move.

By comparing Free Wally and the Object Game, differences in neural preparation for- and awareness of-intentions between spontaneous and deliberate movements are investigated. With this data, we aim to verify that actions are experienced as more deliberate than spontaneous in Free Wally compared to the Object Game. Moreover, we will verify that Free Wally does not determine a single "correct" action, having participants perform a variety of possible actions across identical situations in the game, thus measuring self-paced voluntary actions rather than cue-based actions. We further investigate the influence of stimulus dependence on the neural preparation- and experienced intention-to act using Free Wally. Specifically, we investigate whether there is a difference in the (L)RP/8-30 Hz ERD or the timing of an experienced intention between Free Wally trials that have a clear optimal action (i.e. one action has the highest reward) and those that do not (i.e. all possible actions lead to more or less equal rewards). Although we do not expect any differences in the neural preparation for movement because the performed movements are identical between games (i.e. self-paced left- and right-hand button presses), we do expect potential differences in experience of an intention to act. Free Wally requires active reasoning about the current game situation with a long-term goal in mind, whereas the Object Game requires explicit attention to the occurrence of spontaneous intentions. Perhaps it is easier to report the timing of an intention to act when there are reasons to act (Free Wally), leading to a clearly defined period in time during which vetoes are performed in response to a probe. In absence of these reasons (Object Game), it may be difficult to determine the onset of an intention, providing a very broad window in time during which vetoes are performed. If the (L)RP (and possibly 8–30 Hz ERD) are indeed sensitive to differences in the experience of an intention to act (as suggested above), a difference in these signals may be observed between Free Wally and the Object Game.

1.5. *Testing Free Wally*

In this first experiment, we aim to verify Free Wally as a tool to study ecologically valid intended movements in an experimental context. Although we focus only on the last stages of the neural preparation for movement (i.e. (L)RP and 8–30 Hz ERD) and measure the timing of only the *when* phase of an experienced intention, Free Wally is suitable for further research into the formation and content of motor intentions. Specifically, Free Wally is designed to disentangle the neural preparation and subjective experience of the *what*, *when* and *whether* phases of intending to act. Disentangling these phases will further advance our understanding of human cognition and may benefit the development of brain-controlled prosthetic devices or rehabilitation techniques. If we can detect what movement a person wants to perform at the moment that they experience an intention to do so on the basis of brain activity, we can use this to develop e.g. a prosthetic arm that moves only when a user intends to move. For these devices to work outside of a controlled scientific environment, one needs to acquire datasets that are representative of real-life situations, thus measuring deliberate rather than spontaneous intended actions.

2. Materials and methods

2.1. *Experimental design*

Two computer games are tested in a between-subject experiment[1]: the Object Game and Free Wally. During the experiment, participants are seated on a comfortable chair in front of a table inside a quiet room. A 17-inch TFT screen with a resolution of 800 by 600 pixels and a refresh rate of 60 Hz is used to present stimuli at a distance of roughly 70 cm in front of the participant (visual angle: 12°). Both games are controlled via a button box with 5 buttons. Probes are presented through speakers. Experimental control is done in BrainStream.[2]

Participants are trained on at least 10 trials of their (randomly assigned) target game until they completely understand its rules. After this, the participants complete another training block of at least 20 trials. This block is used to collect some initial data on their action distribution, which is used to create an initial probe distribution. The probes are used to investigate the timing of the awareness of intending to act while playing either game. Each game contains a total of 36 unique trials in terms of stimuli appearance and behavior (see Supplementary Material A). During testing, these trials are repeated 4 times per participant in a random order, adding up to 144 trials per participant. Each test block contains at least 15 trials and takes about 5min to complete. At the end of the experiment the participants complete a short questionnaire on their subjective experience during the

[1] Pilot tests were conducted in a within-subject fashion, where participants played both games. However, the experiment was too long (> 2 h) to be conducted like this without leading to fatigue. Because Free Wally is intended to measure ecologically valid intended actions in an engaging and fun way, this -in our opinion-implies limiting the amount of time that a participant needs to sit still and pay attention (as is required when measuring EEG).

[2] See www.brainstream.nu.

game. In total, the experiment takes about 1 h and 40min.

During the experiment, EEG data is collected using 64 Ag/AgCl active electrodes sampled at 512 Hz, placed according to the International 10/20 system. 4 Electro-oculogram (EOG) electrodes are placed in bipolar pairs above and below the left eye and on the outer sides of both eyes. Furthermore, an electro-myogram (EMG) is recorded from two bipolar electrode pairs on the wrist and the center of the left and right forearm (flexor pollicis longus).

2.1.1. Free Wally

Free Wally is a 2D game made in Unity[3] (see Fig. 1), designed to generate deliberate actions in an artificial environment. The exact instructions for participants are provided in Supplementary Material B. In the game, participants try to free a whale called Wally that is held captive on top of a hill. Every 'day' in the game (corresponding to a trial in the experiment), 5 people appear on each side of the hill. Initially, these people are grey (see Fig. 3). Over time, they show their identity by changing color: friends turn green and hunters turn red. Hunters try to strengthen the cage and friends try to break it down. Wally has one defense mechanism: once each day, he (the participant) can decide to shoot water from his blowhole in order to flush away all the people on one side of the hill and prevent them from approaching the cage. When Wally shoots water, the identity of all the people is revealed. Wally does not need to shoot but can also do nothing. When either all the people have revealed their identity, or after Wally has shot, all remaining people will start walking towards the cage.

Over time, hunters get stronger and friends get weaker, which is displayed by them growing or shrinking in size. Their strength determines how many (between 0 and 2) bars they can remove from, or add to, the cage. Due to this time penalty, there is a trade-off between waiting to gather enough information to make a sensible act, and acting to prevent hunters from gaining power and friends from growing weak. It takes multiple days to free Wally from his cage. However, Wally can only survive 15 days without water. If he shoots, his water supply runs out faster: Wally has enough water to shoot 10 times. This means that the participant has to take Wally's water supply into account when deciding whether or not to act.

In order to minimize eye artifacts, a fixation cross is displayed in the middle of the hill while the people reveal their identity. The game window is small enough that participants can see all people while keeping their eyes fixed on the fixation cross. While the fixation cross is visible, the only things that are animated are Wally (wagging his tail and blinking every once in a while) and the sea (flowing from left to right). In 12 out of all 36 unique trials (see Supplementary Material A), Wally will shortly whistle (animated with musical notes, without sound) or cry during this period, for additional motivation of participants. Once the participant acts or all people are revealed, the fixation cross disappears and the people start walking towards the cage. When they have added or removed their bar(s), the people vanish into thin air.

Free Wally implements all aspects (as described in Section 3.1.1) that we believe are necessary to study deliberate action in an ecologically valid way:

1. *Goal*: in Free Wally, participants can choose to free Wally or let him dehydrate. Moreover, participants will play multiple runs (± 10 to 15) of Free Wally during the experiment to try and break a (fake) high score across these runs.
2. *Strategy*: participants need to come up with a strategy on *whether* or not to act, *when* to act and *what* action to perform.
3. *Deliberation*: Free Wally evokes actions that are in-between self-initiated and stimulus-response: although stimuli provide reasons to act, they do not lead to a specific action. Specifically, stimuli provide reasons to decide *whether* or not to act, *what* action to perform and *when* to act, but avoid a clear stimulus-response design in which certain stimuli directly cue a certain action. The participant has to come up with their own course of action based on the information that is available to them, i.e. they go through a problem-solving process to reach an optimal choice of action. They may not be conscious of this deliberation process, but once they have acted, they should be able, e.g. when asked, to describe their reasons for acting in terms of the presented stimuli. In order to create stimuli that do not provide a direct cue for a specific action, we implemented certain equivocal phases into the game:
   - Equal ratio of friends/hunters on both sides of the hill. For example, if there are 3 hunters on the left and 3 on the right of the hill, shooting left or right is optimal.
   - Random order of revealing friends/hunters. For example, if 2 hunters are revealed on the left side of the hill, you might be inclined to shoot left. However, it can be the case that another 3 hunters will be revealed on the right of the hill, which would make a shot to the right more optimal.
   - Time penalty: friends get weaker over time and hunters get

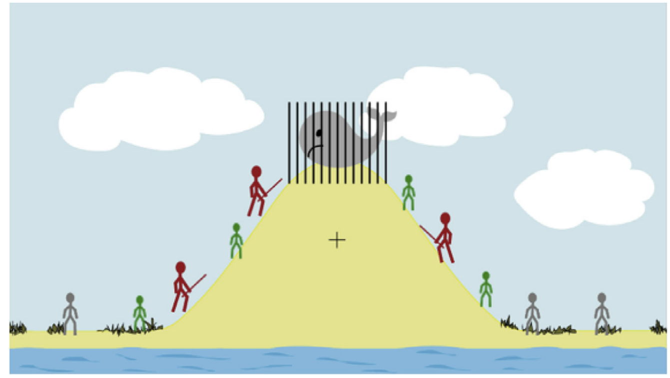

Fig. 1. "Wally is a sad little whale. He has been captured on top of a hill. Wally wants to break free and join his friends in the sea. But he can't because hunters are building a cage around him. Fortunately, he also has some friends who try to break down the cage. Wally (you) can try to flush away the hunters by shooting water from his blowhole. However, he has to be careful not to flush away his friends …" (fragment from Free Wally instructions).

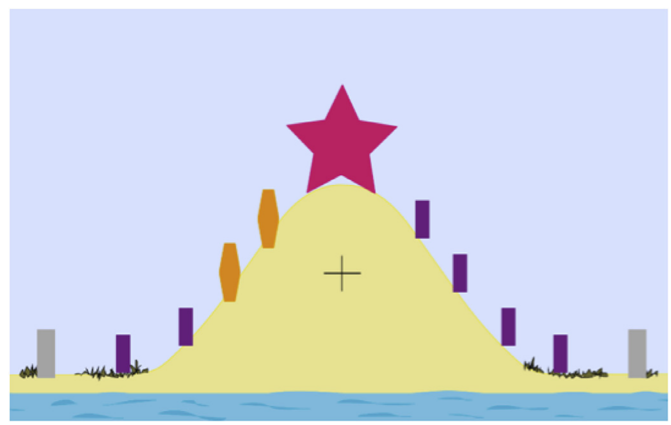

Fig. 2. "This game is set on a hill along a sea side. On top of the hill, is a red moving object in the shape of a star. Each round, grey objects will appear on the hill. Over time, these grey objects can change in size and receive a certain color. The objects, their size and color have no meaning. They do not matter. Your task during this game is to press button 1 or 5 whenever you feel like it. … Important: let the intention to act be the only incentive to act. In other words, do not let the game influence your button presses in any way …" (fragment of Object Game instructions). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

[3] www.unity3d.com.

