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# Habitual control of instrumental behaviour requires conscious stimulus perception

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A B S T R A C T

Habitual behaviour is commonly assumed to operate outside of conscious control, deliberation, or awareness, driven by stimulus–response (S-R) associations rather than goal-directed evaluation. Here, we investigate whether habitual instrumental behaviours can be triggered by stimuli that are prevented from entering subjective awareness with subliminal presentation. In a preregistered within-subjects study (N after exclusions = 75), we examined this question by employing a symmetrical outcome revaluation task. Participants underwent extensive instrumental training, forming strong S-R associations, before completing two testing stages: a conscious stage with fully visible stimuli, and an unconscious stage where stimuli were rendered subliminal via visual masking. In the conscious condition, participants exhibited habitual control, responding more accurately to habit-congruent (still-valuable, still-non-valuable) stimuli than to habit-incongruent (upvalued, devalued) stimuli, replicating prior findings. However, in the unconscious condition participants did not exhibit above-chance accuracy, and responses were not biased toward habitual actions, suggesting that subliminal stimuli were unable to elicit either habitual or goal-directed responses. These findings challenge the notion that habitual control of instrumental behaviour can function independently of stimulus awareness and suggest that conscious access to action-relevant cues may be necessary even for well-established S-R associations to guide behaviour.

## 1. Introduction

Habitual control is an essential mode of instrumental behaviour, boosting efficiency and minimising cognitive load in stable, predictable contexts (Haith & Krakauer, 2018; Wood & Rünger, 2016). In contrast to goal-directed behaviour, which is driven by expectation and evaluation of the outcomes of our actions and which can be flexibly adapted to changes in the environment, habitual behaviour is triggered directly by the stimulus and insensitive to changes in the value of the outcome (Balleine & Dickinson, 1998; Balleine & O'Doherty, 2010; Dickinson, 1985). As habitual responses are engaged automatically in the presence of a contextual cue, they have often been assumed to proceed largely outside of conscious control, deliberation, or awareness (Andrews, 1903; James, 1890; Lisman & Sternberg, 2013; Verplanken, 2018; Wood & Rünger, 2016).

Recent research provides evidence that learning new instrumental behaviours, such as approach and avoidance responses, is

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unlikely to occur when the discriminative stimuli are presented outside of the agent's conscious access to render them subjectively unperceived, for example with visual masking techniques (Reber et al., 2018; Skora et al., 2022, 2023; Skora et al., 2021; Skora et al., 2021). Similarly, the absence of conscious access to the stimuli prevents correct instrumental responding even after successful conscious training (Skora et al., 2024). This research supports the view that consciousness is necessary for flexible, goal-directed behaviour or strategic use of information for behaviour (Baars, 2002; van Gaal et al., 2012), and for more complex forms of learning (Birch et al., 2020, 2021; Ginsburg & Jablonka, 2019), likely due to their reliance on integrating information across longer temporal scales and distinct modalities (e.g., for computing and comparing expected values, deploying selective responses, reinforcement processing), argued to be possible only with conscious access (Ansorge et al., 2014; Baars, 2002; Dehaene & Naccache, 2001; Dehaene et al., 2014; Lamme, 2006).

In contrast, there is a broad assumption that unconscious processing may be sufficient to support highly learned, routine or automatic processes (Ansorge et al., 2014; Baars, 2002; Dehaene & Naccache, 2001; Faivre et al., 2014; Hesselmann & Moors, 2015; Lisman & Sternberg, 2013; Newell & Shanks, 2013; Newell et al., 2023). Indeed, Ansorge and colleagues (2014) propose that a subjectively unperceived visual cue could be used to guide behaviour only under already existing goals or action plans. In line with this assumption, extensive conscious instrumental experience with stimuli during habit formation, resulting in stimulus–response (S-R) associations providing 'ready defaults' (Wood & Rünger, 2016), could plausibly reduce or eliminate the need for conscious access during automatic, habitual responding. Nonetheless, evidence supportive of this notion in the domain of instrumental behaviour, such as whether habitual behaviour can be triggered by stimuli presented outside of conscious awareness, is lacking.

A commonly used method to investigate whether behaviour is under goal-directed or habitual control in humans is a slips-of-action task, where, after an extensive instrumental learning phase establishing stimulus–response-outcome (S-R-O) associations, some of the outcomes are devalued through explicit instruction, and participants must be goal-oriented in order to refrain from making habitualised responses to the devalued stimuli, called slips-of-action (de Wit et al., 2012; Gillan et al., 2011). A recent improvement to the task (Watson et al., 2023) introduced symmetrical revaluation: instead of comparing responses on devalued trials to the remaining still-valuable trials (as a slip-of-action might be driven by habit, or by by confusion, forgetfulness or fatigue; Balleine & Dezfouli, 2019), the testing stage is set up to devalue a quarter of the outcomes and upvalue another quarter (demanding a habit-incongruent response), while leaving a quarter each of still-valuable and still-nonvaluable trials (congruent with the S-R habit). This ensures that the responses can be compared within their required response type − for example, both still-non-valuable and devalued trials require a 'reject' or NoGo response, but the learned S-R association can interfere only on the devalued trials, with the reverse for still-valuable and upvalued trials. Hence, dominance of habitual control is inferred from a poorer performance on upvalued and devalued trials in comparison to still-valuable and still-non valuable trials, respectively.

The outcome-revaluation task presents an opportunity to study the question whether habitual control of instrumental behaviour can be triggered by subjectively unperceived stimuli. While previous work suggested that conscious instrumental learning does not enable successful instrumental responding to the same stimuli rendered subliminal with masking (Skora et al., 2024), it was impossible to assess whether any habitual influence was present, as the task did not require a switch from habitual to goal-oriented control – and it is the difference between habit-congruent and habit-incongruent responses that indicates the dominance of habitual versus goal-directed behaviour.

To address this, here we use the symmetrical outcome revaluation task (Watson et al., 2023) with an added unconscious stimulus presentation condition, allowing us to assess whether subliminally-presented stimuli might trigger responding in line with the habitual responses learned in the training stage. In the conscious control condition, we expect to demonstrate that the task can successfully elicit habitual control, as observed by Watson et al (2023; also Hennessy et al., 2025; van Timmeren and de Wit, 2023; van Timmeren et al., 2023), evidenced by habit-congruent responses (still valuable and still non-valuable) being made with higher accuracy than habit-incongruent responses (upvalued and devalued, respectively). Of crucial interest, if habitual control can operate without conscious stimulus awareness, the subliminal stimuli should facilitate more habit-congruent than habit-incongruent responses in the same way.

