



## OPEN It is a matter of size—manipulating body size with virtual reality modulates reward sensitivity

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Body perception, including the perception of body size, plays an important role in shaping cognitive and motivational processes. Variations in body size have been linked to differences in reward processing, involving neural systems underlying appetite, motivation, and behavioral control. Furthermore, rapid changes in body size have been associated with modulation of reward-related neural responses and changes in food-related motivation. Interestingly, the Full Body Illusion (FBI) has been effective in altering perceived body size and eating attitudes. However, it remains unclear whether such illusory manipulations can affect reward-based behavior per se. To address this question, we investigated whether FBI-induced changes in body size influence reward-based learning and implicit attitudes toward both food and body weight. Embodying a larger avatar enhanced reward-based learning and implicit attitudes toward high-calorie foods, whereas the reduction in implicit weight bias occurred independently of the avatar size. This is the first study to establish a link between reward-based learning and the perception of one's body size, emphasizing the critical role of perceived weight, beyond the actual physical weight, in shaping approach behavior.

**Keywords** Feedback-based learning, Body size, Full body illusion, Body ownership, Social stigma

The motto “*mens sana in corpore sano*” highlights how bodily states are intrinsically linked to cognitive and emotional processes. Body perception, including the perception of body size, plays an important role in this relationship, as it can shape motivation, behavior, and self-related beliefs. Overweight and obesity, while differing in severity and health impact<sup>1</sup>, are both associated with a pervasive social stigma, the weight bias<sup>2</sup>, as well as with changes in cognition and motivation<sup>3</sup>. Understanding how body size interacts with cognitive and motivational processes is therefore of scientific relevance, extending beyond clinical populations.

Alterations in reward processing are increasingly recognized as important contributors to body weight regulation, reflecting disruptions in neural systems involved in appetite, motivation, and behavioral control<sup>4</sup>. Neuroimaging studies show that both obesity and weight gain are associated with abnormal striatal<sup>5–10</sup>, frontal<sup>11</sup>, and dopaminergic<sup>11</sup> responses (i.e., crucial components of the human reward system<sup>5–10</sup>). For instance, Balodis and collaborators<sup>12</sup> reported increased bilateral ventral striatum activation during the anticipation of monetary (non-food) reward in individuals with obesity, indicating a generalized alteration in reward sensitivity. Additional support for the plasticity of reward-related neural response comes from studies investigating the consequences of rapid reduction of body size such as following bariatric surgery, which have been shown to modify mesolimbic activation and food related motivation, including reduced neural responses to high-calorie food cues post-surgery<sup>13</sup>. We cite this line of work as an example of reward-system plasticity following rapid body-size change, not as a clinical comparison with the present sample. Together, these findings indicate that reward processing and food-related motivation are sensitive to change in bodily and physiological states, likely depending on multiple interacting factors, such as hormonal, metabolic, physiological, and also body-size-related ones; contributions of which remain to be empirically tested.

Among these factors, body size can be easily and experimentally manipulated to test its causal role in modulating reward and food-related motivation. The full-body illusion (FBI) provides a controlled way to transiently alter perceived body size without inducing actual physical changes. In the FBI paradigm<sup>14,15</sup> a virtual

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avatar viewed from a first-person perspective, thus visually replacing the participant's body, induces the illusion of owning that body. The illusion of owning a larger avatar induces an increase in one's own body size estimation while owning a slimmer avatar leads to a decrease in body size estimation<sup>16–20</sup>. Crucially, these perceptual manipulations also change food-related attitudes, with larger virtual bodies increasing preference for unhealthy foods<sup>21</sup> and slimmer avatars inducing avoidance of high-calorie foods<sup>20</sup>. These effects are often attributed to the activation of body-related stereotypes (e.g., larger bodies associated with unhealthy eating), though this account remains largely speculative and empirically underexplored.

Research suggests that actual body size is one of the factors influencing both food-related motivation and reward processing. At the same time, robust evidence from FBI studies shows that perceived body size reliably affects food attitudes, effects typically interpreted as stereotype-driven, while its impact on reward sensitivity has not yet been investigated. Based on this evidence, the present study tests two alternative hypotheses. If changes in perceived body size primarily reflect stereotype activation, embodiment should affect attitudes but not reward-related processes. Conversely, if perceived body size directly modulates reward sensitivity, both reward-based learning and food-related motivation should be influenced. To do so, we used the FBI to manipulate perceived body size and assess its effects on reward-based learning, implicit attitudes toward food and body size (i.e., the weight bias)<sup>22</sup>. To this aim, in a within-subjects design, learning preferences in a probabilistic learning task (with reward and punishment feedback), implicit food approach/avoidance behavior, and implicit weight bias were quantified in normal-weight participants before and after embodying an avatar 15% larger (experimental condition) or slimmer (control condition) than their actual body. We expected that embodying a larger avatar would change measured processes in a manner consistent with the avatar's size - increasing approach tendencies toward high-calorie foods if embodiment affects only attitudes or additionally enhancing reward-based learning if it directly modulates reward-sensitivity. In both cases, a reduction in implicit weight bias was expected.

## Results

Thirty-seven right-handed, normal-weight females participated in the study, which consisted of three sessions on consecutive days. On Day 1 (baseline), participants underwent a series of behavioral tasks to quantify their implicit attitudes toward body size and food, along with feedback-based learning performance. On Days 2 and 3, participants experienced the FBI paradigm with a larger (large condition) and slimmer (slim condition) avatar and then repeated the behavioral tasks administered at baseline. Before and after each FBI, participants completed the Body Size Estimation Task (BSET) to quantify their subjective body size perception and the Body Ownership Questionnaire (BOQ) to assess the FBI's effectiveness. See Fig. 1 for a summary of the experimental setup and procedures. The final sample consisted of 35 females since two participants were excluded before statistical analysis due to data loss and the presence of an eating disorder.

### Full body illusion (FBI)

#### *Body size estimation task (BSET)*

The BSET was administered before and after the large and slim FBI to estimate the subjective change in body size. The change in body size estimation in each condition was calculated by subtracting the baseline measurements from each post-FBI measurement (delta-BSE), so that positive values indicate an increase and negative values indicate a decrease in body size estimation. The paired-sample t-test showed that the delta-BSE was positive and significantly larger in the large as compared to the slim condition [ $t(34) = 2.283, p = 0.029, d = 0.386$ ; see Fig. 2A]. In each condition the change of the body size estimation was tested against 0 and resulted to be significant in the large [ $t(34) = 4.20, p < 0.001, d = 0.710$ ] but not slim [ $t(34) = 0.498, p = 0.622, d = 0.084$ ] condition. Furthermore, baseline body size estimation did not differ between sessions [ $t(34) = -1.106, p = 0.277, d = -0.187$ ], thus excluding a possible carry-over effect of the changes induced by the previous FBI session. The Pearson correlation between the delta-BSE in the large condition, which produced a significant change in BSE, and BMI revealed that higher BMI was associated with larger body size estimates ( $r(35) = 0.445, p = 0.007$ ). This means that the higher the participant's BMI and, consequently, the avatar's size in the large condition, the greater the change in body size estimation.