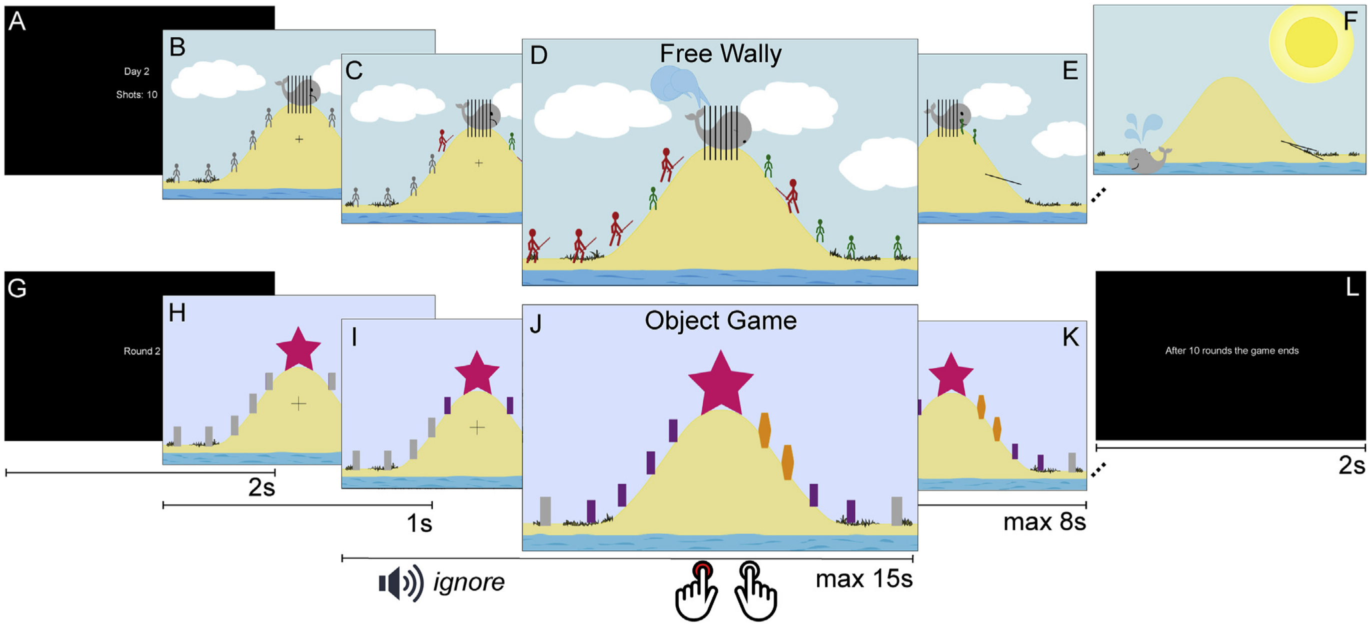

Fig. 3. Screenshots of Free Wally (A–F) and the Object Game (G–L). A, At the start of a 'day' in Free Wally, the current day and water supply (i.e. the remaining number of shots) are indicated. B, Initially, all people are grey. C, At random intervals between 0.5 and 1.5s, people reveal their identity: friends turn green and hunters turn red. Over time, the hunters grow stronger and the friends grow weaker, which is reflected by their size. During this time, a probe can be presented. When the participant is not experiencing an intention to act at that moment in time, they can simply ignore it. D, By pressing a button with their left or right hand, the participant can have Wally shoot water to the left or right side of the hill. This shot will wash away all people on that side of the hill. As soon as the participant presses a button, the fixation cross disappears. E, At the end of a day, the remaining people walk up the hill: friends will remove bars from the cage and hunters will add bars. How many bars are added or removed depends on the strength of the hunter or friend (ranging from 0 to 2 bars). F, Eventually, the goal of the game is to break the cage down completely and have Wally return to the sea. G, At the start of a round in the Object Game, the total number of played rounds is indicated. H, Initially, all objects are grey. I, At random intervals between 0.5 and 1.5s, objects receive a color: rectangles turn purple and hexagons turn orange. Over time, the hexagons increase in size, while the rectangles decrease in size. During this time, a probe can be presented and followed by an ignore or veto response. J, During I, the participant is free to perform a button-press with their left or right hand. K, Once the participant presses a button, the fixation cross disappears and the game will continue for another 0–8s. L, After 10 rounds the game ends, which is displayed on the screen. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

stronger. There is a tradeoff between waiting until you have enough information in order to act sensibly and acting early in order to prevent weak friends and strong hunters. Participants must decide for themselves when the time is right to act.

4. *Intention*: Free Wally is designed in such a way that it provides input for the *what*, *when* and *whether* phases of intending (Brass and Haggard, 2008; Verbaarschot et al., 2016). The *what* phase corresponds to deciding to shoot water to the left or right side of the hill: this corresponds to a left- or right-hand button press. This decision can be based on the ratio of hunters and friends that are visible on the left and right side of the hill. The *when* phase corresponds to deciding to shoot water at a specific time. This decision can be based on the current amount of information about the people's identity and the size of the revealed friends and hunters. The *whether* phase concerns the decisions about whether or not to act during a certain day (in the game). This *whether* decision can be based both on the amount of water that Wally has left before he dehydrates, and the ratio of revealed friends and hunters. In this experiment, a probe method (Matsuhashi and Hallett, 2008) is used to measure the timing of the awareness of the *when* phase of intending.
5. *Action:* Free Wally could involve both immediate and postponed actions.
6. *Outcome*: the outcome of an intended action within Free Wally is a button press, leading to the visualization of Wally shooting water to the corresponding side of the hill and the disappearance of all people on that side.
7. *Consequences*: every action can lead to certain evaluative or emotional experiences: a sense of doing well or badly, feeling happy to have washed away many hunters and being closer to your goal, feeling sad because you could not yet free Wally, etc.

By implementing these aspects, we create an experimental setting in which intended actions are made for a reason and involve some consequence: two ingredients that we believe are especially important for considering experimental actions that could plausibly be performed in daily life.

Reinforcement learning is one plausible strategy that humans may adopt for learning and decision making (Cohen and Ranganath, 2007). Therefore, we believe that the outcome of such a model will be (at least partially) representative of the expected human behavior in Free Wally. We used reinforcement learning to set a time penalty and to identify the optimal order for revealing friends and hunters. To do so, a matrix with all possible game states was defined. Each state was defined as [nr. friends left, nr. hunters left, nr. friends right, nr. hunters right], where each number corresponds to the total amount of revealed friends and hunters on the left and right site of the hill. In addition, the set of all possible actions included: shooting water to the left of the hill, shooting water to the right of the hill and waiting for the next reveal (i.e. state). A transition matrix defined how to navigate through all possible states using all possible actions. A reward matrix determined the reward of each state: where you get a reward for each friend that reaches the cage and an equal punishment for each enemy that reaches the cage. Through a series of iterations, a value matrix (initially set to zero) was continuously updated, learning the associated rewards of performing a certain action in a certain state. The value matrix was updated until the total reward across all possible states and actions did not change more than 0.001 between two subsequent iterations.

Once the value matrix was learned, it was used to identify the

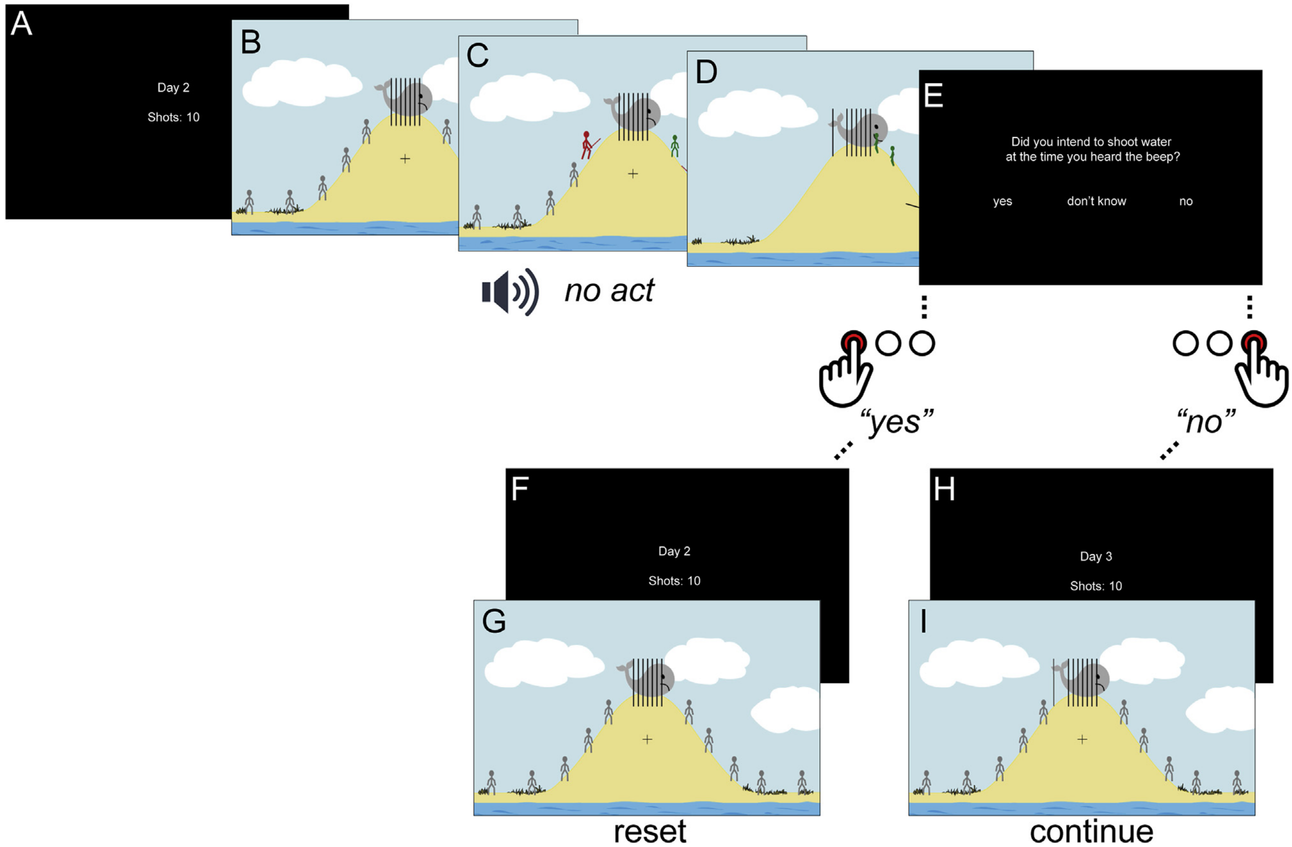

Fig. 4. Screenshots of Free Wally when a participant does not act during a certain day in the game. C, While the people are being revealed, a probe is presented. D, After this happens, the participant does not press a button during that day. E, To clarify whether this was due to a veto or whether the participant simply did not intend to act that day, a question is prompted. F, If the participant confirms that they performed a veto in response to the probe, the current day will be removed from the game history: G, the next day is reset to the start of the current day. H, If the participant did not intend to act during the day, I, the game will continue and start from the final situation of the current day.

optimal order of successive states: an order of friend/hunter reveals that induces ambiguity in action choice (the *what* phase of intending) over time. The sequences of reveals (i.e. states) of which the best and second-best actions maintained equal rewards across multiple friend and hunter reveals were selected. In addition, the reinforcement learning paradigm was repeated using several possible time punishments. For each [state, action] pair of the value matrix, a time penalty was subtracted such that the longer you wait, the stronger the hunters get and the weaker the friends. The optimal time penalty was chosen such that a decision to wait or act would be equally probable for as long as possible within the possible sequences of reveals.