## 2. Methods

### 2.1. Participants

100 participants (49 female, 40 male, 11 other/decline to say) with a mean age of 22.86 years (3 unknown, $SD = 3.62$, range = 18——38) were recruited for participation via online and word-of-mouth advertisement at the Heinrich Heine University Düsseldorf, Germany. Participants received either course credit or 8 euro in compensation. All participants gave written informed consent and stated no current or history of neurological diseases or mental disorder, normal or corrected-to-normal vision, and fluency in German or English. 90 completed the study in German and 10 in English. 93 participants were students (64 in psychology). Sample size was determined according to a Bayesian Stopping Rule, such that data collection stopped once sensitive results were obtained for the relevant pre-registered comparisons in the testing stages (after applying relevant exclusions, see section 3.1; support for $H_0$ or $H_1$). A check was performed every 20 completed participants after passing 60 (this was not pre-registered due to student project constraints). Ethical approval was granted by the Ethics Committee of the Faculty of Mathematics and Natural Sciences at the Heinrich Heine University Düsseldorf (SK01-2021–01-R1), and the study was conducted in line with the Declaration of Helsinki.

### 2.2. Stimuli and materials

The experiment was conducted in Matlab 2019a (MathWorks, 2019), running Psychtoolbox (Brainard, 1997). The task was presented on a 24-inch ASUS PG248Q gaming monitor with a resolution of 1920 x 1080 pixels and a refresh rate of 120 Hz, permitting fast and accurate stimulus presentation. Responses were collected using a standard keyboard.

The target stimuli were six symbols obtained from the Agathodaimon font, out of which two (one vertically symmetrical, one asymmetrical) were randomly assigned to the staircased threshold-finding task, and four (two symmetrical, two asymmetrical) to the main task. In the training stage, the targets were presented in black (RGB: 0, 0, 0). In the testing stages, the contrast of target presentation was reduced in order to maximise stimulus presentation duration under masking, yielding a light grey display (RGB: 242, 242, 242; Skora et al., 2021). The forward–backward visual masks for the threshold-finding task and the unconscious testing stage were created afresh on each trial by re-scrambling a random grey-and-white pixel pattern (block size of 3 x 3 pixels). All target stimuli and masks were 170 x 170 pixels in size and were presented on a white background (RGB: 255, 255, 255).

As outcomes, images of four popular ice-creams were used: Solero and Cornetto in the main task, and Twister and Magnum in the practice task. Outcome images were 100 x 210 pixels in size.

### 2.3. Procedure

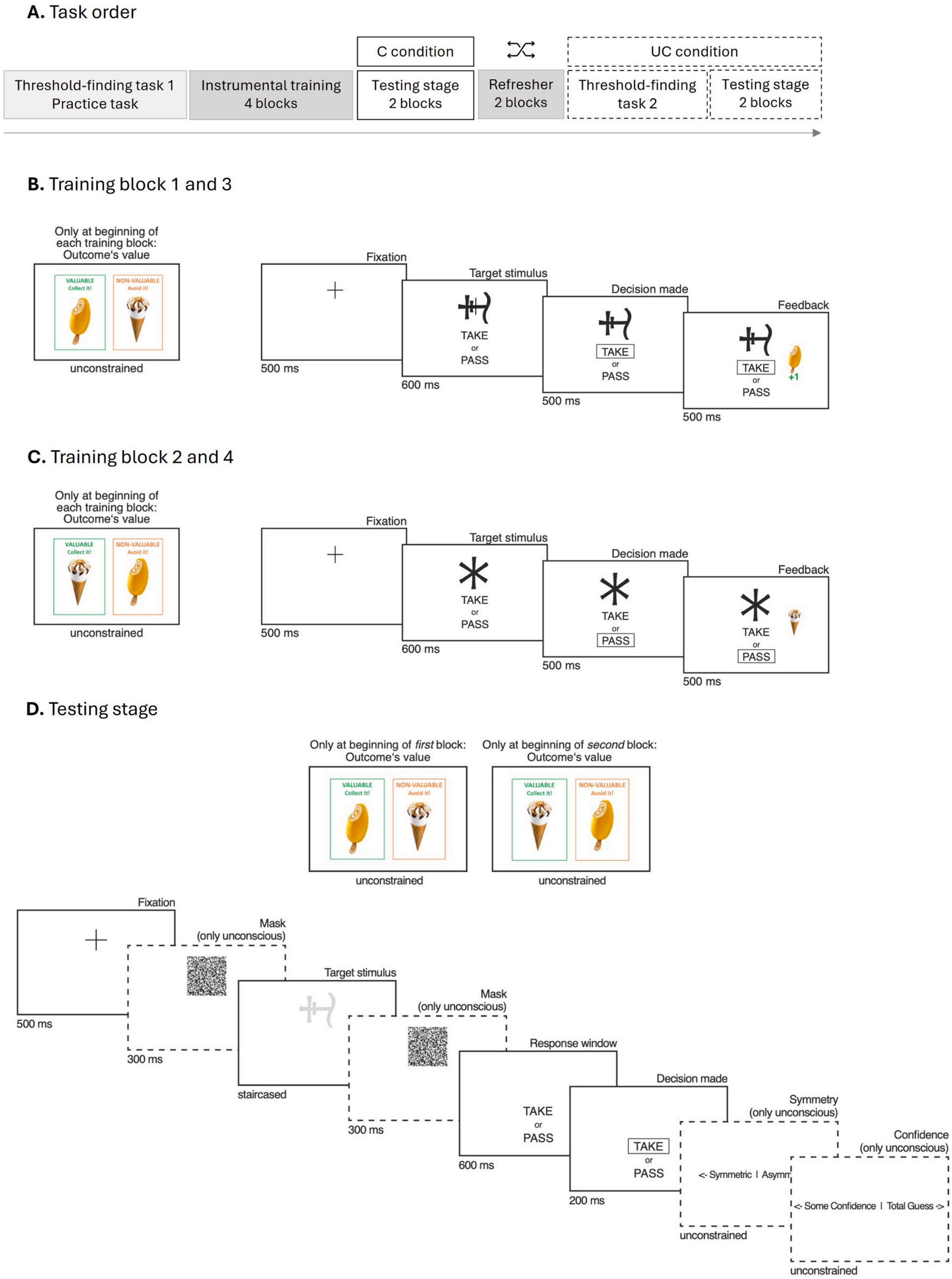
Each experimental session started with a threshold-setting task and brief practice task (using different stimuli than in the task proper). Subsequently, participants completed an instrumental training stage where they learned the stimulus–response-outcome associations, followed by the unconscious (UC) and conscious (C) testing stages, where two of the four outcomes were re-valued relative to the training stage, with the other two remaining the same as in training. The testing stages were separated by a brief, two-block refresher-training stage to counteract extinction. The order of the testing stages was randomised and counterbalanced, whereby half of the participants completed the unconscious testing stage (immediately preceded by another threshold-finding task) first, followed by the conscious testing stage, and the other half the reverse (see Fig. 1). Note that another threshold finding task always preceded the UC condition in order to minimise the risk that the preceding conscious exposure to the stimuli reduced the threshold established at the start of the task, leading to too many aware trials. As this risk did not apply to the C condition, the thresholding task was not repeated immediately prior to conscious testing. Instead, we applied the stimulus exposure duration from the first thresholding if the C condition was first, and from the second thresholding if the C condition followed the UC condition (Fig. 1). Participants were explicitly told that their performance in the task will be tracked and that three top performers will receive a 30 euro shopping voucher (in reality, the prizes were randomly drawn). The entire task lasted up to 60 mins (with breaks).