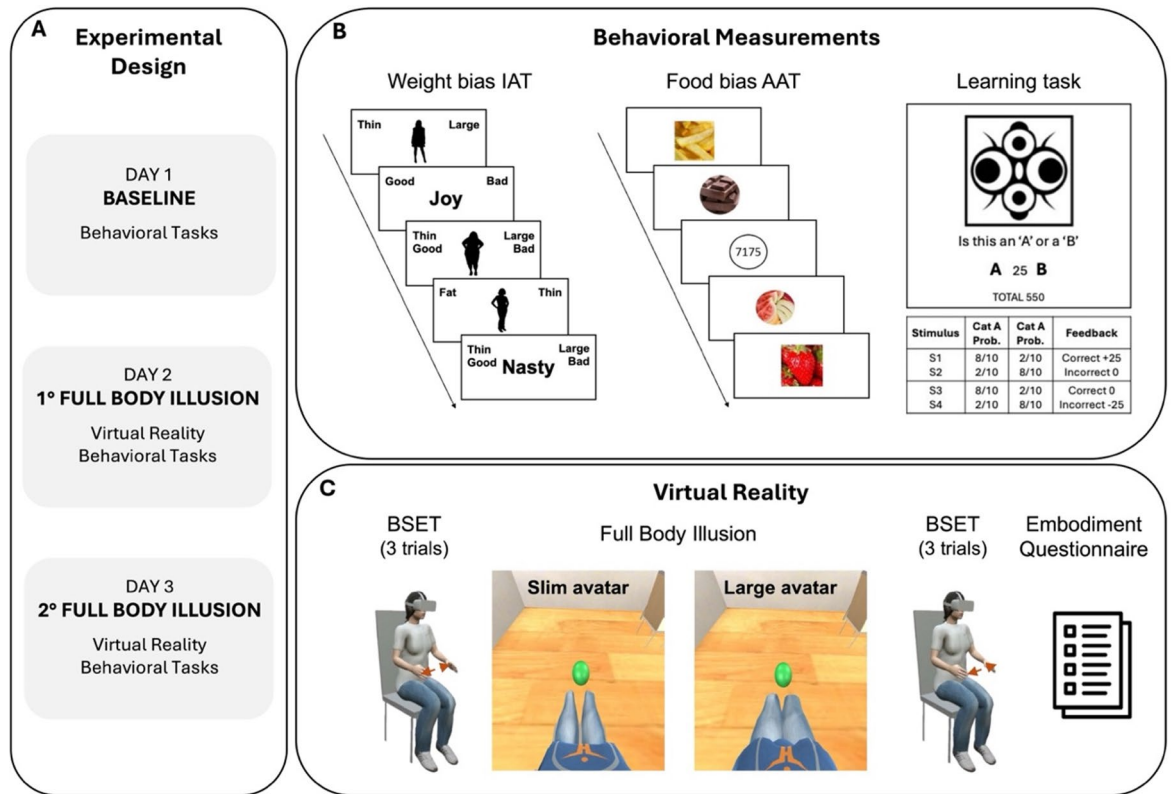
These results indicate that merely experiencing the illusion of owning a larger avatar body led to a relative increase in participants' subjective body size estimate, with the magnitude of this effect being related to their actual BMI.

#### *Body Ownership Questionnaire (BOQ)*

The BOQ was administered after the large and slim illusion to assess the subjective experience of the FBI. One participant was excluded because of missing data, leaving 34 participants for this analysis.

To test whether the illusory experience took place for each FBI condition, we compared the average score of the four "illusion" questions to the averaged "control" statements (see Table 1 in method section for a list of questions). The two-tailed paired t-test revealed that the real questions mean differed from the control one for both the large [ $t(33) = 9.231, p < 0.001, d = 1.583$ ] and slim illusion [ $t(33) = 6.933, p < 0.001, d = 1.195$ ], meaning that both FBI conditions induced the subjective illusory experience (Fig. 2B). Furthermore, no difference was found for the real questions between the large and slim illusion [ $t(33) = 1.880, p = 0.069, d = 0.195$ ], indicating that the illusory experience did not differ between avatar's size.

These results of the FBI paradigm show that the subjective illusory experience occurred in both conditions and did not differ between the two avatars' sizes.



**Fig. 1.** Experimental design, behavioral measurements, and embodiment procedure. **(A)** Experimental design. Three ~ 1.5-hour sessions on consecutive days. Each session included a series of behavioral tasks (panel **B**). Day 1 served as baseline; Days 2 and 3 measured changes induced by the Full Body Illusion (FBI; panel **C**). **(B)** Behavioral Measurements. The Weight Bias Implicit Association Task (WB-IAT) assessed implicit attitudes toward body size. Participants categorized body silhouettes (slim or large) into groups labeled with positive (e.g., happy, pleasure) or negative (e.g., dirty, awful) words, following the standard IAT procedure. The Food Bias Approach-Avoidance Task (FB-AAT) assessed implicit attraction/repulsion toward food. Stimuli included hypercaloric (e.g., pizza), hypocaloric (e.g., fruit), and neutral numeric digits. Half of each appeared in circular frames, half in square ones. Participants categorized stimuli by shape and responded by pulling (attraction) or pushing (repulsion) the mouse. The Learning Task assesses feedback-based learning. Participants learned to categorize four abstract stimuli into two categories, receiving point feedback (reward or punishment) based on accuracy. Two stimuli were mostly rewarded, two mostly punished, each associated with Category A or B on 80% of trials. **(C)** Virtual reality. The Body Size Estimation Task (BSET) was administered before and after the FBI to measure changes in perceived hip width. With eyes closed, participants estimated their hip size using their arms. After the FBI, the Embodiment Questionnaire (BOQ) assessed subjective experience using four illusion and four control statements across four embodiment dimensions. The FBI was induced once with an avatar 15% slimmer and once with an avatar 15% larger than the participant's body (order counterbalanced). To induce ownership, participants received 180 s of synchronous visuo-tactile stimulation: a green ball moved toward/away from the avatar's abdomen, synchronized with vibrotactile feedback upon contact.