2.1.2. Object Game

Similar to Free Wally, the Object Game is also a 2D game made in Unity (see Fig. 2). In contrast to Free Wally, the Object Game is designed to measure spontaneous self-initiated actions that are performed independently of the presented stimuli (mimicking the most well-known studies on intended action: Libet et al., 1983; Soon et al., 2008; Bode et al., 2011; Fried et al., 2011). In order to evoke similar visual artifacts, the stimuli are made as similar as possible to those of Free Wally in terms of their shape, size and behavior (see Fig. 3). The exact instructions for participants are provided in Supplementary Material B. Once every round (corresponding to a trial in the experiment), participants are free to press a button with their left or right hand whenever they want to. They do not need to act every round and can also decide to do nothing. While doing so, participants view a scene consisting of a big red star sitting on top of a hill surrounded by 10 rectangles and hexagons that turn purple or orange over time (see Fig. 3). The rectangles decrease in size while the hexagons increase in size. If participants do not act on a given trial, the trial will end once all objects have revealed their color. To minimize eye artifacts, participants are instructed to look at a fixation cross displayed at the middle of the hill (similar to Free Wally). Once they act, the fixation cross disappears and the game continues for a random amount of time between 0 and 8s. In contrast to Free Wally, the Object Game is actually not much of a game at all as it lacks a storyline and actions have no effect on the game.

2.1.3. Probe method

While playing either game, a short (110 ms) auditory beep (1716 Hz) can be presented at most once every trial (similar to Matsuhashi and Hallett, 2008). This probe will evoke an intention report on the *when* phase of intending. When a probe is presented and: (1) at that moment the participant did not intend to act, then they should *ignore* the probe and continue the game, or (2) at that moment the participant did intend to act, then they should cancel (*veto*) the intended act and wait for the next day to start. Importantly, participants veto their action in response to a probe only when they experienced an intention to act *now* at that moment in time, i.e. reporting the *when* phase of intending, similar to Matsuhashi and Hallett (2008) and to Libet et al. (1983).

During training, probes times are drawn from a normal distribution such that, on average, probes are presented 7s ± 2s after trial start. After training, the probe distribution is initialized based on the second training block. A running mean and standard deviation of the participant's action times are calculated during the test phase. Based on Matsuhashi and Hallett (2008) and Verbaarschot et al. (2016), we expect awareness of intending no earlier than 2s prior to action onset. Each trial, a minimum cost function takes the current mean and standard deviation of the action times, and calculates a distribution of possible probe times such that: 33% of probes are presented before the earliest expected onset of intending (probe time < -2s prior to action), 33% of probes are presented while the participant is expected to be aware of their intention to act (-2s ≤ probe time < 0s prior to action) and 33% of probes are presented after action onset (probe time ≥ 0s prior to action). The probe time for a given trial is drawn randomly from this distribution. If a participant needs to veto an intended action due to a probe in Free Wally, that day is removed from the game history will not count towards their score (i.e. the game will reset to the situation at the start of that day, see Fig. 4).

2.1.4. Questionnaire

At the end of the experiment, participants fill in a short questionnaire of 4 open and 15 closed questions on their subjective experience during the game: see Supplementary Material C for the full questionnaire. The questions were designed to investigate: (1) whether participants followed instructions correctly; (2) whether participants experienced their actions as more deliberate than spontaneous in the Free Wally game compared to the Object Game; (3) the strategies for deciding *what* movement to make, *when* to move, and *whether* or not to move; (4) any differences in the experienced “freedom” of acting between the two games; and (5) any difficulties that participants may have had in reporting their intention to act using the probe method. A two-sided independent samples Wilcoxon Signed Rank test (with a Bonferroni corrected alpha level of 0.025/15 = 0.002) is used to assess the statistical significance between Free Wally and the Object Game for each of the 15 closed questions.

2.2. Participants

The experiment is conducted in accordance with the ethical standards provided by the 1964 Declaration of Helsinki. The study protocol is approved by the local Ethics Committee of the Faculty of Social Sciences of the Radboud University in Nijmegen, The Netherlands. 41 Healthy adult participants volunteered to participate in the experiment, providing their written informed consent. 21 Participants played Free Wally (mean 27 ± 10 years old, 13 females) and 20 the Object Game (mean 26 ± 9 years old, 14 females). All participants are right-handed and have normal or corrected-to-normal vision and hearing. All participants reported not to suffer from color blindness.

2.3. Statistical analysis

2.3.1. Probes

The probe method of Matsuhashi and Hallett (2008) is edited to optimize the probe distribution such that 33% of probes are presented roughly prior to awareness of intending to act, 33% while a participant is aware of their intention to act, and 33% after the action is already performed. To check whether the presented probes indeed follow this predicted distribution, the timing of predicted and observed probes is compared. In order to do so, probe times that are followed by a left-hand action, right-hand action, or veto are extracted relative to trial start (see Fig. 3-B,-H) across participants. Subsequently, the action times are subtracted from the corresponding probe times to calculate the probe timing relative to action onset. The number of probes occurring more than 2s prior to action onset, between 2 and 0s prior to action onset and after action is calculated as a percentage of all presented probes. The probes that were followed by a veto are added to the percentage of probes that fall within 2 to 0s prior to action onset. A two-sided dependent samples Wilcoxon Signed Rank test (with an alpha level of 0.025) is used to determine whether the percentages of predicted and observed probes differ significantly across participants within each game. Moreover, the percentage of presented probes that were followed by no action, a veto, or an ignore response are analyzed. These percentages are compared between games using a two-sided independent samples Wilcoxon rank sum test (with an alpha level of 0.025).

2.3.2. Actions

The EMG measurement serves to check the timing accuracy of the button presses. This is done for all left- and right-hand actions separately. For analysis, the difference in activity of two bipolar EMG electrodes is computed and band-pass filtered between 51 and 250 Hz. Subsequently, the absolute value is taken and the data is sliced in epochs of −0.5 to 0.5s around a button press. Individual thresholds for muscle activation are set to the median EMG activity plus 2x the standard deviation. The average onset of muscle activity is determined as the point in time at which the average EMG activity exceeds the set threshold. To investigate whether there are any differences in action timing (i.e. the timing of a left- or right-handed button press relative to trial start) between Free Wally and the Object Game, the mean and standard deviations of the individual action times are compared separately between games using an independent samples *t*-test (alpha level is set to 0.025).

Lastly, Free Wally is designed to evoke actions that are in-between self-initiated and stimulus-response. In order to verify whether Free Wally does not compel one to perform a single optimal action at a single point in time, the variability in action choice and time was analyzed across participants in identical situations. For this purpose, we calculated the mean and standard deviation of the action times relative to trial start, for each of the 36 unique trials within Free Wally, across participants. Moreover, for each unique trial, we calculated the percentage of left hand, right hand and no action choices across all participants. For comparison, the same analysis was performed across the 36 unique trials of the Object Game.

2.3.3. Intentions

Using the probe method, the timing of the awareness of the *when* phase of intending was investigated during each game. Differences in the timing of this awareness are compared between games. In order to do so, the distribution of scheduled and ignored probes is calculated. The distribution of *scheduled probes* indicates how many probes are, on average, presented to a participant at a certain point in time prior to action. During the experiment, maximally one probe is selected for presentation per trial. We simulate running this probe-selection step multiple times to get a probe distribution relative to action onset. To determine the distribution of scheduled probes relative to action onset, the scheduled probe onsets that precede each individual action are sampled per participant. Subsequently, the action onset is subtracted from each corresponding sampled probe onset in order to calculate the probe timing relative to action onset. A histogram with 51 time bins of 100 ms, running from 5s prior to action until action onset, is constructed of the scheduled probe timings. This histogram is divided by the total number of actions of a participant to calculate the average number of presented probes prior to action onset. The distribution of *ignored probes* contains the timing of all probes relative to action onset that were presented and ignored by the participant (indicating that the participant was not experiencing an intention to act at that moment in time). Each of these probes is followed by an action at a later point in time. To get this distribution, a histogram is created of the ignored probe times using the same bins as those of the scheduled probe distribution.

The sum of the histograms of scheduled and ignored probes is taken over all participants per condition, resulting in one distribution of scheduled probes and one distribution of ignored probes across all participants per condition. A bootstrap approach (Efron and Tibshirani, 1994) with 10000 repetitions is used to re-generate the histogram of scheduled and ignored probes across participants. For each bootstrap: a random sample with replacement of equal length to the original sample is taken from the scheduled and ignored probe times of each participant. For each time bin between 5s prior to action until action onset, it is investigated whether the number of ignored probes is less than the number of scheduled probes. In order for two bins to differ significantly, the number of ignored probes should be lower than the number of scheduled probes across 10000-9.804 = 9990.196 of the bootstrap samples. The alpha level is Bonferroni corrected for the number of bins: 50/51 = 9.804 (1-sided test).

Furthermore, the distribution of ignored probes is expressed as percentages of the corresponding distributions of scheduled probes (i.e. ignored probe distribution/scheduled probe distribution) for each condition. These distributions of ignored probes are compared between the two games. The alpha level is set at 250/51 = 4.902 (2-sided test). This means that in order for two bins to differ significantly, the percentage of probes in a bin of Free Wally should be consistently higher/lower than the corresponding bin of the Object Game for 1000-4.902 = 9995.098 of the bootstrap samples.

Lastly, the onset of intending and point of no return are calculated from the distribution of ignored probes of each bootstrap. The onset of intending is calculated as the earliest time bin after which the distribution of ignored probes is consistently lower than that of scheduled probes. The point of no return is taken as the earliest time bin after the onset of intending after which the distribution of ignored probes is consistently higher or equal to the distribution of scheduled probes. The onset of intending and point of no return were considered to differ significantly between conditions when they were consistently earlier/later across 9750 bootstrap samples (2-sided test).

2.3.4. Brain

Analysis of the recorded EEG data is performed using Fieldtrip.[4] Preprocessing consists of the following steps: (1) trials are sliced running from −10 to 5s, time-locked to action onset; (2) trials in which the participant acted within 4s after trial start are removed to ensure an artifact free baseline period; (3) the EEG data is re-referenced using a linked “mastoid” reference (i.e. channels P9 and P10); (4) the EEG and EOG data are demeaned; (5) EOG artifacts are removed using linear decorrelation of the EEG and EOG (Gratton, 1998); (6) a band-pass filter is applied between 0.2 and 47 Hz to filter out slow drifts and 50 Hz line noise; (7) bad channels are removed (> 3.5 standard deviations from mean power); (8) bad trials are removed (> 3.5 standard deviations from mean power); (9) bad channel removal is repeated (as sensitivity has been improved by removing bad trials); (10) missing channels are recreated using spherical spline interpolation (Perrin et al., 1989); and (11) the EEG is baselined between −3.5 and −2.5s prior to action onset.