#### 2.3.1. Threshold-finding task

At the start of the task (serving as practice and setting the threshold for the C condition, should it occur first) and again immediately preceding the unconscious testing stage, a perceptual discrimination task was used in order to find the sub-threshold stimulus display duration for each participant, to be used in the testing stage. Each trial consisted of a fixation cross (500 ms), followed by a forward mask (300 ms), a symmetrical or asymmetrical neutral stimulus (starting at 600 ms), and a backward mask (300 ms). Participants were then asked to judge if the stimulus was symmetrical or asymmetrical by pressing the left- or −right arrow key (they were instructed to guess if they failed to perceive the stimulus). They were then asked whether they had any confidence in their judgment or if they were guessing, using the same arrow keys (following Skora et al., 2024). They were explicitly instructed to report 'some confidence' ('etwas sicher' in German) if they had any degree of confidence, including an intuition, and 'total guess' ('völlig geraten') if they felt they did not see the stimulus and responded genuinely at random. This distinction was applied as we considered any stimulus-related feelings, such as hunches or intuitions, to be conscious experience (Dienes et al., 2010; Skora et al., 2024). The combination of objective perceptual report with subjective confidence report ensures that conscious experience is related to the first-order perception of the relevant feature of the target stimulus, which can then be used to guide choices (Dienes et al., 2010). Every time a correct symmetry response was made with confidence (indicating awareness), stimulus display duration was reduced by 50 ms on the subsequent trial. Upon reaching a display duration of 100 ms, or when 'total guess' was first reported, presentation duration returned to the previous level (+50 ms), and reduced in smaller steps of 8.35 ms (single screen refresh) on following trials. This reduction continued until the next guess response, at which point the display duration remained the same if the participant continued guessing, but would decrease again with another correct and confident response. The duration maintained over six consecutive guesses (regardless of accuracy) was used as the display duration in the remainder of the corresponding testing stage (threshold finding 1: $M = 175$ ms, $SD = 38$ ms, $SE = 0.004$; threshold finding 2: $M = 146$ ms, $SD = 36$ ms, $SE = 0.004$; $t(74) = 6.49$, $p < 0.001$). This corresponds to the subjective threshold, argued to produce optimal conditions for demonstrating unconscious influences on perception and behaviour in comparison to objective threshold (pure chance discrimination performance), where effects tend to be smaller and short-lived (see Scott et al., 2018, for a discussion).

#### 2.3.2. Training stage

The goal of the training stage was to extensively train the S-R associations in order to build habitual responding, closely following the design of Watson et al. (2023). The training stage consisted of four blocks of 100 trials each (50 per target stimulus). Each block trained the correct instrumental action (accept or reject – implemented in the task as TAKE / PASS or NEHMEN / VERMEIDEN) for a single pair of target stimuli, with blocks one and three training pair 1, and blocks two and four training pair 2. In each pair, one stimulus was deterministically associated with a valuable outcome (e.g., the ice-cream Solero), in which case the correct response was




*(caption on next page)*

**Fig. 1. A:** Order of the tasks in an experimental session. Following the first threshold-finding task and the practice task, participants completed four blocks of instrumental training. This was followed by either the conscious (C) or unconscious (UC) condition, randomised and counterbalanced across participants. Another threshold finding task always preceded the UC condition in order to minimise the risk that the preceding conscious exposure to the stimuli reduced the threshold established at the start of the task. **B:** Example block instruction and trial illustration for blocks 1 and 3, training stimuli pair 1. Each trial began with fixation (500 ms), followed by one of the two target stimuli (600 ms). Once a decision was made within 600 ms (TAKE / PASS), the choice was framed (500 ms). The stimulus-contingent ice cream (outcome) was presented alongside feedback ('+1 /'-1'). In the example trial, the participant chose to TAKE the target which was associated with the valuable ice-cream (Solero) and was rewarded with 1 point. **C:** Example block instruction and trial illustration for blocks 2 and 4, training stimuli pair 2. Trials in blocks 2 and 4 had the identical sequence as A., but the outcomes were symmetrically reversed, i.e., Cornetto was the valuable outcome. In this example, the participant chose to PASS the target associated with the valuable ice-cream (incorrect response), leading to the ice-cream being displayed but no points being added or deducted. **D:** Example block instruction and single trial illustration of the testing stage. Each trial began with a fixation cross (500 ms), followed by forward–backward-masked (300 ms each) stimulus (duration staircased, now in grey) in the unconscious testing condition, or only the stimulus (also grey) in the conscious testing condition. Subsequently, participants were shown the choice options and were required to make a response within 600 ms. Once a response was made, the choice was framed for 200 ms. The unconscious condition concluded with a symmetry and confidence check.

accept (TAKE), and the other stimulus was associated with a non-valuable outcome (e.g., the ice-cream Cornetto; randomised and counterbalanced across participants), in which case the correct response was reject (PASS; see Table 1). Importantly, the valuable outcomes were counterbalanced between stimulus types, such that in the other pair the valuable outcome was Cornetto, while the non-valuable outcome was Solero. This produced a symmetrical matrix (see Table 1), where each of the four target stimuli has a desired response leading to a distinct outcome.

At the onset of each block, participants were informed of the valuable outcome which should be collected (e.g., Solero) and the non-valuable which should be passed (e.g., Cornetto) for that block (see Fig. 1 for trial chronology). They were also reminded that they would gain a point for collecting each valuable ice-cream, and lose a point for collecting a non-valuable ice-cream (note that PASS responses did not yield a gain or loss). Each trial began with a fixation (500 ms), followed by the stimulus presentation (one of a pair), accompanied below by the TAKE or PASS choice options, presented for 600 ms. Participants were instructed to make their choice by pressing the spacebar for TAKE or refraining from action for PASS within the 600-ms window of target presentation. A frame appeared (500 ms) around the TAKE option if it was chosen, or around PASS if no action occurred within 600 ms. Subsequently, the associated ice-cream was presented to the right of the target, accompanied by a green '+1' point if the participant took the target associated with a valuable ice-cream, or a red '-1' point if the participant took the target associated with a non-valuable ice-cream. Passing was followed by the presentation of the associated ice-cream, but no point was gained or lost.

After each training block, explicit S-R knowledge was measured identically to Watson et al (2023). Each stimulus of the pair trained in the corresponding block was presented individually in the centre of the screen. Participants used the mouse to indicate 'which action is correct for this stimulus', choosing between TAKE or PASS. If they responded correctly, a green frame was shown around their chosen option. A red frame was shown if they were incorrect to alert them to the error. Subsequently, with the stimulus still visible, participants completed a four-item Self-Report Behavioural Automaticity Index (SRBAI; Gardner et al., 2012, following Watson et al., 2023), reflecting if they felt their response to the corresponding stimulus 'is made automatically', 'begins before I realise I am doing it', 'is made without having to consciously remember', and 'is made without thinking'. Each question was accompanied by a 7-point visual analogue scale ranging from 1 (strongly disagree) to 7 (strongly agree), and participants used a mouse to indicate their answer. Finally, in order to maintain motivation, the participants were shown their current score, followed by a prompt to take a self-paced break.