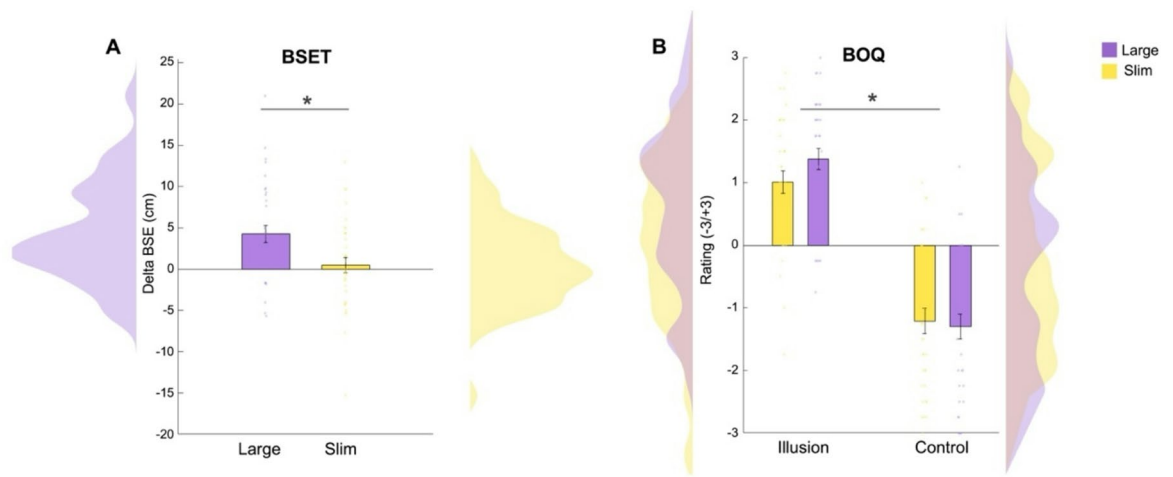
### Feedback-based probabilistic learning task

The task was administered at baseline and after the large and slim illusion to assess changes in the feedback-based learning. Two participants' data were discarded because they performed below chance across the three sessions (baseline, large, and slim), leaving 33 participants for this analysis.

The analysis revealed a significant effect of Subblock [ $t(31.91) = 3.170$ ,  $p = 0.003$ ,  $R^2 = 0.239$ ], indicating that optimal responding increased across blocks regardless of Session, BMI, and Feedback. A significant main effect of Feedback was also detected [ $t(2290) = 2.97$ ,  $p < 0.001$ ,  $R^2 = 0.004$ ], indicating that optimal responding was higher for punished trials compared to rewarded trials.

The interaction between Feedback and Session was also significant [ $t(2290) = -3.606$ ,  $p < 0.001$ ,  $R^2 = 0.006$ ]. When we unpacked this interaction by Session (baseline, large, slim), we found that performance on punishment trials was superior compared to rewarded trials at baseline [ $t(718.1) = 4.784$ ,  $p < 0.001$ ,  $R^2 = 0.031$ ] as well as after the slim illusion [ $t(718.2) = 3.184$ ,  $p = 0.002$ ,  $R^2 = 0.014$ ], but the opposite was true after the large illusion [ $t(718.0) = -2.993$ ,  $p = 0.003$ ,  $R^2 = 0.012$ ]. These results indicate that the large illusion significantly improved performance on rewarded trials compared to punished trials.

We also identified a significant Subblock by BMI interaction [ $t(31.91) = -2.329$ ,  $p = 0.026$ ,  $R^2 = 0.145$ ]. To unpack this interaction, we performed a median split of participants by BMI and conducted separate analyses



**Fig. 2.** Results of the FBI. (A) BSET calculated as the difference in BSE post-embodiment and BSE pre-embodiment in the large and slim FBI conditions; (B) Subjective embodiment quantified as the mean ratings in the illusion and control statements of the Body Ownership Questionnaire (BOQ) in the large and slim FBI conditions. In all panels, bar plots show means with standard errors, dots represent individual values, and the side distributions illustrate data variability for each condition. BSE = body size estimation; \*  $p < 0.05$ .

N.	Domain	Type	Statements content
1	Location	Real	At times, it seemed to me that my body was where the virtual body was
		Control	At times, it felt like I was out of my body
2	Ownership	Real	At times, it seemed to me that the virtual body that I saw looking down was my body
		Control	At times, it felt like the virtual body belonged to someone else.
3	Appearance	Real	At times, it seemed to me that the virtual body resembled my body (e.g., shape, skin color, or other characteristics)
		Control	At times, it felt like my body disappeared
4	Touch	Real	At times, it seemed to me that I felt the touch in the same place where the virtual body was being touched
		Control	At times, it seemed to me that my body was touched in a different part than the virtual body was

**Table 1.** Body Ownership Questionnaire. Four statements and respective controls.

for each group. We found that the effect of Subblock was highly significant for participants with higher [ $t(15.97) = 5.474, p < 0.001, R^2 = 0.652$ ] and lower [ $t(15.11) = 7.988, p < 0.001, R^2 = 0.809$ ] BMI. These results indicate that, while both groups experienced significant learning, participants with lower BMI showed steeper (stronger) learning.

The interaction between Feedback and BMI also achieved significance [ $t(2290) = -3.127, p = 0.002, R^2 = 0.004$ ]. To unpack this interaction, we split participants by BMI and analyzed the groups separately. We found that while participants with higher BMI showed a non-significant trend favoring better performance on reward trials [ $t(1181) = -1.873, p = 0.061, R^2 = 0.003$ ], participants with lower BMI showed no significant difference [ $t(1110) = -0.437, p = 0.662$ ]. These results indicate that participants with higher BMIs were more responsive to rewarded feedback than participants with lower BMIs.

The interaction between Feedback, Session, and BMI was also significant [ $t(2290) = 3.817, p < 0.001, R^2 = 0.006$ ]. When we unpacked this interaction by BMI, we found that the interaction between Feedback and Session was significant for participants with higher BMI [ $t(1181) = 3.888, p < 0.001, R^2 = 0.013$ ], but not for participants with lower BMI [ $t(1110) = -0.924, p = 0.356$ ]. These results indicate that participants with higher BMI were more responsive to reward feedback than to punishment, particularly after the large illusion.

The interaction between Feedback, Session, and Sub-block (quadratic) was also significant [ $t(2290) = 3.443, p < 0.001, R^2 = 0.005$ ]. When we unpacked this interaction by Session, we found that the Feedback by quadratic interaction was significant at baseline [ $t(718.1) = -2.572, p = 0.010, R^2 = 0.009$ ] and after the slim illusion [ $t(718.2) = -3.005, p = 0.003, R^2 = 0.012$ ], indicating significantly faster punishment learning compared to reward. However, we found that the opposite was true after the large illusion [ $t(718.0) = 2.892, p = 0.004, R^2 = 0.012$ ]. These results show that the FBI of larger avatars significantly increased the rewarded learning rate relative to punished trials.