In order to analyze the RP, the event-related potential (ERP) is calculated per participant and game. A between-subject cluster-permutation test (1000 permutations, alpha = .05) is used to detect any significant differences between Free Wally and the Object Game across 2.5 to 0s prior to action (Maris and Oostenveld, 2007). To assess differences between left and right hand actions, the LRP is calculated for each participant as: $[(C3_{left} - C4_{left}) + (C4_{right} - C3_{right})]/2$ (Trevena and Miller, 2002), where C3 and C4 are the EEG recordings over the motor cortex of the left and right hemisphere corresponding to left and right hand trials. A between-subject cluster-permutation test (1000 permutations, alpha = .05) is used to detect any significant differences in LRP activity between Free Wally and the Object Game across 0.5 to 0s prior to action.

In order to analyze the alpha/beta ERD, a spectrogram is calculated between −5 and 3s around action onset. Frequencies of interest are defined from 5 to 30 Hz using 2 Hz bins. A flexible Hanning window is used such that it includes at least 7 cycles of each frequency of interest. The baseline activity is defined per electrode, frequency, and trial as the median power between 3.5 and 2.5s prior to action. The data is baselined using a relative baseline (where a value of 1 means no signal change compared to baseline). The ERD is calculated per participant by taking the median power across trials for each electrode, frequency and trial. Again, a between-subject cluster-permutation test (1000 permutations, alpha = .05) is used to detect any significant differences between the spectrograms of Free Wally and the Object Game, averaged across 8–30 Hz, running from 2.5 to 0s prior to action.

To investigate potential differences in neural preparation prior to easy and difficult action decisions, under the assumption that difficult decisions result in more variation in action choice and timing across trials and participants, Free Wally trials were divided into two categories: low variance and high variance trials. These low and high variance trials were calculated for each of the *what*, *when* and *whether* phases related to an intended act. To calculate the low and high variance trials related to the *what* phase, the 25th and 75th percentiles were calculated of the percentage of left- and right-hand decisions per unique trial across participants. The same was done on the percentage of act and no act trials for the *whether* phase. To calculate the low and high variance trials related to the *when* phase, the 25th and 75th percentiles of the standard deviation of action times per unique trial across participants was calculated. Differences in action choice or standard deviations in action timing that fall above the 75th percentile were considered as high variance trials, whereas those that fall below the 25th percentile were considered as low variance trials. Using a within-subject cluster-permutation test with 1000 permutations, the RP and alpha/beta ERD are compared between the low and high variance trials of each phase across 2.5 to 0s prior to action onset (with an alpha level of 0.025).

3. Results

Eight Participants had to be excluded from the analysis because they were not following instructions correctly. These participants used the probes to cheat in Free Wally, always ignored the probes, were counting time and planning their actions in the Object Game, or were making decisions based on stimuli in the Object Game. This leaves 33 participants for analysis: 17 of which played Free Wally.

3.1. Probes

The relative percentages of the predicted and observed probe times before the awareness of intending, during awareness of intending, and after action are analyzed for Free Wally and the Object Game (see Fig. 5A). The median percentages of predicted and observed probes in Free Wally all roughly approach the expected 33%. However, those of the Object Game deviate slightly, with less observed probes during awareness of intending and more after action. The percentage of predicted and observed probes before awareness of intending is not significantly different for both Free Wally ($z = 1.160$, $r = 0.199$, $p = .246$) and the Object Game ($z = -0.465$, $r = -0.080$, $p = .642$). Moreover, the percentage of predicted and observed probes during intending is not different for Free Wally ($z = -1.302$, $r = -0.223$, $p = .193$), but is different for the Object Game ($z = 2.585$, $r = 0.443$, $p = .010^*$). Similarly, the percentage of predicted and observed probes *after* action is not different for Free Wally ($z = -0.592$, $r = -0.102$, $p = .554$), but is different for the Object Game ($z = -2.275$, $r = -0.390$, $p = .023^*$). We believe that these differences between the predicted and observed probes in the Object Game can be explained by the fact that participants acted faster in the Object Game compared to the Free Wally Game (see Section 3.1.2). When participants act faster, probes are less likely to occur during the awareness of intending and more likely to occur after action.

The percentage of presented probes followed by no action (Free Wally: 26.38% ± 12.29%; Object Game: 18.17% ± 12.72%), a veto (Free Wally: 20.65% ± 18.15%; Object Game: 13.53% ± 11.44%) or an ignore (Free Wally: 52.97% ± 20.14%; Object Game: 68.31% ± 17.52%) response are calculated per game across

[4] See www.fieldtriptoolbox.org.

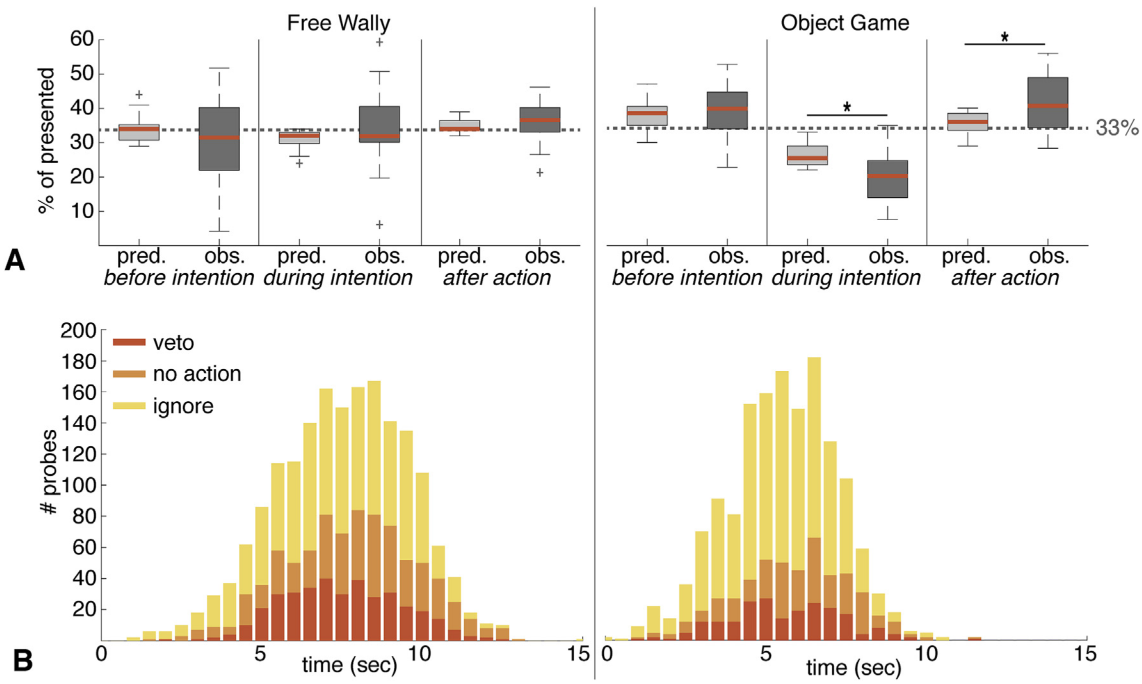

Fig. 5. A, Percentages of predicted (pred.) and observed (obs.) probes within Free Wally and the Object Game. The predicted and observed probes can fall in 1 of 3 categories: before the earliest expected awareness of intending to act (< 2s prior to action), during awareness of an intention to act (> 2 and < 0s prior to action) or after action (> 0s). The percentage of predicted and observed probes during intending and after action differed significantly ($p < .025$) within the Object Game. B, A probe can be followed by: no action, a veto or an ignore. The distribution of these responses is visualized as a stacked histogram showing the sum of occurrences of each response across participants for each game.

participants (see Fig. 5B). No significant differences are found for the percentages of probes followed by an ignore ($z = -2.035$, $r = -0.354$, $p = .042$), veto ($z = 0.919$, $r = 0.160$, $p = .358$) or no action ($z = 1.819$, $r = 0.317$, $p = .069$) response between Free Wally and the Object Game.

3.2. Actions

Action times correspond to the timing of a left or right handed button press relative to trial start. Mean action times are calculated per participant for each game (see Fig. 6A). The standard deviations of the individual action times are indicated in Fig. 6B. On average 93 (± 24) actions were measured per participant in Free Wally with a mean action time of 9.093s (± 1.867s). In the Object game 112 (± 19) actions were measured on average per participant with a mean action time of 7.340 (± 2.561s). The mean action times are significantly different between the Object Game and Free Wally ($df = 31$, $t = 4.5224$, $p < .025$): the actions in the Object Game are performed earlier than those in Free Wally. Moreover, the standard deviations of the action times are significantly different between the Object and Free Wally game ($df = 31$, $t = -4.9015$, $p < .025$): the action times in the Object Game show a greater spread than those of Free Wally.

The average onset of muscle activity as measured using EMG differs by −39.637 ms (± 60.867 ms) for Free Wally and −53.223 ms (± 70.876 ms) for the Object Game relative to the button press (see Fig. 6C). Because this difference is so small (< 100 ms) relative to the action times (< 1%), the button presses are used to time-lock the EEG data throughout the rest of the analyses.

The variability in action choice and timing across each unique trial of Free Wally and the Object Game are determined across participants (see Fig. 7). The percentages of actions vs. no actions (*whether*) and the percentages of left vs. right hand actions (*what*) are investigated. In

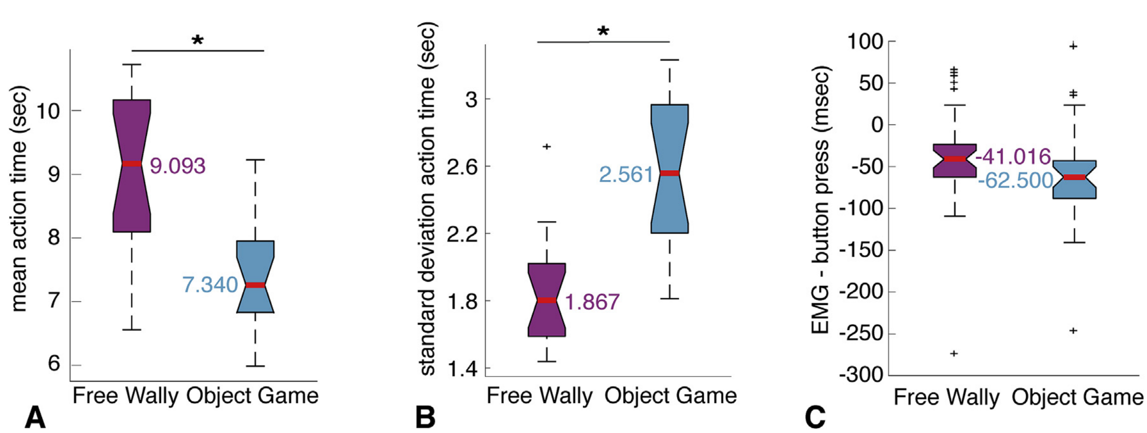

Fig. 6. A, Distribution of mean action times (relative to trial start) of all participants for the Free Wally and Object Game. The distributions differ significantly ($p < .025$). B, Standard deviations of the action times of all participants. The standard deviations differ significantly ($p < .025$). C, Distribution of median EMG onsets (relative to the button press) across participants for Free Wally and the Object Game.