### *2.3.3. Testing stages*

The goal of the testing stages was to assess the strength of the habitual actions, following the symmetrical outcome re-valuation procedure by Watson et al (2023). Each testing stage (UC, C) consisted of two blocks of 80 trials each. Importantly, each block now presented all four stimuli trained previously, whereby two remained congruent in value with the training stage (still-valuable or still-non-valuable, i.e. habit-congruent), and the other two became revalued (upvalued or devalued, i.e. habit-incongruent). In the second block, these contingencies were reversed (the first two were revalued, while the other two remained habit-congruent; see Table 1). To prevent re-learning the new contingencies, participants would no longer see the ice-cream or points as feedback.

At the onset of each block, participants were instructed to 'put their habit in action' and continue to accept or reject the stimuli correctly to win points, despite no longer receiving feedback. Subsequently, they were shown a screen informing them of the outcome

**Table 1**
All stimulus–response-outcome combinations in the training and testing stages of the task. In the testing stages, one pair of the stimuli were revalued (upvalued, devalued), while the other remained the same as in the training stage (still valuable, still non valuable) in block 1 (B1). In the second block (B2), the reverse was applied.

| **TRAINING STAGE** | | | | | **TEST B1: Collect O1** | **TEST B2: Collect O2** |
|---|---|---|---|---|---|---|
| **Pair** | **Stimulus** | **Value** | **Response** | **Outcome** | **Outcome (response)** | **Outcome (response)** |
| 1 | S1 | Valuable | TAKE | Solero (O1) | Still valuable (TAKE) | Devalued (PASS) |
| | S2 | Non-valuable | PASS | Cornetto (O2) | Still non-val (PASS) | Upvalued (TAKE) |
| 2 | S3 | Non-valuable | PASS | Solero (O1) | Upvalued (TAKE) | Still non-val (PASS) |
| | S4 | Valuable | TAKE | Cornetto (O2) | Devalued (PASS) | Still valuable (TAKE) |

values valid for the coming block (e.g., Solero is valuable, Cornetto is non-valuable, and the reverse for the other block, counterbalanced across subjects). In this example, the target stimulus linked to valuable-Solero in the training stage would remain still-valuable and continue to demand a TAKE response (habit-congruent), while a target linked to non-valuable Cornetto would remain still-non-valuable and continue to demand a PASS response (also habit-congruent). Conversely, a target previously linked to *non-valuable* Solero would now become upvalued and demand a TAKE response, while a target previously linked to a *valuable* Cornetto would become devalued and demand a PASS response.

In both testing stages, each trial began with a fixation cross (500 ms), followed by stimulus presentation (duration determined in the threshold-finding task; in the UC stage, the stimulus was forward–backward masked, both 300 ms). Due to the short stimulus display duration and, in the unconscious condition, masked presentation, the 600 ms response window displaying the TAKE or PASS options opened immediately after the stimulus was shown. As in the training stage, the chosen option was framed for 500 ms. No feedback was given. Instead, each trial ended with an awareness check to determine objective awareness of the stimulus shown and a subjective level of confidence, identically to the threshold-finding task (see section 2.3.1.). Participants were asked whether the stimulus shown was vertically symmetrical or asymmetrical and gave their responses using left- and right-arrows, respectively (unconstrained). Subsequently, they rated their confidence in that decision between 'some confidence' and 'total guess' (left- and right-arrows, respectively). As in the threshold-finding task, they were explicitly instructed to report 'some confidence' if they had any degree of confidence, even a hunch. See Fig. 1 for trial chronology. In the UC testing blocks, participants were made aware that they would not be able to perceive the stimuli reliably, but if they ever would, they should indicate this in the awareness check. They were also instructed to trust their 'gut feelings' when deciding whether to accept the stimuli or not, as they should not be able to see them. No net score was provided at the end of the blocks to prevent learning, and no breaks were included between the testing blocks of the same condition, apart from the new value instruction screen.

#### 2.3.4. Refresher training stage

The unconscious and conscious testing stages were separated by a brief refresher training, implemented to counteract the risk of extinction during the revaluation in the first testing stage affecting the second testing stage. The refresher stage consisted of two blocks of 20 trials each (10 trials per target stimulus), with one block per stimulus pair, preserving their original values. The refresher trials were identical in all respects to the training stage proper (see 2.3.2. Training stage).

## 3. Analysis and results

### 3.1. Exclusions

Two participants were excluded post-hoc as they indicated not meeting exclusion criteria after completing the task. None of the remaining participants were excluded based on our preregistered criterion of failing to reach 90 % accuracy in the averaged training blocks 3 and 4 (participants' accuracy ranged between 91–100 %). Five participants who failed to accept the stimuli on over 20 % of the total testing trials were excluded. We then applied awareness exclusions on a trial-level, excluding any trials from the UC testing blocks where participants reported the stimulus symmetry correctly and with confidence, considering such trials as 'aware' (19 % of all unconscious trials). Where participants had over 20 % of aware trials in both blocks, they were excluded altogether (N = 18). For the remaining participants who reached over 20 % of aware trials in any UC block, only the affected block was removed from analysis ($N_{B1} = 9$, $N_{B2} = 9$). This approach (following Skora et al., 2023) ensures that analyses of the unconscious testing stage are not contaminated by conscious, explicit knowledge of stimulus type. After all exclusions, the final sample was 75 participants (37 females, 31 males, 7 other/decline to say). Among those participants, most showed some degree awareness during the task ($M_{B1} = 7.8$ trials; $M_{B2} = 7.7$ trials), which resulted in a drop in duration of exposure for 12 participants in block 1 ($M_{\text{start}} = 146$ ms, $M_{\text{end}} = 144$ ms), and nine in block 2 ($M_{\text{start}} = 144$ ms, $M_{\text{end}} = 143$ ms).

### 3.2. Analyses

The crucial, theory-driven analyses were pre-registered at https://osf.io/syk5j and conducted in R (v4.2.0, R Core Team, 2021) through R studio (v 2023.12.0.369, Posit Team, 2023). For the training stage, base-R one-sample and paired *t*-test functions were used to assess performance. For both testing stages, we first conducted one-sample t-tests for each stimulus type to assess performance relative to chance level (a non-crucial and not pre-registered step), followed by linear mixed effect models (LMMs) to assess the core question whether accuracy was higher for habit-congruent stimuli (still-valuable, still-non-valuable) compared to the corresponding habit-incongruent stimuli (upvalued, devalued). We deviated from the pre-registered ANOVAs in favour of equivalently specified linear LMMs due to their superiority in accounting for individual variability through modelling individual intercepts as random effects, and greater robustness (e.g., to missing data points; Barr et al., 2013; Singmann & Kellen, 2019). Those models were implemented with *lme4* package (Bates et al., 2015), and evaluated with the *car* (Fox & Weisberg, 2011) and *emmeans* (Lenth, 2023) packages. All graphical representations were created with *ggplot2* (Wickham, 2016).