Finally, the interaction between Feedback, Session, BMI, and Sub-block (quadratic) was also significant [ $t(2290) = -3.542, p < 0.001, R^2 = 0.005$ ]. When we unpacked the interaction by BMI, we observed a three-way interaction between Feedback, Session, and Sub-block (quadratic) for participants with higher BMI [ $t(1181) = -2.123, p < 0.034, R^2 = 0.004$ ], but not for participants with lower BMI [ $t(1110) = 0.872, p = 0.383$ ]. For the higher BMI group, we further unpacked the interaction by Session and observed a significant interaction between

Feedback and Sub-block (quadratic) after the large illusion [ $t(370) = -2.923, p = 0.004, R^2 = 0.023$ ], but not at baseline [ $t(370.0) = 1.644, p = 0.101$ ] or after the slim illusion [ $t(370.1) = 0.674, p = 0.501$ ]. These results indicate that the large illusion increased the rate of reward-based learning, specifically for participants with higher BMI.

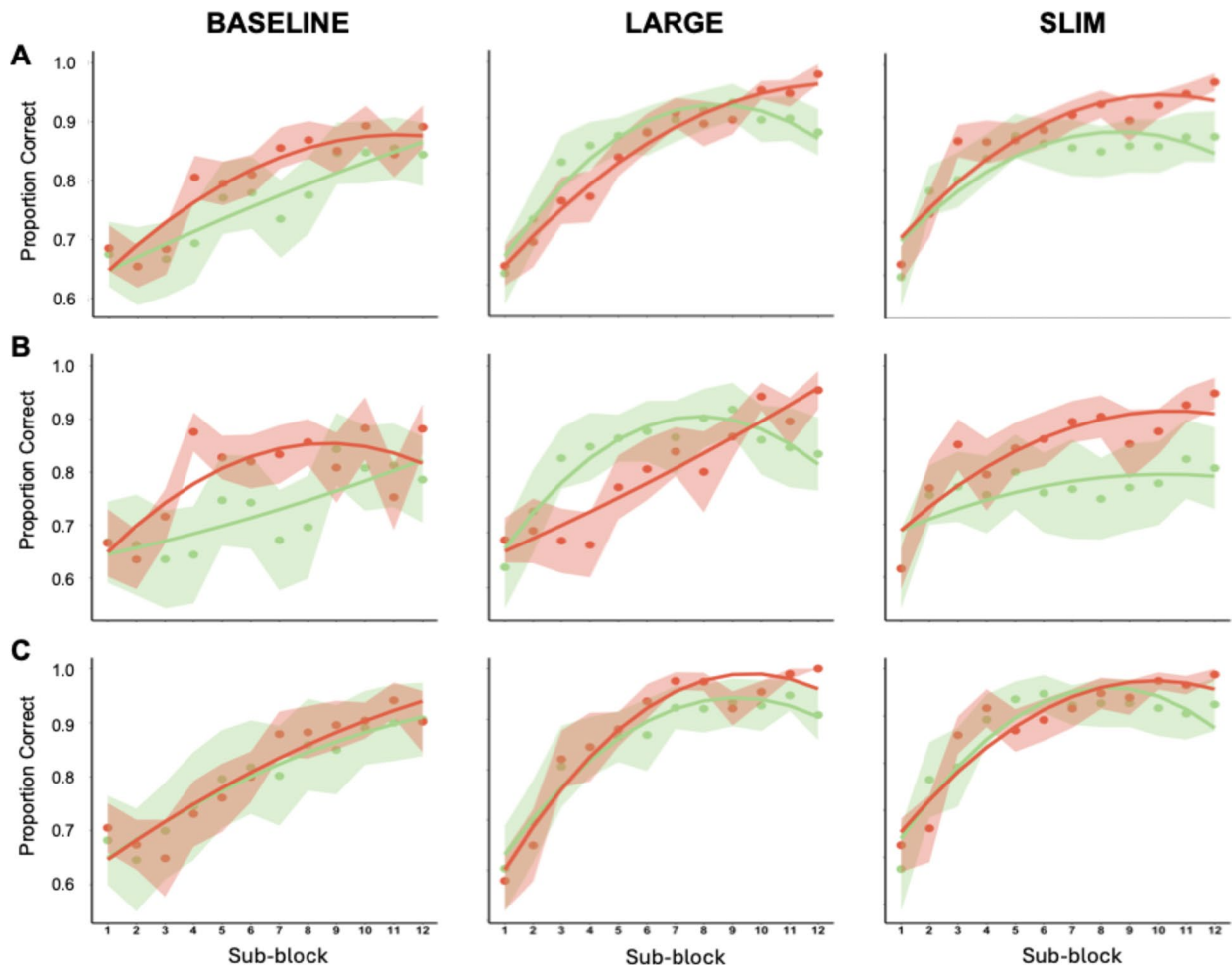
To summarize, the embodiment of a larger, but not slimmer avatar, increased both responsiveness and learning rate to rewarded feedback, specifically for participants with higher BMI. Figure 3 shows the proportion of optimal responding for each session for all participants (Fig. 3A), those with higher BMIs (Fig. 3B), and those with lower BMIs (Fig. 3C) according to a median split.

### Food preferences approach-avoidance test (FP-AAT)

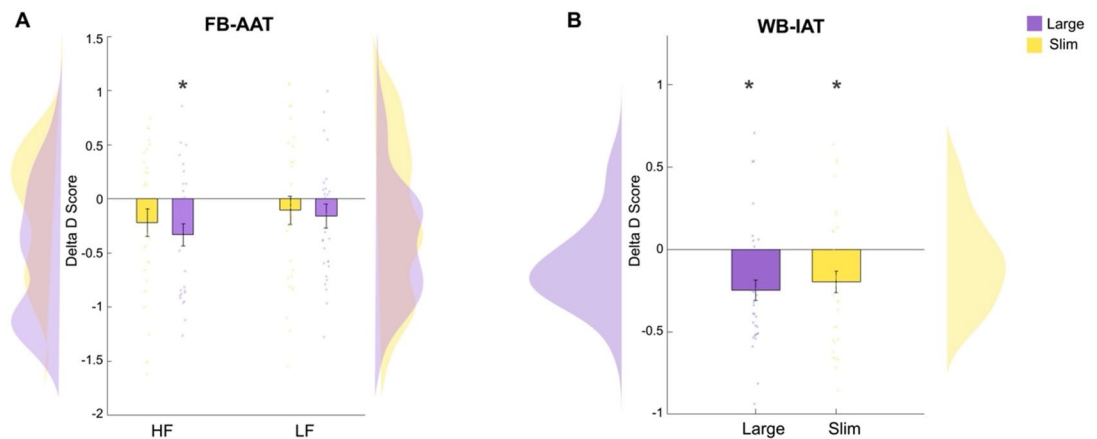
The FP-AAT was administered at baseline and after the large and slim illusion to assess the change in implicit food preferences. Five participants were excluded because their scores exceeded 2 standard deviations, leaving 30 participants for this analysis.