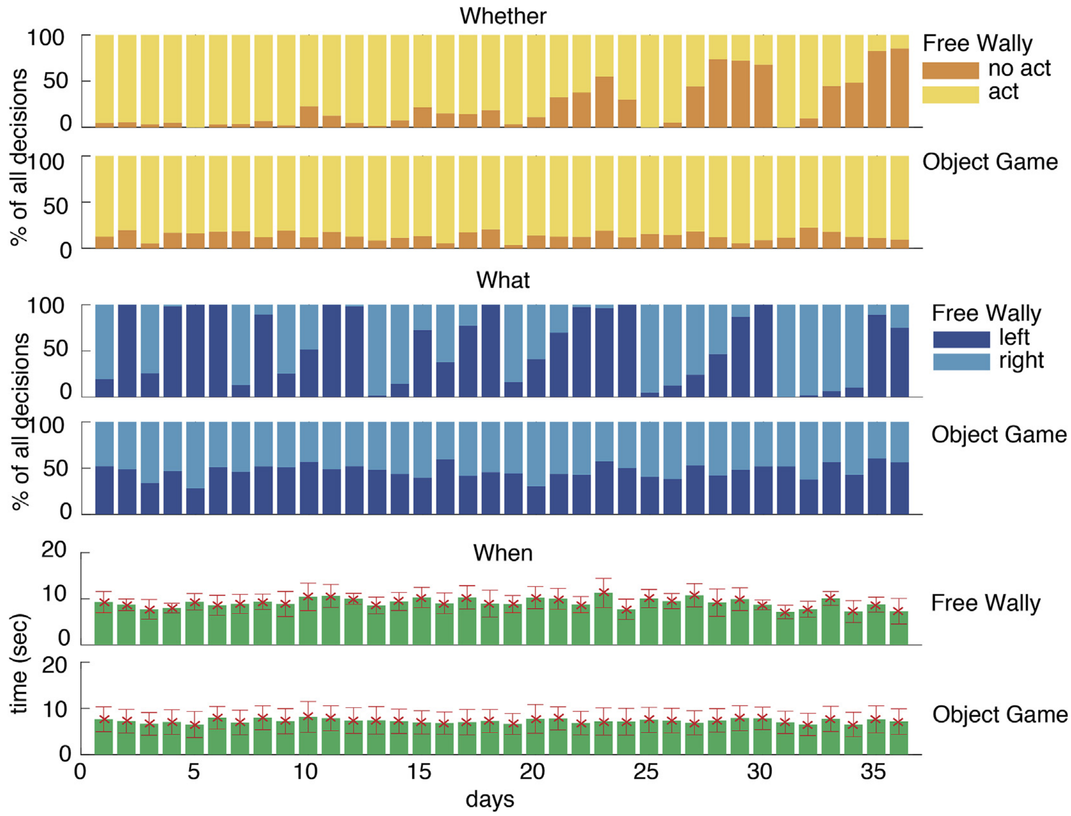

Fig. 7. Average trial-by-trial variability in action choice and timing across all participants. From the top (whether) plot, it is obvious that participants are more inclined to act in the Object Game compared to Free Wally. From the middle (what) plot, we see that the choice for left and right handed action is quite random for the Object Game and not random for Free Wally. The bottom (when) plot shows that the Object Game has more or less equal variance across the action timings of all days whereas Free Wally shows more variability across days.

addition, the mean and standard deviation of the action times (*when*) are investigated. From Fig. 7, we see that participants are more inclined to act in the Object Game compared to Free Wally. Furthermore, we see that the choice for left and right handed action is quite random for the Object Game and not random for Free Wally. Lastly, we see that the Object Game has more or less equal variance across the action timings of all trials whereas Free Wally shows more variability. Overall, these results show that action timing and choice depend at least to some extent on the presented stimuli in Free Wally, whereas this is not the case in the Object Game. Moreover, some trials in Free Wally show more variance across action choice and timing than others, whereas the variance is more or less equal across trials in the Object Game. This indicates that there is not a single optimal action choice and time for every trial of Free Wally. In other words, Free Wally is not a pure stimulus-response task but requires some form of internal deliberation to come up with an action strategy to achieve a certain goal based on the current game situation.

3.3. Intentions

Fig. 8A shows the distribution of scheduled and presented probes across all participants for Free Wally and the Object Game. For both games, we observe a dip in the number of ignored probes relative to the number of scheduled probes between roughly 2 and 0.2s prior to action. During this time period we know that multiple probes were presented to participants, but most of these probes were followed by a veto response, and create a dip in the histogram of ignored probes. The period after which vetoes are consistently performed across all participants is seen as the period during which awareness of intending to act arises. This period starts at 1.1s prior to action for Free Wally and at 1.3s prior to action for the Object Game. Subsequently, this period ends at 0.4s prior to action for Free Wally and the Object Game (see Fig. 8A).

Shortly prior to action, the dip in the number of ignored probes seems to disappear: the number of ignored probes approaches the number of scheduled probes again. The time point at which this happens is referred to as the point of no return (Matsuhashi and Hallett, 2008). At this point of no return, probes are presented so close to action performance that the participant is no longer able to veto their action. This point of no return is found at 0.3s prior to action for both Free Wally and the Object Game. No significant differences are found

3.4. Brain

Fig. 9A shows a grand average of the RP in Free Wally and the Object Game. In both games, we observe a slowly increasing negative potential that is maximal over the central motor cortex (Cz), starting around -2s prior to action onset. The shape and timing of this RP matches those found in previous research (Libet et al., 1983; Shibasaki and Hallett, 2006; Verbaarschot et al., 2016). A between-subject cluster-permutation test on the RPs of Free Wally and the Object Game with a pre-selected time range of -2.5 to 0s prior to action did not find any significant differences between the two games. Any post-action differences in the ERP are likely due to differences in stimuli after action onset: visualized consequences of acting in Free Wally vs. no change in stimuli in the Object Game.

Fig. 9C shows a grand average of the LRP in Free Wally and the Object Game. We observe the LRP as a small positive potential, showing the difference in neural activity between hemispheres for left- and right-handed actions. This shape matches that of previous literature (Trevena and Miller, 2002). On average, the LRP seems to start round 400 ms prior to action in the Object Game and a bit later, around 200 ms prior to action in Free Wally. However, a between-subject

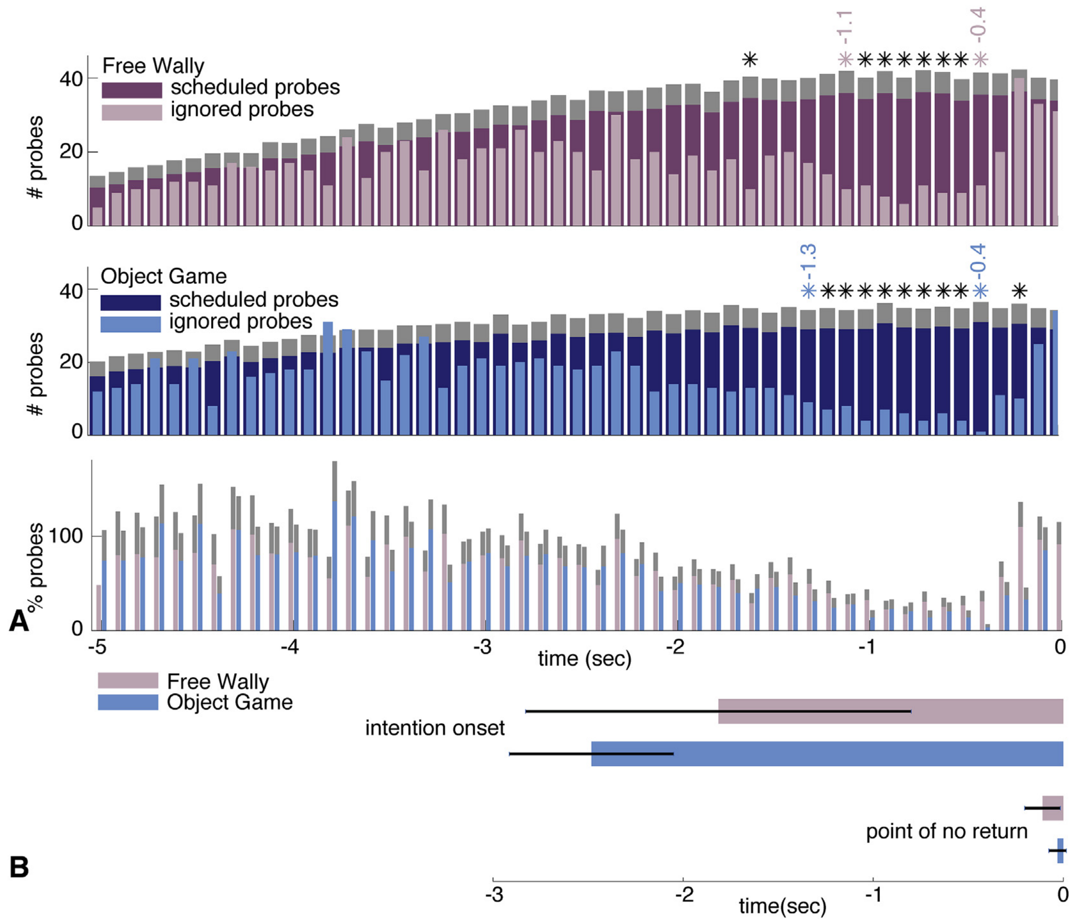

Fig. 8. A, The top and middle plot show the distribution of scheduled and ignored probes summed across all participants per game. The asterisk(*) indicates significant differences between the ignored and scheduled probes across the 10000 bootstrap samples. The bottom plot shows the percentage of ignored probes relative to the number of scheduled probes across all participants per game. These percentages can be greater than 100% in cases where the number of presented and ignored probes exceeded the number of expected (scheduled) probes. Standard deviations are indicated in grey. B, Mean and standard deviation of the onset of intending and point of no return across the 10000 bootstraps per game.

cluster-permutation test on the LRP's of the Free Wally and Object Game conditions with a pre-selected time range of −0.5 to 0s prior to action did not find any significant differences between the two games (see Fig. 9).

Fig. 10 shows a spectrogram of the grand average alpha and beta activity prior to action in Free Wally and the Object Game. In both spectrograms, we see a clear ERD starting around 2s prior to action. Around 0.5s after action, we observe an event-related synchronization (ERS), confirming previous literature on the alpha/beta signatures related to movement preparation and performance (Pfurtscheller and Berghold, A, 1989). A between-subject cluster-permutation test on the ERD's from 8 to 30 Hz of Free Wally and the Object Game with a pre-selected time range of −2.5 to 0s prior to action did not find any significant differences between the two games.

In order to analyze differences in neural preparation prior to trials in which actions show more or less variability, high and low variance trials are selected within Free Wally. Fig. 11 shows the grand average RP for low and high variance trials of the *what, when* and *whether* phases. The late RP, starting around 0.5s prior to action onset, seems more pronounced in the low variance *what* trials than the high variance ones. Moreover, the low variance *whether* trials seem to have an earlier onset of the RP than the high variance ones. No visual difference is observed in the low and high variance *when* trials. When looking at the individual RPs across all phases between the low and high variance trials (see Fig. 12), the high variance trials seem to show a larger general variance across participants than the low variance trials. However, no significant differences are found between the low and high variance trials across the *what, when* and *whether* phases.