Bayes factors (B) were computed for all comparisons (for parameters of each test, see results). In line with the Bayesian Stopping Rule (Dienes, 2015), data collection continued until a sensitive result was found for the comparisons of interest in the testing stages in support of either $H_0$ (difference absent; by convention indicated by a B smaller than 0.3; Dienes, 2014; Jeffreys, 1983) or $H_1$ (difference present; indicated by a B larger than 3).

### 3.3. Training stage: Evidence for learning

One-sample t-tests against the chance performance level of 0.5 were computed for each training block to assess whether participants have learned the stimulus–response associations. Bs were calculated for each test, with a half-normal distribution, mean specified as 0 and an empirical prior of 0.35, corresponding to an estimated effect size of 35 % over the chance level, approximating learning (Watson et al. 2023; note that raw values entered into the test were re-scaled accordingly). Group level accuracy in all four training blocks was significantly above chance, indicating participants' ability to learn the S-R associations (see Table 2).

To examine performance improvement in the second relative to the first half of the training, accuracies were averaged for blocks 1 and 2, and blocks 3 and 4, and entered into a paired *t*-test. B was computed for the estimated accuracy difference of 0.05 found between the first and second halves of the first experiment in Watson et al (2023). As expected, participants reached a significantly higher accuracy in the second half of training ($M = 0.99$, $SE = 0.002$) compared to the first half ($M = 0.97$, $SE = 0.003$; $t(149) = -4.56$, $p < 0.001$, Cohen's $d = 0.46$, $B_{H(0,\ 0.05)} = 130297.51$).

In the refresher-training stages, one-sample tests against chance revealed significantly above-chance performance in block 1 ($M = 0.97$, $SE = 0.01$; $t(74) = 89.08$, $p < 0.001$, $B_{H(0,\ 0.35)} = 1.64 \times 10^{54}$) and block 2 ($M = 0.97$, $SE = 0.01$; $t(74) = 77.63$, $p < 0.001$, $B_{H(0,\ 0.35)} = 1.64 \times 10^{54}$) alike, indicating that participants maintained the trained S-R contingencies after undergoing risk of extinction during the first testing stage.

### 3.4. Exploratory: Self-reported behavioural automaticity index

Upon completion of each training block, participants were 100 % correct in indicating the response required for both stimuli (valuable, non-valuable) in the block.

For the SRBAI, following Watson et al. (2023), we first computed an averaged SRBAI sum score for valuable and non-valuable stimuli during the training stage, separating the first half (blocks 1 and 2) and the second half (blocks 3 and 4). The raw values were then scaled to a 7-point Likert scale. A paired *t*-test revealed a moderate but significant increase in self-reported automaticity from the first to the second half of training (Half1: $M = 5.28$, $SE = 0.14$; Half2: $M = 5.68$, $SE = 0.15$; $t(73) = -4.35$, $p < 0.001$, Cohen's $d = -0.32$ (95 % CI [-0.47, −0.17]), $B_{10} = 439.16$ (note that in the absence of an expected difference, we used a default Cauchy prior for this computation using the R package *BayesFactor;* Morey et al., 2024)). See Supplementary Materials for a breakdown of scores by question.

### 3.5. Conscious testing stage

One-sample t-tests against the chance performance level of 0.5 were computed for each stimulus type. Bs were calculated for each test, with a half-normal distribution, mean specified as 0 and an empirical prior of 0.35, corresponding to an estimated effect size of 35 % over the chance level, as in the training stage. Across both blocks of the conscious testing stage, participants showed above-chance performance accuracy in response to the still-valuable stimuli ($M = 0.86$, $SE = 0.02$; $t(74) = 16.92$, $p < 0.001$, $B_{H(0,\ 0.35)} = 1.69 \times 10^{32}$), to the non-valuable stimuli ($M = 0.86$, $SE = 0.02$; $t(74) = 15.54$, $p < 0.001$, $B_{H(0,\ 0.35)} = 1.69 \times 10^{32}$), and to the devalued stimuli ($M = 0.67$, $SE = 0.04$; $t(74) = 4.16$, $p < 0.001$, $B_{H(0,\ 0.35)} = 729.01$), but not to the upvalued stimuli ($M = 0.54$, $SE = 0.05$; $t(74) = 0.95$, $p = 0.172$, $B_{H(0,\ 0.35)} = 0.3$; see Fig. 2). The lower accuracy and greater variability in performance on the devalued and upvalued trials is suggestive of the S-R habits interfering with the reversed goals on those trials, in line with other tasks using this paradigm (Watson et al., 2023; van Timmeren & de Wit, 2023; van Timmeren et al., 2023).

For the crucial analysis, a linear mixed effect model was fitted, with accuracy as a response variable, stimulus type (still-valuable, still-non-valuable, upvalued, devalued) as a fixed effect, and subject-specific random intercepts (note that a maximum random effect specification with subject-wise random intercepts failed to converge). The model was fitted by maximum likelihood estimation. An Anova (Type II Wald test, *car* package) conducted on the model-estimated parameters revealed a significant main effect of stimulus type on accuracy ($\chi^2 = 99.17$, $p < 0.001$). We then conducted pairwise comparisons (Tukey-corrected) on the estimated marginal means (see Table 3 for full results). Bs were computed for each pair, with a normal distribution, mean centred at 0, and the mean differences of 12 % obtained from Watson et al. (2023) as empirical priors. The results for the crucial comparisons support the theory-

**Table 2**

Descriptive statistics and one-sample *t*-test results (one-tailed) for choice accuracy in each of the four blocks of the training stage. Note that *M* values were re-scaled for B calculation with reference to the model mean ($H_0$) centred at 0.

| Training Block | *M* | *SE* | *t* (df) | *p* | Cohen's d [95 % CI] | $B_{H(0,\ 0.35)}$ |
|---|---|---|---|---|---|---|
| 1 | 0.96 | 0.006 | 82.22 (74) | < 0.001*** | 9.49 [7.88, 11.11] | $4.10 \times 10^{69}$∼ |
| 2 | 0.98 | 0.003 | 150.42 (74) | < 0.001*** | 17.37 [14.51, 20.23] | $1.22 \times 10^{93}$ ∼ |
| 3 | 0.99 | 0.002 | 289.23 (74) | < 0.001*** | 33.40 [27.94, 38.85] | $5.55 \times 10^{106}$∼ |
| 4 | 0.98 | 0.003 | 175.98 (74) | < 0.001*** | 20.32 [16.98, 23.66] | $1.22 \times 10^{935}$∼ |

*Note:* For *p*-values, asterisks represent: ***: p < 0.001. For B, ∼ represents support for H1.