Delta D-score were calculated as session minus baseline, with positive values indicating an increase in avoidance (pushing away from the body) and negative values indicating an increase in approach (pulling toward the body). To test for significant changes in implicit attitudes toward food, we first compared the delta D-scores against zero. This analysis revealed that when participants embodied a larger avatar (large condition), they showed a greater approach to high-calorie food [ $t(29) = -3.207, p = 0.003, d = -0.586$ ]. No significant change in approach/avoidance behavior was found for low-calorie food or any kind of stimulus in the slim condition (all  $p$ s > 0.05; see Fig. 4A). The repeated-measures ANOVA with Embodiment condition (large, slim) and Calorie content (high, low) as between-subjects factors showed no significant effects or interactions on delta D-scores (all  $p$ s > 0.05).

These results indicate that the embodiment of a larger avatar increased the implicit bias of approaching high-calorie food.



**Fig. 3.** Results of the probabilistic reward-based learning task. Average proportions correct are modeled across 12 sub-blocks for all participants (A), participants with BMI above the median (B), and participants with BMI at or below the median (C). Lines, dots, and shading represent modeled learning curves, raw data, and SEM, respectively, for rewarded (green) and punished (red) trials.



**Fig. 4.** Results of weight and food biases tasks. (A) Food bias calculated for the FP-AAT as the difference in the D-scores in each of the FBI conditions (large, slim) and the baseline; (B) Weight bias calculated for the WB-IAT as the difference in the D-scores in each of the FBI conditions (large, slim) and the baseline. In all panels, bar plots show means with standard errors, dots represent individual values, and the side distributions illustrate data variability for each condition. HF = high-calorie food; LF = low-calorie food; \*  $p < 0.05$ .

### Weight bias implicit association task (WB-IAT)

The WB-IAT was administered at baseline and after the large and slim illusion to assess the change in implicit weight bias. One participant was excluded because their D-score exceeded two standard deviations, leaving 34 participants for this analysis.

Delta D-scores were calculated as session minus baseline. Positive values indicate an increase in weight bias, reflecting a stronger implicit negative attitude toward larger individuals (i.e., “large = bad”), whereas negative values indicate a decrease in weight bias. To test for significant changes in the implicit attitudes toward weight, we first compared the delta D-scores against zero. This analysis revealed that when a participant embodied a larger avatar (large condition), weight bias significantly decreased [ $t(33) = -3.94, p < 0.001, d = -0.676$ ] and the same happened when the participant embodied the slimmer avatar [ $t(33) = -2.939, p = 0.006, d = -0.504$ ]. The two D-scores did not differ ( $p > 0.05$ ; see Fig. 4B).

These results reveal that embodying an avatar, regardless of its size, reduced implicit negative attitudes toward large bodies.

### Discussion

We investigated whether the illusory experience of owning a virtual body larger than one’s real body affects cognitive processes linked to reward-based learning and implicit attitude toward food and weight. After confirming that subjective embodiment occurs independently of the avatar size, we quantified changes in feedback-based learning, food-related approach–avoidance behavior, and implicit weight bias before and after embodying either a larger or slimmer avatar. Drawing on evidence that body size influences food-related motivation and reward, as well as FBI findings linking body size to food attitudes, we tested whether embodiment affects reward sensitivity or only stereotype-driven attitudes. We predicted that embodying a larger avatar would increase approach tendencies toward high-calorie foods and, if reward sensitivity is directly modulated, enhance reward-based learning, with both scenarios reducing implicit weight bias. The results support the hypothesis that body size directly modulates reward sensitivity: embodying an avatar 15% larger increased both reward-based learning and approach behavior toward high-calorie foods, whereas no such effects were observed in the slim-avatar condition. Finally, embodying a different body size, regardless of the direction, reduced implicit social weight bias, suggesting that transient alterations in body representation can modulate social and affective dimensions of body-related cognition.

### Full body illusion

The subjective feeling of embodiment, as quantified by the embodiment questionnaire, was successful for both larger and slimmer avatars, indicating that it occurred regardless of the virtual body size. This is consistent with evidence suggesting that embodiment is independent of body appearance<sup>14</sup> and size<sup>17,20</sup>. The sense of body ownership is indeed malleable and can extend to bodies that look different from one’s own, but solely if the key condition for embodiment illusions are met, namely, first-person perspective, anatomical plausibility, and synchronous multisensory stimulation<sup>15,23</sup>.

The same flexibility/malleability does not hold for changes in perceived body size, since only the large FBI condition shifted body size estimation in the direction of the avatar’s size. Participants judged their hips to be larger after embodying a large avatar compared to baseline, whereas the opposite did not occur after embodying a slim avatar. While some studies reported changes across both embodiment conditions<sup>20</sup>, others have found a reduction in body size estimation only in the slim condition<sup>17</sup>, and still others suggested that embodying larger limbs produced stronger effects<sup>24–26</sup>. Our finding aligns with the latter evidence, further confirming the idea

that body representation might adapt more readily to increases in body size<sup>25</sup>. In addition, discrepancies with previous findings might be due to differences in the embodiment paradigm. In both previous studies, only the virtual body's hip size was modified, whereas here we adjusted the entire virtual body based on each participant's body measurements. As a result, the slim avatar might have appeared too thin (as reported by some participants) and unrealistic, potentially affecting perceived body size. However, it is necessary to point out that, as described above, the subjective embodiment was equally present in both conditions.

### Feedback-based probabilistic learning

Results showed that performance on punishment trials was superior to that on rewarded trials both at baseline and after the slim illusion, however, this pattern reversed following the large illusion. Embodying a larger avatar significantly improved performance on rewarded trials compared to punished ones. This effect interacted with BMI, indicating that participants with higher, but not lower, BMI were more responsive to rewarded feedback than to punishments, specifically after the large illusion. Importantly, the large FBI also modulated the learning rate. While faster punishment than rewarded learning was observed at baseline and after the slim illusion, the opposite was true after the large illusion. Interestingly, also this effect interacted with BMI, such that embodying a larger avatar significantly increased reward-based learning rates specifically in participants with higher BMI.

BMI was examined as a potential moderator to account for inter-individual variability in how the avatar manipulation - defined as a  $\pm 15\%$  change relative to each participant's own body dimensions - may have been perceived and processed. This approach was also theoretically motivated, as previous research has reported dimensional associations between BMI variability and reward-related neural responses in non-clinical samples drawn from the general population<sup>[e.g.27,28]</sup>. This observed pattern may therefore reflect the way avatar sizes were scaled. Although all participants were within the normal BMI range, for individuals at the higher end of this range, a 15% increase in body size may have appeared more pronounced, and more salient or behaviorally relevant, than for those at the lower end. At the same time, the findings are consistent with evidence suggesting that BMI-related variability in non-clinical samples can be associated with differences in reward-related processes.