Fig. 13 shows the spectrograms of low and high variance trials across the *what, when* and *whether* phases. Although we observe a clear ERD in the alpha and beta bands for low variance trials, we only see a very vague ERD for the high variance trials. This difference seems most expressed for the *what* and *whether* phases, and is confirmed by a between-subject cluster permutation test ($p < .025$). No significant difference is found between low and high variance trials of the *when* phase.

3.5. Questionnaire

The full questionnaire and accompanying answers can be found in Supplementary Material C. On average, participants judged their actions to be more *spontaneous* in the Object Game and more *deliberate* in Free Wally (see Fig. 14A). “Spontaneous” was interpreted as acting randomly, impulsively, immediately, without strategy, without consideration, without control, irrespective of presented stimuli or based on feeling. “Deliberate” was interpreted as pre-meditated, intentional, with consideration, with control, related to stimuli or in line with a certain strategy. Although *internal deliberation* was important for acting in both Free Wally and the Object Game (see Fig. 14B), the *current game situation* was judged to be more important for acting in Free Wally than the Object Game (see Fig. 14C).

Most participants in Free Wally used some strategy to decide

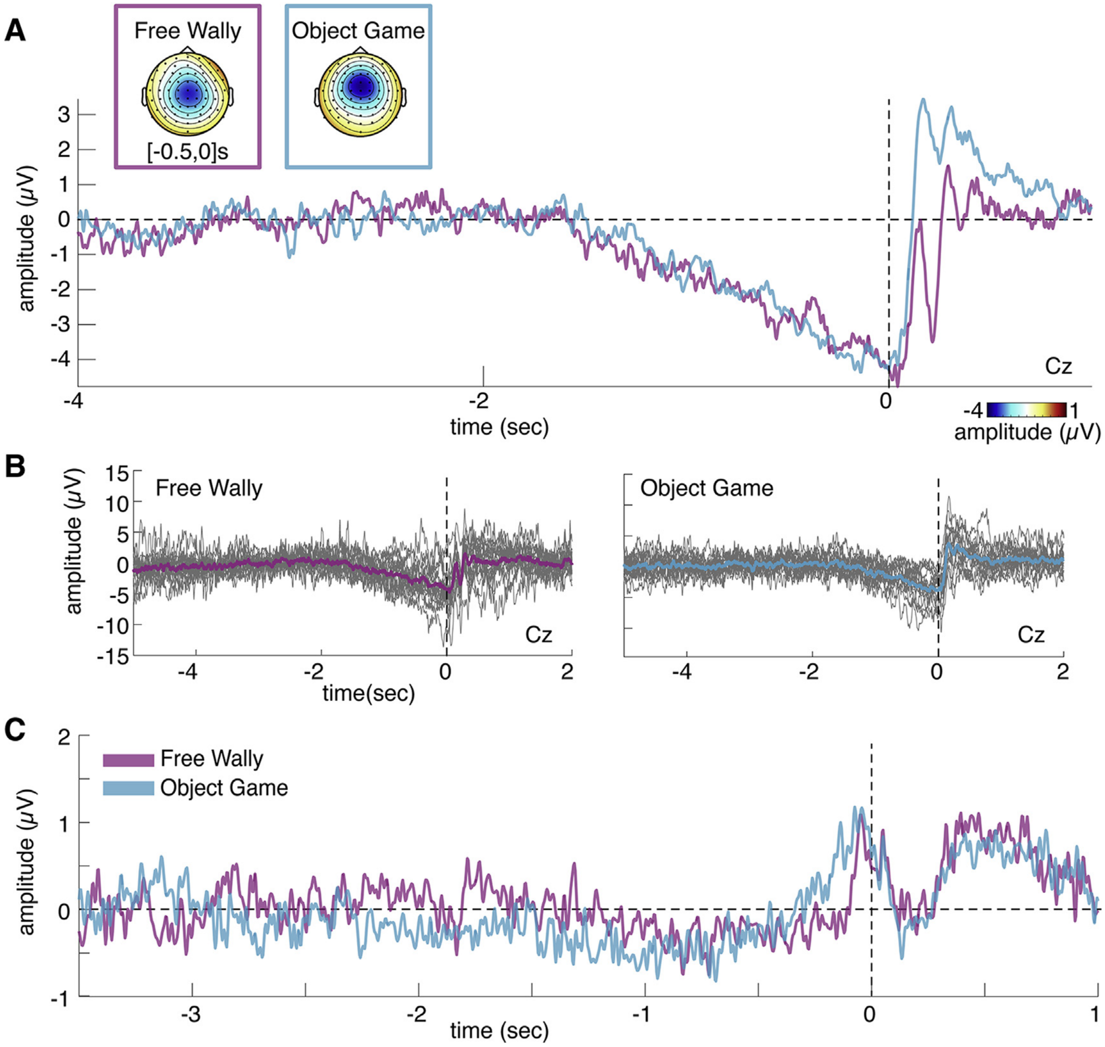

Fig. 9. A, Grand average RP at electrode Cz for Free Wally and the Object Game, including a topoplot of the grand average RP from −0.5 to 0s. B, Grand average RP on top of all individual RPs per participant for Free Wally and the Object Game. C, Grand average LRP for Free Wally and the Object Game. between the distributions of ignored probes of Free Wally and the Object Game (see Fig. 8A). Furthermore, no significant differences were found between the onset of intending or point of no return between Free Wally and the Object Game (see Fig. 8B).

whether or not to act (see Fig. 14E). Reported strategies include: shoot if there are more hunters than friends, always act, be more inclined to shoot when the cage is large, act when there or more than 2 hunters on one side of the hill, etc. Even though participants were instructed to act spontaneously and unrelated to the stimuli, some (3) participants in the Object Game still used some strategy to decide *whether* or not to act. These strategies include: deciding beforehand whether or not to act during the trial, not act if an itch was experienced, act if there are 2

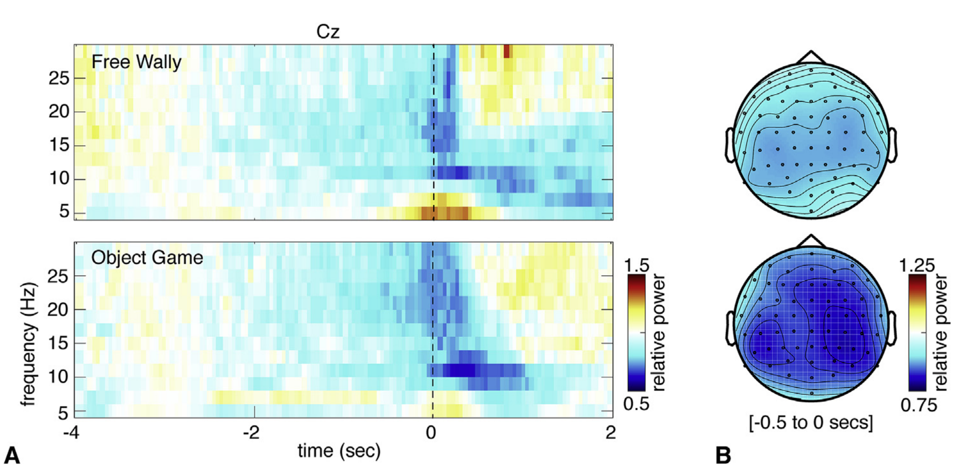

Fig. 10. A, Grand average ERD for Free Wally and the Object Game at electrode Cz. B, Topoplot of the ERD from −1 to 0s of Free Wally and the Object Game.

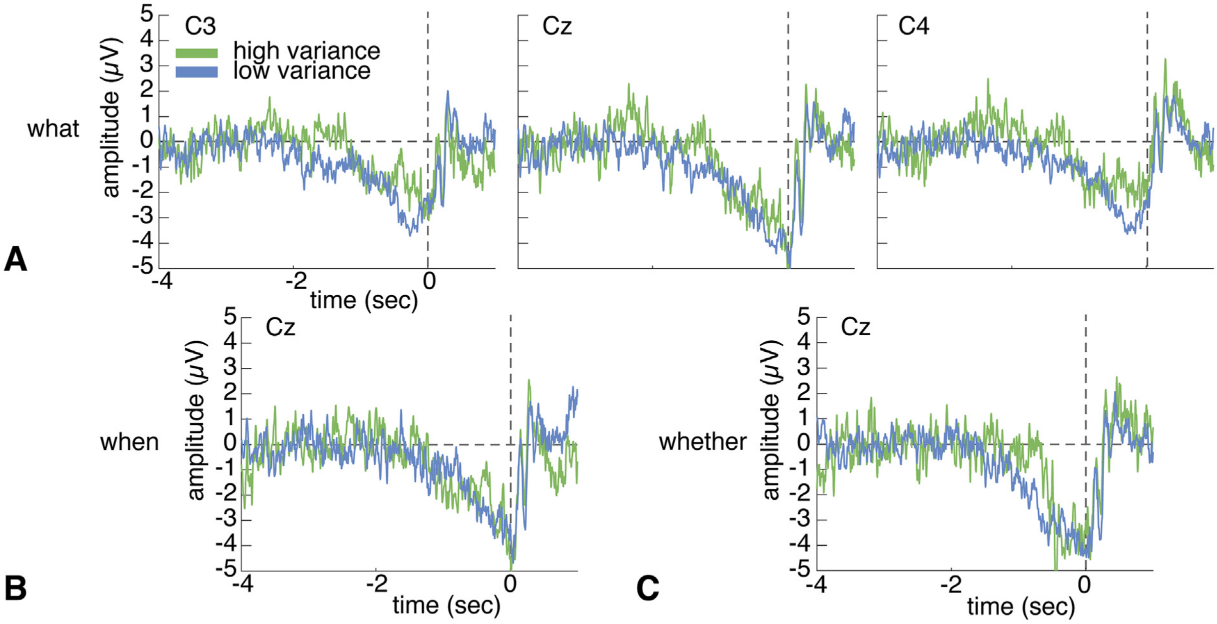

Fig. 11. Grand average RP for low and high variance what, when and whether trials of Free Wally.

orange objects at the start of a trial. A similar observation is made for the decision on *what* action to perform: most participants used a strategy in Free Wally, whereas most participants in the Object Game acted randomly (See Fig. 14E). For Free Wally, the reported strategies on *what* action to perform largely overlap with those reported for deciding *whether* or not to act. In addition, four out of twenty participants reported some strategy for deciding *what* action to perform in the Object Game: switch between button 1 and 5, only press button 5, experienced an urge to act when an object popped up fast, felt a preference for button 5 and actively pressed button 1 every once in a while. The majority of participants reported to decide randomly *when* to act during both Free Wally and the Object Game (see Fig. 14E). Strategies that were used and reported in Free Wally include: shoot when 3 people are revealed, act faster if the cage is large, act faster if there are only a few days left, wait as long as possible, etc. Strategies reported in the Object Game include: act based on the reveal of objects, or act after a certain number of pre-defined seconds.

Most participants felt largely in control over Wally's fate (see Fig. 14D). Moreover, most participants felt moderately or completely free to do what they wanted during both games (see Fig. 14F). Similarly, most participants felt moderately or very responsible for their actions or the outcome of their actions in both games (see Fig. 14G). Although Free Wally aroused either positive or negative emotions (but not much in-between), the Object Game mostly aroused mostly nothing, or only mild negative or positive emotions (see Fig. 14H).