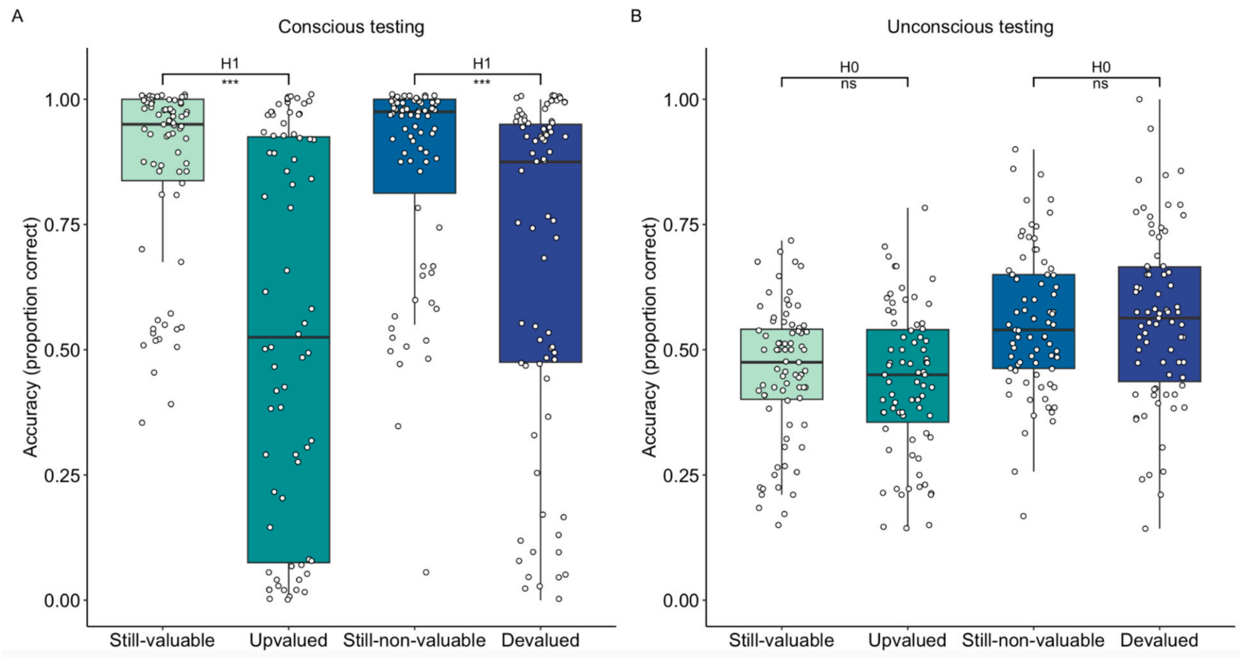



**Fig. 2.** Boxplots showing average accuracy (proportion of correct responses) for all stimulus types in conscious (A) and unconscious (B) testing (both blocks averaged). Asterisks indicate the significance level (*** = $p < 0.001$) for the theory-driven crucial comparisons (still-valuable vs upvalued and still-non-valuable vs devalued).'H1′ indicates a Bayes factor supporting $H_1$ (B > 3),'H0′ indicates a Bayes factor supporting $H_0$ (B < 1/3).

**Table 3**
Estimated marginal means (EMMs) for all possible contrasts in conscious testing (Tukey-corrected). Contrasts highlighted in bold are the crucial, theory-driven pairwise comparisons conducted to test whether participants responded in line with habit. Specifically, we predicted that habitual responding would yield a higher mean accuracy for habit-congruent stimuli (still-valuable, still-non-valuable) than for the corresponding habit-incongruent stimuli (upvalued, devalued, respectively).

| Conscious testing: Contrast | EMM | *SE* | df | t | *p* | $B_{N(0,\ 0.12)}$ |
|---|---|---|---|---|---|---|
| **De-valued vs. Still-non-valuable** | **−0.20** | **0.04** | **229** | **−5.00** | **< 0.001***** | **13583.19∼** |
| De-valued vs. Up-valued | 0.12 | 0.04 | 229 | 3.18 | 0.009* | |
| De-valued vs. Still-valuable | −0.20 | 0.04 | 229 | −5.07 | < 0.001*** | |
| Still-non-valuable vs. Up-valued | 0.32 | 0.04 | 229 | 8.20 | < 0.001*** | |
| Still-non-valuable vs. Still-valuable | 0.00 | 0.04 | 229 | −0.07 | 1.000 | |
| **Up-valued vs. Still-valuable** | **−0.32** | **0.04** | **229** | **−8.25** | **< 0.001***** | **27015471061.47∼** |

*Note:* For *p*-values, asterisks represent: ***: p < 0.001. For B, ∼ represents support for H1.

driven hypothesis that participants would be significantly more accurate in response to still-valuable versus upvalued stimuli, and to still-non-valuable versus devalued stimuli (Table 3; Fig. 2). This provides evidence for the existence of habitual, as opposed to goal-directed, responding in the conscious testing stage, replicating the Watson et al. (2023) symmetrical outcome revaluation task.

As a control, we checked whether the performance differed between each block of the testing stage by repeating the above mixed model including the block (1, 2) as a fixed effect, interacting with stimulus type. There was no significant main effect of block on accuracy and no significant interaction with stimulus type (*ps* > 0.5), while the main effect of stimulus type remained significant (see Supplementary Materials).

### 3.6. Unconscious testing stage

One-sample t-tests against the chance performance level of 0.5 were computed for each stimulus type. Across both blocks of the unconscious testing stage, participants failed to show above-chance performance accuracy for the still-valuable stimuli ($M = 0.46$, $SE = 0.02$; $t(74) = -2.88$, $p = 0.997$, $B_{H(0,\ 0.35)} = 0.02$) and the upvalued stimuli ($M = 0.44$, $SE = 0.02$; $t(74) = -3.76$, $p = 0.999$, $B_{H(0,\ 0.35)} = 0.01$), but reached above-chance accuracy for the still-non-valuable stimuli ($M = 0.56$, $SE = 0.02$; $t(74) = 3.39$, $p < 0.001$, $B_{H(0,\ 0.35)} = 8.32$) and the devalued stimuli ($M = 0.56$, $SE = 0.02$; $t(74) = 3.12$, $p = 0.001$, $B_{H(0,\ 0.35)} = 8.32$; see Fig. 2). While the above-chance accuracy for the still-non-valuable and devalued stimuli could reflect a genuine priming effect, asserting it would require the still-valuable and upvalued stimuli to also exhibit above-chance accuracy (Watson et al., 2023). As such, the elevated performance obtained for the still-non-valuable and the devalued stimuli (as well as the below-chance performance for still-valuable and upvalued stimuli) might jointly reflect a response bias in favour of reject implicit in the task: the reject response, correct for those stimuli, might also be more readily chosen, or defaulted to, by participants under uncertainty (likely for the same reason, accuracy is higher for the devalued compared to upvalued stimuli in the conscious condition; see also Du & Haith, 2025). Indeed, a general bias towards reject is evident across the unconscious condition (see Supplementary Materials). Importantly, however, subsequent analyses comparing the stimuli requiring the same response type render this issue tractable, as evidence for habit would require still non-valuable stimuli to show higher accuracy than devalued stimuli.