The observed reward-based modulation induced by the FBI likely reflects the engagement of shared and interacting brain regions linking body representation and reward processing. Embodiment has been consistently associated with the activation of a fronto-parietal network, including the intraparietal sulcus and premotor cortex, that supports multisensory integration and the sense of body ownership and self-location<sup>29-32</sup>. Among the key components of embodiment, self-location is primarily linked to activity in the intraparietal cortex, hippocampus, posterior cingulate, and retrosplenial cortex, whereas body ownership is supported by activation of premotor and intraparietal regions<sup>33</sup>. The posterior cingulate cortex mediates these two neural systems, suggesting its crucial role in integrating self-location and body ownership. The parietal cortex and the hippocampus, two core regions of the FBI network, are anatomically and functionally connected, as shown by an influential study by Wang et al.<sup>34</sup>, in which excitatory TMS applied to the parietal cortex increased hippocampal activity. The hippocampus also strongly connects with the nucleus accumbens (NAcc), a central node in the mesocorticolimbic dopamine system responsible for reward processing<sup>35</sup>. In animal models, the strength of this connection has been shown to increase with the presentation of rewards, leading to dopamine release<sup>36</sup>. Additional support for the NAcc's role in reward sensitivity comes from recent findings showing that ultrasound stimulation of the human NAcc enhances reward-related behaviors, such as increased learning from positive feedback<sup>37</sup>. Building on this evidence, we propose that the FBI may influence reward-based learning by modulating connectivity among the parietal cortex, hippocampus, and NAcc. This modulation could, in turn, affect the mesolimbic circuit and the processing of reward signals. However, this remains a hypothesis, and further research is needed to elucidate the neural mechanism underlying the observed behavioral outcomes.

### Implicit attitudes

Embodying a larger avatar increased implicit food preferences toward high-calorie foods. Although partially agreeing with previous findings<sup>20</sup>, this result is consistent with prior evidence linking higher BMI (dimensionally, including within non-clinical ranges) to stronger preferences for high-calorie foods, possibly reflecting differences in reward sensitivity<sup>38,39</sup>. Observing such food-related behavior after a temporary embodiment of a larger body, without physical (i.e., weight loss) body-size changes, further supports the crucial role of one's body perception on cognition<sup>14</sup> and suggests potential applications of the FBI-based protocols in various contexts, although this would need to be directly tested in future studies. Beyond food-related effects, we also observed a reduction in implicit weight bias following avatar embodiment compared to baseline. This finding, although only partially consistent with our initial hypothesis, extends prior work by showing for the first time that embodying either a larger or slimmer virtual body can attenuate social stereotypes linking body size to negative traits<sup>40</sup>. This reduction may stem from increased self-focus and body acceptance during embodiment, or from temporarily inhabiting a body perceived as "other," a condition known to reduce out-group bias<sup>14</sup>. From this perspective, embodying a body different from one's own may foster greater openness toward diverse body types and thereby reduce implicit weight bias.

In summary, embodying a larger virtual body enhances reward-based learning and increased implicit preference for high-calorie foods, whereas reductions in weight bias occurred regardless of avatar size. These results disentangle reward sensitivity from food-related behavior. Although both avatars were equally embodied subjectively, only the larger one modulated body perception and cognitive responses, likely due to the personalized scaling procedure and participants' BMI.

We acknowledge several methodological constraints that should be considered when interpreting our findings. The study relied on a relatively homogeneous sample of young, normal-weight women, which limits the generalizability of the results to broader populations. In addition, the  $\pm 15\%$  manipulation of avatar body size may have differed in perceived salience depending on individual BMI, and, as in our previous work<sup>20</sup>,

body-size estimation was assessed proprioceptively and without computing a Body Perception Index (BPI). As a result, comparability with standard visually based body size estimation tasks remains unclear, and our findings should be interpreted as reflecting relative, rather than absolute, changes in body size estimation. Finally, BMI served as a coarse proxy of body composition, and more refined and sensitive measures should be employed in future studies. Although these factors may have introduced some variability, they do not detract from the main conclusion that changes in perceived body size can systematically modulate reward sensitivity and food-related attitudes.

Overall, the results underscore the profound interplay between body and mind. Given that the body is a constant and inseparable part of human experience, changes in its representation can shape cognitive processes. These findings support the view that physical and psychological states are mutually influential - a principle rooted in the idea that *a healthy mind in a healthy body* reflects a bidirectional relationship rather than a one-way effect.

Although conducted in a non-clinical sample, the ability to transiently modulate body representation and reward-related processes through virtual embodiment may have broader relevance. Future research should examine whether such an approach could inform experimental and applied strategies targeting body image and eating behaviors. Finally, the observed reduction in implicit weight bias further suggests potential for embodiment-based approaches, reduce weight stigma and promote more adaptive social attitudes toward body diversity, although these implications require direct empirical validation.

## Materials and methods

### Participants

Based on similar previous studies<sup>20,41</sup> reporting medium-to-high effect sizes, we conducted an a priori power analysis in G\*Power<sup>42</sup> for a two-tailed paired t-test with a medium effect size ( $d=0.50$ ) and alpha level 0.05. This analysis revealed that a sample size of 34 subjects is necessary to obtain power  $>0.8$ . Thirty-seven right-handed volunteers were recruited for the study. Since body size stereotyping is more prevalent among young women<sup>43,44</sup>, we recruited healthy females between 20 and 30 years of age, with normal weight as quantified by the Body Mass Index (BMI) and no eating disorder symptoms, as assessed by the Eating Disorder Inventory (EDI)<sup>45</sup>. Before statistical analysis, one participant was excluded because of missing data, and one because the EDI score was above the cut-off ( $>50$ )<sup>45</sup>. The final sample consisted of 35 females (mean age = 23.21, SEM = 0.5; mean EDI = 13.97, SEM = 1.87; mean BMI = 20.73, SEM =  $\pm 0.31$ ). All participants gave informed consent and were compensated for participation. The study was approved by the Human Experimental Ethics Committee of the University of Trento (Protocol 2019-011) and was conducted in accordance with the ethical standards of the Helsinki Declaration<sup>46</sup>.

### Procedure

The within-subjects study consisted of three sessions on consecutive days. Each session lasted about 1.5 h and started, for each participant, at approximately the same time of day.

As shown in Fig. 1, Day 1 included consenting, EDI<sup>45</sup>, and weight and height measurements to calculate participants' BMI. The experimenter then took participants' body measurements to create the avatars for the full body illusion (FBI). Once this preliminary phase was completed, participants underwent a series of behavioral tasks to quantify the implicit attitudes toward body size (Weight Bias Implicit Association Task) and food (Food Preferences Approach-Avoidance Test), as well as feedback-based learning performance (Fig. 1B).

In the second and third sessions, participants experienced the virtual FBI paradigm. All participants were exposed to the large avatar (large condition) and the slim one (slim condition) in a counterbalanced manner. Before and after each FBI, participants completed the Body Size Estimation Task (BSET) to quantify their subjective body size perception and the Body Ownership Questionnaire (BOQ) to assess the FBI's effectiveness. Following each FBI, participants repeated the behavioral tasks administered at baseline. Since the FBI duration is unknown, the order of the behavioral tasks was kept stable across sessions, and task administration started, for all participants,  $\sim 5$  min after the FBI. Participants were debriefed at the end of the experiment, and their impressions and thoughts about the FBI were recorded.