Lastly, in Free Wally some participants perceive the probes as stressful (3 participants), unfair (1 participant) or as a means to cheat the game (2 participants). In the Object Game some participants perceived the probes as stressful (2 participants), loud (1 participant), frustrating (1 participant), or unexpected (1 participant). Most

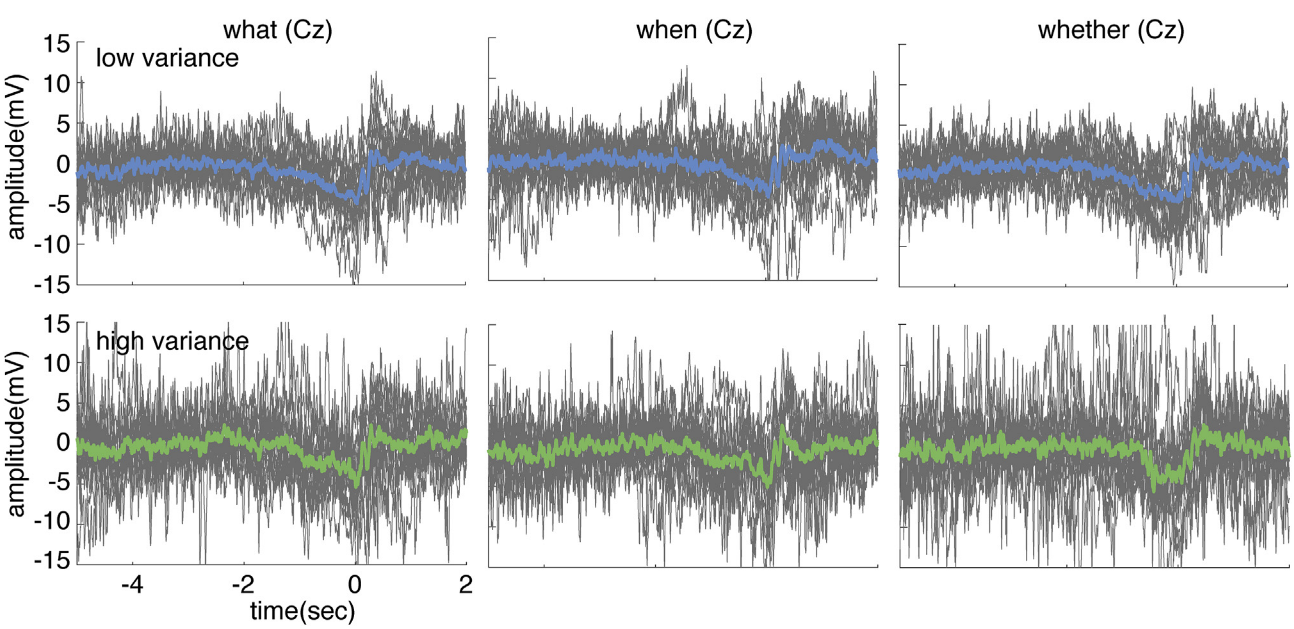

Fig. 12. Individual RPs across electrode Cz for low and high variance what, when and whether trials of Free Wally. The grand average RP is shown in blue (low variance) and green (high variance). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

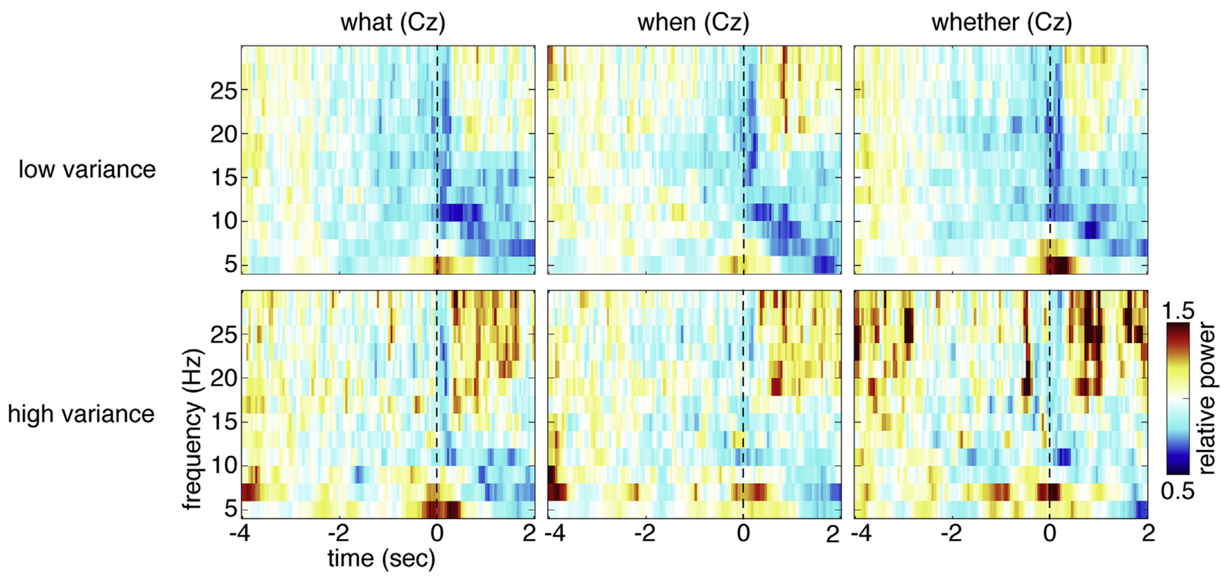

Fig. 13. Grand average ERD of electrode Cz for low and high variance what, when and whether trials. Both the low and high variance what and whether trials differ significantly from each other ($p < .025$).

participants sometimes ignored the beeps in Free Wally, whereas they did not do so in the Object Game (see Fig. 14I).

4. Discussion

In this experiment, participants played one of two computer games that measured their intended actions within an artificial environment. One of them, Free Wally, was designed to measure deliberate actions that are performed for a reason and involve some consequence. In the game, participants are responsible for accepting to attempt to free Wally as their goal, and for selecting, evaluating and executing an action strategy to achieve that goal. Moreover, in contrast to previous Libet-style paradigms, Free Wally provides input to each of the *what*, *when* and *whether* phases of intending. The other, the Object Game, measures spontaneous actions that are performed independently of presented stimuli, have no consequences and serve no goal. These urge-based actions are similar to those studied previously in the field of neuroscience (e.g. Libet et al., 1983; Bode et al., 2011), but may lack a clear conscious intention to act and may not resemble the intended actions for which we take or are assigned responsibility to in daily life. To investigate whether the results of previous research hold within the more ecologically valid context of Free Wally, the deliberate actions of Free Wally were compared to the spontaneous actions of the Object Game. Specifically, differences in the neural preparation for action (i.e. LRP, RP, alpha/beta ERD) and the timing of the *when* phase (i.e. consciously deciding to act *now*) of intending to act were compared between Free Wally and the Object Game.

Both games seem to have been successful in measuring the two targeted types of intended action. Participants rated their actions in Free Wally as mostly deliberate, while those in the Object Game rated theirs as mostly spontaneous. Moreover, participants indicated that the current game situation was important to the timing and choice of their actions in Free Wally, whereas this was not the case for the Object Game. This was confirmed by the measured variability of actions within the unique trials of both games: the variability in action choice and timing was quite consistent across the unique trials of the Object Game, but it clearly differed between the unique trials of Free Wally. This suggests that participants were indeed using the presented stimuli as reasons for acting in Free Wally, whereas they acted mostly independent of the presented stimuli in the Object Game. Moreover, participants reported specific strategies on the *what* and *whether* phases of intending within Free Wally, whereas they indicated to act mostly random during the Object Game.

Although our behavioral data suggests that action timing depends more on stimulus presentation in Free Wally than the Object Game, participants report to choose the timing of their actions mostly randomly in both games. This is perhaps not surprising, since Free Wally was designed to include certain equivocal phases that prevent actions from becoming purely stimulus-response (see Section 2.1.1). This means that the timing of actions is not dictated by a clear stimulus, which may lead to a more or less random time of acting once decisions on *whether* or not to act and *what* action to perform have been made. Therefore, one could argue that the decision on *when* to act is more spontaneous than deliberate, creating similar conditions on *when* to act in both Free Wally and the Object Game. However, even though participants may not be able to report a clear stimulus as a reason for their decision on *when* to act in Free Wally, we believe their action timing is not completely spontaneous: in Free Wally, one needs to wait until enough information is revealed to make a reasonable decision to act. In other words: action timing matters in Free Wally. This is not the case for the Object Game, in which we believe that choices on action timing are completely spontaneous.

No significant differences were found between the Object Game and Free Wally in terms of brain signals or the timing of the awareness of the *when* phase of intending to act. The RP, LRP and alpha/beta ERD all confirm previous research, considering their shape and timing. Furthermore, awareness of the *when* phase of intending was found, on average, up to 1.3s prior to action for the Object Game, and 1.1s for Free Wally (similar to Matsuhashi and Hallett, 2008 and Verbaarschot et al., 2016). This suggests that at least the last stages prior to action performance are similar between spontaneous and deliberate actions in terms of their neural preparation for action and awareness of *when* to act. In other words, increasing the ecological validity of the experimental context did not affect any results compared to those of previous research. Some researchers may find this surprising, as the brain signals and timing of a conscious intention to act are often expected (or hoped) to differ between spontaneous and deliberate actions in order to ‘save’ a libertarian notion of free will (Saigle et al., 2018). However, since the performed movement is identical between the two games, we would also not expect to find any differences in these final stages of intended action that seem to concern action preparation mostly.