For the crucial analysis, identically to the conscious testing analysis, we then fitted a linear mixed effect model with accuracy as a response variable and stimulus type (still-valuable, still-non-valuable, upvalued, devalued) as a fixed effect, and subject-specific random intercepts (note that a maximum random effect specification with subject-wise random intercepts failed to converge). The model was fitted by maximum likelihood estimation. An Anova (Type II Wald test, *car* package) conducted on the model-estimated parameters revealed a significant main effect of stimulus type on accuracy ($\chi^2 = 44.04$, $p < 0.001$). We then conducted pairwise comparisons (Tukey-corrected) on the estimated marginal means (see Table 4 for full results). Again, Bs were computed for each pair, with a normal distribution, mean centred at 0, and the mean difference of 12 % obtained from Watson et al. (2023) as empirical priors. For the crucial comparisons (still-valuable versus upvalued, and still-non-valuable versus devalued stimuli), we found an absence of a difference in accuracy (see Table 4). The significant main effect of stimulus type again appears to be driven by the response bias towards PASS driving higher accuracy for the still-non-valuable and devalued stimuli (see t-tests above). Those results suggest that participants failed to respond in a habit-congruent manner, as they did in the conscious condition. Notably, however, they also failed to respond in a goal-directed way, which would be indicated by increased accuracy in response to the re-valued (upvalued, devalued) stimuli. Instead, participants' accuracy hovered around the chance-performance level, suggesting that none of the masked stimuli were able to evoke an appropriate response, whether habitual or goal-directed.

Again, we checked whether the performance differed between each block of the testing stage by repeating the above mixed model including the block (1, 2) as a fixed effect, interacting with stimulus type. There was no significant main effect of block on accuracy ($p > 0.05$) and a significant effect of stimulus type ($p < 0.001$), as well as a significant interaction with stimulus type ($p = 0.013$), Inspecting the paired comparisons between the estimated marginal means, this interaction is driven by significant differences in block-stimulus type pairings which are not relevant to our inferences – for the comparisons of interest, there are no significant differences for the stimuli types between the blocks(see Supplementary Materials).

## 4. Discussion

In the present study, we experimentally tested whether habitual control of instrumental behaviour can be triggered by stimuli presented outside of conscious awareness using visual masking. Participants underwent an extensive instrumental training task, which successfully established S-R associations for four different stimuli. Training was followed by the symmetrical outcome revaluation task adapted from Watson et al. (2023), where values (and associated responses) of two of the stimuli remained the same, while the remaining two stimuli were re-valued to become upvalued and devalued. In the conscious test, where the stimuli were in plain view, we confirmed that behaviour was under habitual control – performance was better in response to habit-congruent (still-valuable, still-non-valuable) stimuli than to the matched revalued stimuli (upvalued, devalued, respectively), thus replicating the previously observed pattern in this task (Watson et al., 2023; van Timmeren et al., 2023; van Timmeren & de Wit, 2023) and similar habit-probing tasks (de Wit et al., 2012; Gillan et al., 2011; Hardwick et al., 2019; Tricomi et al., 2009). In the unconscious testing stage, however, this pattern of results failed to emerge. Instead, choice accuracy did not differ between habit-congruent compared to habit-incongruent stimuli, suggesting that behaviour was not under habitual control. Crucially, responses also failed to reach an accuracy level indicative of goal-directed behaviour, instead pointing towards random behaviour. This result extends the previous findings from similar tasks that rendering stimuli subjectively unperceived through visual masking abolishes both instrumental learning and instrumental performance (Reber et al., 2018; Skora et al., 2021; Skora et al., 2022; Skora et al., 2023; Skora et al., 2024).

While in the conscious testing stage the habitualised associations impacted performance in the predicted directions, response accuracy for devalued stimuli was higher than for upvalued stimuli – suggesting, at first glance, that participants may have been better at flexibly overriding the habitual accept (TAKE) response in favour of a reject (PASS) response, than at overriding the reject response

**Table 4**
Estimated marginal means (EMMs) for all possible contrasts in unconscious testing (Tukey-corrected). Contrasts highlighted in bold were the crucial, theory-driven pairwise comparisons conducted to test whether participants responded in line with habit. In contrast to our prediction, participants failed to exhibit habitual responding: mean accuracy for habit-congruent stimuli (still-valuable, still-non-valuable) was not higher than accuracy for the corresponding habit-incongruent stimuli (upvalued, devalued, respectively).

| Unconscious testing: Contrast | EMM | *SE* | df | t | *p* | $B_{N(0, 0.12)}$ |
|---|---|---|---|---|---|---|
| **De-valued vs. Still-non-valuable** | **0.01** | **0.02** | **230** | **0.27** | **0.993** | **0.1857**$^{+}$ |
| De-valued vs. Up-valued | 0.12 | 0.02 | 230 | 5.13 | < 0.001 | |
| De-valued vs. Still-valuable | 0.11 | 0.02 | 230 | 4.390 | < 0.001*** | |
| Still-non-valuable vs. Up-valued | 0.12 | 0.02 | 230 | 4.87 | < 0.001*** | |
| Still-non-valuable vs. Still-valuable | 0.10 | 0.02 | 230 | 4.12 | < 0.001*** | |
| **Up-valued vs. Still-valuable** | **−0.02** | **0.02** | **230** | **−0.74** | **0.880** | **0.2676**$^{+}$ |

*Note:* For *p*-values, asterisks represent: ***: $p < 0.001$. For B, $^{+}$ represents support for H0.

in favour of accepting. Although this possibility cannot be entirely rejected, here it is likely to be an artefact of the Go/NoGo design, which can artificially increase the accuracy for devalued stimuli, where the desired response is PASS – for example, if participants fail to respond due to uncertainty, the habit-goal conflict, or for unrelated reasons, such as boredom, confusion, or fatigue (Balleine & Dezfouli, 2019; Du & Haith, 2025). A similarly elevated accuracy for devalued stimuli, in comparison to the other stimulus types, is evident in the unconscious condition. Nevertheless, the design of Watson et al (2023) accounts for this caveat by assessing habitual control through comparing stimuli requiring the same response type (still-valuable and valuable requiring Go, and still-non-valuable and devalued requiring NoGo), rather than accuracies for the individual stimuli. An alternative solution to circumvent this problem could be a constrained response space (e.g., different actions).

In the unconscious testing stage, we hypothesised that if habitual control can operate without stimulus awareness, the highly trained stimuli would still facilitate habit-congruent responses relative to habit-incongruent responses when rendered subliminal. However, we found no evidence for such an effect: habit-congruent stimuli evoked no better performance than habit-incongruent stimuli matched for response type. In addition to the absence of evidence for habitual behaviour, there was also no evidence for goal-oriented behaviour – instead, behaviour appeared to be at chance level and unaffected by the subliminal stimuli (taking the reject-bias into account). This suggests that subjectively unperceived stimuli cannot cue either goal-oriented or the relevant habitual responses, despite clear evidence from the conscious control condition that the task is suitable for observing habitual behaviour.