### Assessment of eating and body representation disorders

#### Body mass index (BMI)

The BMI was computed by dividing the weight (kilograms) by the square of the height (meters). Only Participants with a BMI within the normal range (18.5–24.9) were included in the study.

#### Eating disorder inventory (EDI)

The EDI<sup>45</sup> was used to assess the presence of eating disorders. It comprises 64 items divided into eight subscales (i.e., drive for slimness, bulimia, body dissatisfaction, ineffectiveness, perfectionism, interpersonal distrust, interoceptive awareness, and maturity fears). Participants were asked to rate their level of agreement on a 6-point Likert scale from 0 (never) to 5 (always). As in the Tambone et al.<sup>20</sup> study, the EDI cut-off score was 50<sup>45</sup>, and individuals who exceeded this score were excluded.

### Full body illusion (FBI)

The FBI timeline and a view of the virtual scene in the two conditions are presented in Fig. 1C. Participants wore a Head Mounted Display, [HMD, Oculus Quest 2 2021 equipped with RGB LCDs 1832  $\times$  1920 pixels, refresh rate at 120 Hz, the field of view of 110° (diagonal FOV) and 6 degrees of freedom]. The scenario was created in 3D Studio Max 2023 (Autodesk, Inc.) and implemented in Unity 2017 game software environment (<http://unity.com>). It included a simple room with a chair, a table, and a window. A dressed female avatar was placed sitting on the

chair. The avatars were created using MakeHuman software ([www.makehumancommunity.org](http://www.makehumancommunity.org)) and animated with MotionBuilder 2023 (Autodesk, Inc.). The avatars' body size was individually calculated by subtracting (slim condition) or adding (large condition) 15% of each participant's body measurements (i.e., circumference of neck, arm, wrist, upper and lower bust, waist, hips, thigh, knee, ankle, and neck-shoulder distance).

At the beginning of the FBI procedure, once participants put on the HMD, the virtual scene was occluded, leaving them with only a blue background. During this phase, the pre-embodiment BSET was administered (see details below). Once the BSET was completed, the virtual scene and one of the avatars (slim/large, depending on the condition) were activated and became visible. Participants, who were also sitting on a chair, were asked to position themselves as the avatar, adjusting the position of their body and the chair until they felt to be located exactly in the avatar's position, they were seeing from a first-person perspective. Their position was further adjusted by shifting the virtual camera up or down until participants reported feeling as if they were looking at the virtual scene and body precisely from the avatar's perspective.

Participants familiarized themselves with the virtual environment for 30 s by moving their heads to look around, including at themselves (i.e., avatars). To induce a sense of ownership over a virtual body, we employed synchronous visuo-tactile stimulation. An Arduino-controlled vibrotactile stimulator (diameter x height = 8 mm x 3 mm, 3 V, rated speed = 12,000 RPM) was located on the participants' abdomens and was used during the FBI to deliver the tactile stimulation. After the 30-second familiarization phase, the three-minute synchronous visuo-tactile stimulation started. A green ball moved towards and away from the avatar's abdomen synchronously with the vibrotactile stimulation that occurred when the ball touched the avatar's body. Frequency and duration of each set of touches were 6 Hz and 500 ms, respectively; a set of touches was delivered every 4–5 s. After three minutes, the visuo-tactile stimulation stopped, the blue background occluded the virtual environment, and the BSET and BOQ were administered again.

#### *Body size estimation task (BSET)*

The BSET was used to quantify subjective body size estimates before and after each FBI [adapted from<sup>20</sup>]. Participants stood up and, while still wearing the HMD and keeping their eyes closed, were asked to extend their arms along their body (without touching it), then raise their arms in front of them with their palms facing each other and adjust the distance between their palms to the perceived size of their hips. This procedure was repeated three times. Each time, the distance between their palms was measured with a measuring tape (accuracy of 0.5 cm), and the mean of the three measurements was considered.

#### *Body Ownership Questionnaire (BOQ)*

The BOQ was adapted from questionnaires used in previous studies<sup>41,47,48</sup> to assess the subjective experience of the FBI. It consisted of eight statements: four directly related to the illusion experience and four control items. Control statements were unrelated to the illusion experience but corresponded to the four dimensions of embodiment - location, ownership, appearance, and touch (see Table 1). Participants answered the questions asked in random order by specifying their level of agreement on a Likert scale varying from -3 (total disagreement) to +3 (total agreement), with 0 meaning "I don't know". The questionnaire was administered right after the BSET while participants were still standing, wearing the HMD, and keeping their eyes closed.

### **Experimental tasks**

#### *Weight bias implicit association task (WB-IAT)*

The WB-IAT (<https://implicit.harvard.edu/>) was used to quantify illusion-induced changes in the implicit attitude towards large people<sup>49</sup>, following the embodiment of a slim and large avatar (Fig. 1C, left panel). Participants were asked to categorize stimuli (i.e., concepts) into two categories (i.e., attributes). The concepts "slim people" and "large people" were represented by pictures of black "slim" or "large" silhouettes, and the "good" and "bad" attributes by words in the "good" (e.g., happy, glorious, pleasure) and "bad" (e.g., awful, dirty, negative) categories. Twenty pictures (10 in each category) and 16 attributes (8 in each category) were presented. Black silhouettes and the concept words were presented at the center of the screen. At the same time, categories were at the top left or top right of the screen and aligned with the response key side (e.g., to categorize the concept, the left or right category was used, respectively, with E or I response keys on a QWERTY keyboard). Participants were asked to categorize items into groups as fast and accurately as possible by pressing the corresponding key on the keyboard. Throughout the task, stimuli and category labels were presented until a response was given. If participants made a mistake, a red cross appeared on the screen, and they had to press the appropriate key to continue the task. The procedure followed the standard IAT structure<sup>50</sup>, with seven task blocks: three practice blocks (blocks 1, 2, and 5) and four test blocks, two for congruent and two for incongruent mapping of category pairs (blocks 3–4 and 6–7, respectively). The categories were mapped as congruent when the response key was the same for the concept "slim people" and the attribute "good", and the other response key corresponded to the concept "large people" and the attribute "bad". These pairs were switched in the incongruent blocks, thus mapping "slim people" and "bad" to one response key, and "large people" and "good" to the other. The task uses the D-score algorithm (as in the IAT<sup>50</sup>, which computes the difference in mean RT between incongruent and congruent blocks divided by the pooled standard deviation, with positive D-scores indicating faster responses when "Fat + Bad" and "Thin + Good" are paired (i.e., anti-fat bias) and negative D-scores indicating faster responses when "Fat + Good" and "Thin + Bad" are paired (i.e., pro-fat bias that is rare). Blocks 1, 2, 3, and 6 included 20 trials; Blocks 4, 5, and 7 included 40 trials. The order of the association blocks (i.e., congruent and incongruent) was counterbalanced across participants. The task lasted about five minutes.