The current study focused only on the (L)RP and 8–30 Hz ERD. Although we may not expect any differences in these brain signals between spontaneous and deliberate actions, we may expect to find

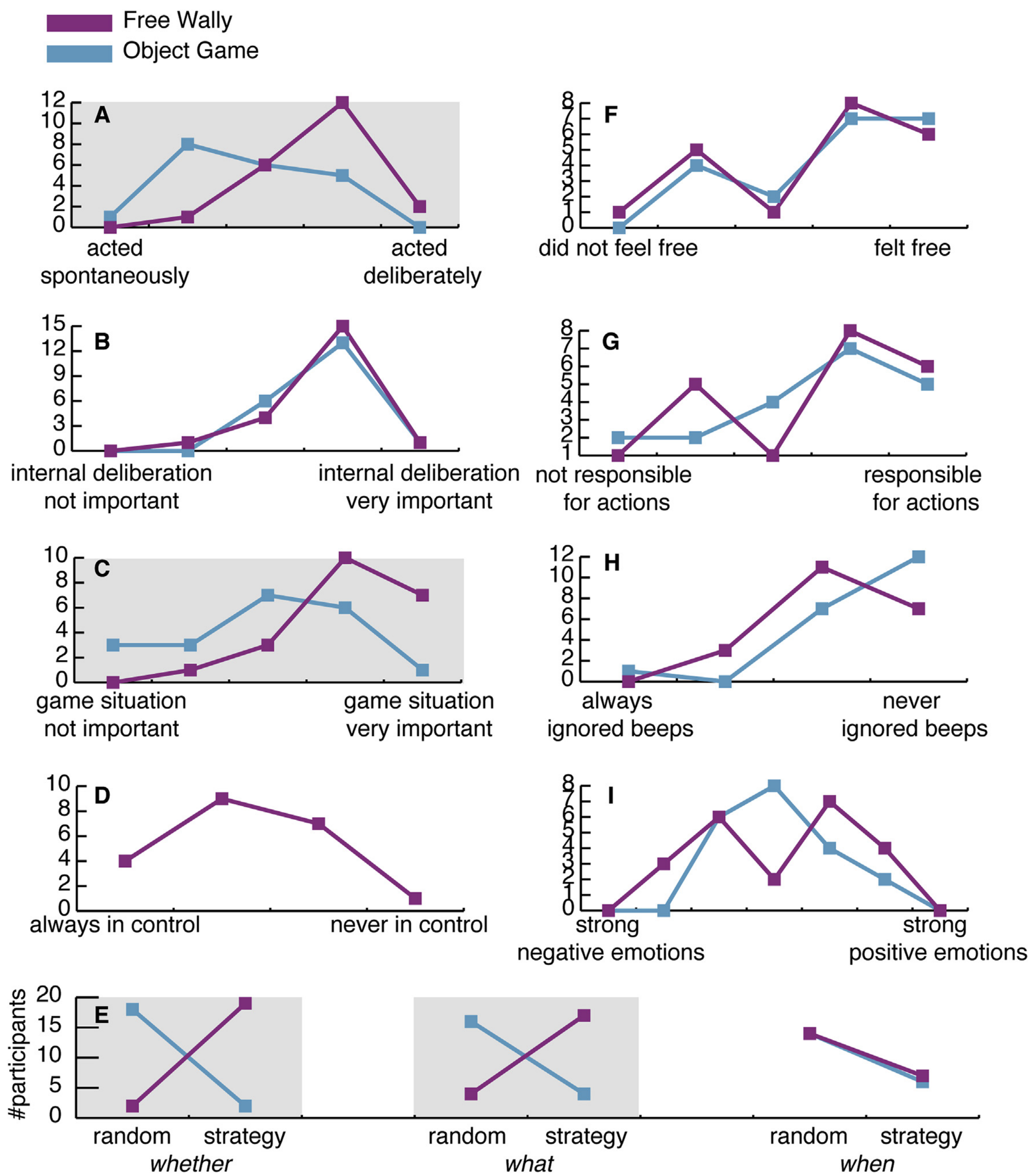

Fig. 14. Overview of questionnaire results across 21 participants of Free Wally and 20 of the Object Game. Note: (D) is about whether participants felt in control over Wally's fate, therefore no results on the Object Game are presented. Significant differences ($p < .002$) are indicated with a grey rectangle. For the full questionnaire and accompanying answers, see Supplementary Material C.

differences in brain signals that are related to intention formation and selection. Activity in frontopolar cortex, precuneus, and posterior cingulate cortex has been found predictive of action outcome up to 8s in advance of movement onset (Soon et al., 2008; Bode et al., 2011). Moreover, different frontal regions seem responsible for each of the *what, when* and *whether* phases of an intended act (Brass and Haggard, 2008; Brass et al., 2013). Specifically, Zapparoli et al., (2017) found a rostro-caudal gradient within the medial prefrontal cortex, where more anterior regions (right anterior cingulum, right anterior insula) are related to abstract decisions of *whether* or not to act, and posterior regions are involved in determining *what* action will be performed (middle cingulum, supramarginal gyrus) and *when* it will be performed (supplementary motor area, frontal operculum). In future research, we will focus on these brain regions to assess potential differences in the *what, when,* and *whether* phases of intending between the Object Game and Free Wally.

We did expect to find some differences in subjective experience between the two games in terms of responsibility, experienced freedom and vividness of intending. However, this was not the case. In both games, participants reported to feel free to do what they wanted, felt responsible for their actions, and experienced their intentions as moderately vivid to vivid. We did find a difference in the level of emotions that each game evoked in their players: whereas Free Wally evoked either positive or negative emotions, the Object Game was experienced as mostly neutral. This confirms that at least in Free Wally, participants were engaged in the consequences of their actions and committed to their goal. This is strengthened by the fact that most participants indicated that they felt in control over Wally's fate.

Our findings contradict those of Maoz et al. (2017), who conducted a similar study comparing the ERP activity prior to arbitrary and deliberate decisions. In their study, participants chose, on a per-trial basis, which one out of two non-profit organizations they would like to donate money to. In “deliberate” trials, the chosen organizations would advance to a lottery at the end of each experimental block, where they could win a 20 dollar donation. Furthermore, each winning organization would advance to a between-subject lottery, where they could win an additional 1000 dollar donation. In “arbitrary” trials, the organizations of one random trial would both receive 10 dollars at the end of each experimental block. The randomly selected trials would further advance to a between-subject lottery where two organizations of a randomly selected trial would both receive 500 dollars. In other words, the participant's choice did not matter in arbitrary trials, as randomly selected organizations would receive an equal amount of money. In both arbitrary and deliberate trials, participants were instructed to act (i.e. press a button with their left or right hand) as soon as they made their decision. In contrast to our study, Maoz et al. found a clear RP prior to arbitrary but not prior to deliberate decisions. Similar to our study, the LRP was equally visible prior to both arbitrary and deliberate decisions.

Prior to the experiment of Maoz et al., participants were asked to rate all participating organizations, pre-defining the participant's preferences across organizations at the start of the experiment. During the experiment, this may lead to a kind of stimulus-response action because the participant already decided what organizations they prefer over another: as soon as they see their preferred organization (stimulus), they act accordingly (response). In other words, there is a clear predecided “optimal” action in the experiment of Maoz et al. that participants select as soon as they detect it. In contrast, Free Wally did not include a clear optimal action across all trials, and was specifically designed to evoke self-paced actions: stimuli were designed in such a way that multiple actions may receive equal rewards over time, making the decision on *when* to act slightly random. The absence of an RP prior to deliberate decisions in the experiment of Maoz et al. may be due to the possible stimulus-response nature of the actions: stimulus-response actions are usually not preceded by an RP, whereas self-paced actions are (Jahanshahi et al., 1995; Shibasaki and Hallett, 2006).

The questionnaire showed that 14 people often or sometimes wrongfully ignored the probes in the Free Wally game, whereas only 8 people always or sometimes wrongfully ignored the probes in the Object Game. We suspect because participants were trying to reach a goal, they were more likely to ignore the veto instruction in the Free Wally game compared to the Object Game. In future research, one could potentially avoid this issue by reversing the veto instruction: in case a probe is presented at the moment a participant experiences an intention to act, they should perform the intended act as soon as possible. If they do not experience an intention at probe onset, they can ignore the probe and continue the game. This makes the experimental instructions more intuitive as it avoids the requirement of a veto and any consequences of having to veto (i.e. resetting the state of Wally's cage to the previous day). Moreover, it removes the possibility of using the probes as a means to cheat the game. Although these instructions would not allow the measurement of the point of no return, they still allow the measurement of the timing of the awareness of intending to act. The actions that are made in response to a probe (because the participant is aware of their intention to act) would cause a local change in the distribution of probes. In contrast to the original design of Matsuhashi and Hallett (2008), this local change would consist of an increase rather than decrease in the number of probes shortly prior to movement onset. In a short calibration task, one would need to determine how fast participants are able to respond to a probe, so the movements that are performed in response to a probe can be separated from the movements that are performed after an ignored probe.

Lastly, we investigated whether the neural preparation for action differs between easy and difficult action decisions in Free Wally. For instance, in the case that 5 hunters are revealed on the left of the hill and 5 friends on the right, the decision to shoot water to the left of the hill is quite easy. However, in when 3 hunters are revealed on both the left and right of the hill, the decision to shoot left or right is much trickier. In cases with an easy decision, the presented stimuli are all pointing more or less towards one optimal action choice and time. Therefore, these trials should involve less variance in action choice and timing across repetitions. In contrast, difficult decisions involve stimuli that provide evidence for multiple concurring action choices. Therefore, these trials should show more variance in action choice and timing across repetitions. Although no significant differences were found between the RPs of low and high variance trials, significant differences were found between the ERDs of low and high variance concerning the *what* and *whether* phases of intending. A clear pre-movement ERD is visible for the low variance *what* and *whether* trials, but is much less pronounced in their high variance counterparts. This result is perhaps not surprising, as easy action decisions can be more easily planned than difficult action decisions: whereas more and more evidence is collected towards a single action choice in easy trials, conflicting evidence in action choice is gathered in difficult trials.

The easy trials are largely stimulus-driven, whereas the difficult trials are more dependent on internal deliberation. Although the current study examined the difference between these stimulus-driven and internally deliberated trials to some extent, future research should make this comparison explicit. One could test a version of Free Wally in which the identity of all friends and hunters is revealed at the start of a trial, providing a player with complete information and removing the time penalty. In this way, the optimal action is stimulus-driven and dictated by the presented stimuli (although trials in which two possible actions would receive equal reward should be excluded from this condition). When comparing this stimulus-driven version of Free Wally with the original game, one can explicitly investigate the element of intentionality that differs between these conditions.

Although participants were not explicitly instructed to free Wally, all participants attempted to do so. One could say that the goal of the game was set, or emotionally coerced upon the participants, by the stimulus design: the sad looking whale invokes a general desire to help him. Therefore, it may be debated whether the performed deliberate actions can be considered “free”, as their overall goal is pre-determined by the game. However, in daily life, we believe that the context in which we intend and act will also co-determine our goals and subsequent actions, even though this may be less apparent than in the simplistic Free Wally game. Importantly, in daily life as well as Free Wally, the choice of action is not forced upon a person. People are free to determine their own strategies to reach their goal. Even though a goal may be context dependent, this -in our opinion-does not make the performed action less free.

To the best of our knowledge, Free Wally is a first attempt to measure deliberate actions in an ecologically valid context that provides information for the *what, when* and *whether* phases of intending to act. Although this study measured only the timing of the awareness of the *when* phase of intending, Free Wally can easily be adjusted to measure the timing of the awareness of the *what* and *whether* phases as well. To measure these phases, players need to veto in response to a probe when they have consciously decided *what* action to perform or *whether* or not they will act during a certain trial. In this way, Free Wally can be used to investigate the link between the neural signatures that have been found predictive of the *what, when* and *whether* phases of an intended act and the timing of subjective awareness of these phases. With this game as a tool, we hope to enable future research into the formation and content of ecologically valid intended action.

Conflicts of interest

The research was conducted without any commercial or financial relationships that could create a conflict of interest.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

CRediT authorship contribution statement

Ceci Verbaarschot: Conceptualization, Methodology, Software, Formal analysis, Investigation, Resources, Writing - original draft, Writing - review & editing, Visualization, Project administration. **Jason Farquhar:** Conceptualization, Methodology, Formal analysis, Writing - review & editing, Supervision. **Pim Haselager:** Conceptualization, Methodology, Writing - review & editing, Supervision.

Acknowledgements

We would like to thank Frank van Caspel for his creative insight, helpful feedback and endless playtesting of the Free Wally game.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.neuropsychologia.2019.107156.

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