Previously, we speculated that the absence of successful instrumental learning or responding to previously trained (albeit not controlled for habitualisation) subliminal stimuli could result from their inability to recruit sufficiently widespread activation of relevant neural circuits to drive the processes involved in selective action (Skora et al., 2021; Skora et al., 2024). Those processes include retrieving the representation of expected value, choosing an action policy, engaging motor control, and assigning credit for the outcome to the stimulus and the choice that caused it, in order to update the expected values (Balleine, 2019; Balleine & Dickinson, 1998; Jocham et al., 2016; Klein-Flügge et al., 2013; Sutton & Barto, 1998). During unconscious instrumental behaviour, outcomes may not be able to be successfully linked to the subliminally presented stimuli, and the stimuli never acquire any value in order to drive subsequent choices. However, habitual control is known to be insensitive to value – action selection is controlled by stimuli, rather than consequences of actions (Balleine & Dezfouli, 2019; Haith & Krakauer, 2018). Hence, it was plausible that consciously habitualised appropriate responses could be cued through the automatic mapping of responses to stimuli in a priming-like effect. Yet, subliminal stimuli appear incapable of cueing such responses. One interpretation of this effect could be that instrumental behaviour, whether goal-directed or habitual, requires conscious experience of the stimulus as a contextual cue, in order to select the most adequate response in the given context – either by pursuing a goal-oriented strategy, or delegating the response to the cached S-R mapping. A related view could be that habitual behaviour is in fact less separable from goal-directed behaviour than commonly postulated (see Kruglanski & Szumowska, 2020; De Houwer et al., 2023), and both might require a conscious representation of the stimulus in order to select an action.

Those interpretations support the views linking conscious experience to action control and adaptive behaviour, where consciousness could be providing a frame of reference for agents' interactions with the world (Clark, 2016; Land, 2012; Lev-Ari, Beeri & Gutfreund, 2022; Martin et al., 2021; Merker, 2005, 2013; Seth et al., 2016). In a similar vein, the function of (valenced) subjective experience has been proposed to guide behaviour by linking objective properties of the stimuli with intrinsic value for the agent (Cleeremans & Tallon-Baudry, 2022; Solms, 2021). Elsewhere, complex forms of learning (including trace conditioning, second-order conditioning and reversal learning) have been proposed to be evolutionarily intertwined with the phylogenetic development of consciousness (Birch et al., 2020, 2021; Ginsburg & Jablonka, 2019). Those perspectives imply that instrumental behaviour might be closely tied to the awareness of our surroundings, in contrast to reflexes or rigid action-independent associations, which have been shown to be susceptible to subliminal influences (Lin & He, 2009; Raio et al., 2012; Rosenthal et al., 2016; Scott et al., 2018; Seitz et al., 2009).

Importantly, the pattern of results observed in the unconscious testing stage does not imply that habitual behaviour as a whole is not unconscious, or that habits do not operate outside of conscious control. Instead, it might be the case that awareness of the contextual cues or action targets (note that while in this study these were the same, this might not always be the case) is essential for engaging in the relevant behaviour, while the process of engaging in the behaviour can remain outside of conscious awareness or deliberation. This would pertain to an 'implicit', rather than 'unconscious', control of habitual behaviour. This has been shown previously in a study of two patients with temporal lobe lesions and no capacity for declarative memory, who could learn S-R associations without being able to report on the task (Bayley et al., 2005; Knowlton et al., 1996). Hence, it could be that during habitual behaviour the stimuli are fully processed, but due to the direct mapping to a response, they do not receive sufficient attention to gain access to working memory (let alone the long-term memory). In a comparable case, while instrumental learning has been shown to fail when participants were not conscious of the discriminative stimuli (Skora et al., 2021; Skora et al., 2022; Skora et al., 2023; Skora et al., 2024), it succeeds when they could fully perceive the stimuli but were not explicitly aware of the reward contingencies (Jurchiș, 2022). Nonetheless, we cannot unequivocally dismiss the possibility that our task was not sensitive enough to detect the influence of unconsciously presented stimuli on behaviour. Our key manipulation of stimulus awareness – masking – necessitated that the testing stages differed from the training stage such that the response was no longer made while the stimulus was on screen, but following it. Importantly, however, this change was still able to produce the dominance of habitual control in the conscious testing stage, so it was unlikely to have negative consequences for the unconscious testing stage. Secondly, due to the re-thresholding immediately prior to the unconscious testing stage (see 2.3. Procedure), the stimulus presentation duration may have differed between unconscious and the conscious testing stages when the unconscious condition was second. We prioritised re-staircasing only prior to the unconscious condition in order to counteract any potential visual adaptations from conscious exposure affecting the masking – otherwise, we risked losing too many individual trials to awareness. As this was not a concern in the conscious condition, we felt there was no need to rethreshold.

Thirdly, visual masking in our experiment may have been too powerful as a suppression method, preventing any kind of processing of the stimulus and precluding any effects on behaviour. In such a case, absence of evidence for a process under masking can stem either from the limits of unconscious processing, or from the weakness of the signal. Additionally, it might be affected by participant's biases in reporting their experience (Michel, 2023). However, visual masking has often been used to successfully demonstrate other associative, but non-instrumental, processes (e.g., learning semantic associations; Faivre et al., 2014; Scott et al., 2018), suggesting that unconscious processing might not be able to support sufficiently complex or action-related tasks. Finally, the methodology for finding the individual threshold of conscious perception employed here invariably results in visual experience oscillating closely around it – nearly all participants experience transient moments of awareness, yielding some trials with correct objective discrimination made with confidence. Hence, at a display duration so close to the threshold of conscious perception, it is unlikely that the signal would be so poor as to render the stimuli completely unprocessed. However, auxiliary methods to assess processing such as neuroimaging or psychophysiological measures could be used to support this point in the future and increase the sensitivity of the measures, as well as other methods for finding thresholds of conscious perception (e.g., Tsikandilakis et al., 2021).

To conclude, this work shows that neither habitual nor goal-directed control of instrumental behaviour can operate in the absence of subjective stimulus awareness in a symmetrical outcome re-valuation task. While the task proved to be suitable for eliciting habitual control in the conscious condition (where the stimuli were in plain view), once the stimuli were presented just below the individual threshold of conscious awareness, they were unable to trigger the habitualised response in line with the S-R association. Importantly, participants were also unable to override the habitualised response and respond in a goal-oriented manner, instead demonstrating chance-level performance. This result extends the recent evidence that instrumental behaviour might rely on conscious access to the stimuli serving as contextual cues or targets of actions, showing that even strongly habitualised instrumental behaviour depends on conscious access.

## 5. Open practices statement

The study was pre-registered at https://osf.io/syk5j. The task code and data are available at https://osf.io/whc8t/.

## CRediT authorship contribution statement

**Jan-Daniel Höhmann:** Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Gerhard Jocham:** Writing – review & editing, Supervision, Resources. **Lina I. Skora:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Formal analysis.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.concog.2025.103937.

## Data availability

link in the ms

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