*Food preferences approach-avoidance test (FP-AAT)*

The FP-AAT was used to assess the implicit attraction or repulsion towards food<sup>20,51</sup> (see Fig. 1C, middle panel). The stimuli used, conveying implicit emotional valence (i.e., attraction or repulsion), were eight images of hypercaloric foods (e.g., pizza, french fries, chocolate), eight images of hypocaloric foods (e.g., fruits and white meat), and eight numerical digits served as neutral stimuli. For each category, half of the stimuli were presented within a round frame and the other half within a square frame. Participants had to categorize stimuli by shape, while the stimulus category (hyper- or hypo-caloric foods and numbers) was task-irrelevant. They were asked to pull the mouse towards them (i.e., attraction) or push it away from them (i.e., repulsion) based on the stimulus shape (i.e., circle or square). The stimulus semantic features (e.g., calorie content) are associated with specific valence (attraction or avoidance). Thus, it affects the participant's response time according to whether the relationship between answer modality (i.e., pull or push) and frame shape feature (i.e., circle or square) was congruent or incongruent with the stimulus's semantic (e.g., calorie content). For example, if participants had an implicit preference for hypercaloric foods, they should have been faster when asked to pull the mouse than when asked to push it. To enhance the perception of pulling, the picture progressively grew larger as the participant executed the action, until it occupied the whole screen. Similarly, when pushing the picture, it progressively shrank until it became a dot. A red "X" would appear in the middle of the screen when an incorrect response was made, and the stimulus would remain on until the participant gave the correct response. The task consisted of eight blocks of 10 trials each: four blocks containing emotional valent food stimuli (two blocks for high-calorie food and two blocks with low-calories food) and four blocks containing neutral, numerical, stimuli. The task was preceded by 20 practice trials, which were excluded from the analysis. The D-score was calculated for each emotionally valent stimulus type (high- or low-calorie food), subtracting the mean RT of approach (pull) from avoidance (push), divided by the total standard deviation, such that positive values indicate a bias toward avoidance (push) and negative values toward approach (pull). The association between the action (pull and push) and stimulus shape (circle and square) was counterbalanced across participants. The task lasted about five minutes.

*Feedback-based probabilistic classification learning task*

As in Schintu et al<sup>52</sup>, we used a probabilistic feedback-based learning task to assess reward and punishment learning (Fig. 1C, right panel). Participants were instructed that they would receive 500 points to begin the task and that they should maximize their point total by optimizing overall accuracy. The cumulative score was continuously visible on the screen. Participants completed three blocks of 40 trials (120 total) using abstract monochrome figures. On each trial, one of four possible abstract stimuli appeared on the screen, and participants needed to learn whether that stimulus belonged to Category A or Category B by pressing one of two masked keyboard keys. Immediately after each response, participants received either positive feedback (+25 points), negative feedback (-25 points), or no feedback (0 points). Of the four abstract stimuli, two were "rewarded" and the other two were "punished." Correct responses to rewarded stimuli increased the participant's point total by 25 points. Incorrect responses to punished trials decreased the participant's point total by 25 points. No feedback was given on incorrect rewarded and correct punished trials. Thus, by learning the stimulus response mappings, participants both increased their point total on rewarded trials and prevented the loss of points on punished trials. Each stimulus was probabilistically linked to each response, such that one rewarded and punished stimulus was more often linked (80% of trials) to Category A and the other to Category B. The stimulus-response mappings and the mappings of stimuli as rewarded or punished were also counterbalanced across participants. Each stimulus remained visible until a response was made, followed by a 2-second inter-trial interval. For each session, a unique set of four abstract stimuli was used (12 total). The order of the three sets of stimuli (baseline, large avatar, small avatar) was counterbalanced across participants. The entire task lasted ~15 min. Before the main task, participants read the instructions, completed a brief guided example showing correct and incorrect responses, and then performed a 20-trial practice block with different stimuli (not included in the analysis).

**Statistical analyses**

Analyses were performed using JASP (Version 0.19.3) and R (R Development, 2023.06.0 + 421) with alpha set at .05 (two-tailed). Bonferroni correction was used to correct for multiple comparisons. All data are presented as means with the Standard Error of the Mean (SEM). Effect sizes are indicated for significant effects. In the feedback-based probabilistic classification learning task, participants performed a two-choice reaction time task where the reinforcement rate for each stimulus was 80%. As in other procedural learning studies, we used optimal responding rather than trial-wise accuracy<sup>53</sup> as a performance metric for the analysis. Optimal responses were defined as the response most likely to produce a reward or avoid punishment. Data from the three training blocks were divided into twelve sub-blocks (four sub-blocks per block) to more adequately characterize learning curves, as in our prior work<sup>52</sup>. Optimal responses were modeled across sub-blocks (1–12) using a linear mixed effects model in which the slope parameter indexed the rate of learning, and the quadratic slope indexed the acceleration or deceleration in learning rate. The model was fit to sub-block-specific performance using the lme4 package in R<sup>54</sup>. Before modeling, the sub-block variable was centered so the intercept corresponded to the halfway point during task performance. The fixed effect of Feedback was effect-coded ("1" for reward and "-1" for punished). The model included dummy-coded contrasts between baseline, large, and slim sessions. Finally, because the size of avatars is directly related to participants' BMI, we included BMI scores as a continuous factor. Indeed, model comparisons showed that including BMI in our model significantly improved the model fits. Maximum likelihood was used to estimate all fixed and random effects simultaneously. Chi-square model comparisons indicated that the most complex model, including random intercepts and slopes of the linear and quadratic terms on participants, provided significantly better model fits than models where these random effects were removed:

$$\begin{aligned}
 \text{Performance} \sim & (\text{SUBBLOCK} * \text{FEEDBACK} * \text{SESSION} * \text{BMI}) \\
 & + (\text{SUBBLOCK}^2 * \text{FEEDBACK} * \text{SESSION} * \text{BMI}) \\
 & + (1 + \text{SUBBLOCK} + \text{SUBBLOCK}^2 | \text{SUBJECT})
 \end{aligned}$$

Fixed effects for the best-fitting model were then interpreted as described in the Results section.  $R^2$  values are reported for all significant effects and interactions. Missed responses occurred infrequently (two times across all participants).

## Data availability

Data presented in this paper will be available upon request to the corresponding author (selene.schintu@unitn.it).

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## Author contributions

LP, MZ, and SS designed the study, RB, ANH, CML, and SS performed the experiments, LP, MF, MP, and SS analyzed the data, and LP, MF, MP, and SS wrote the paper. All authors reviewed the manuscript.

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## Declarations

## Competing interests

The authors declare no competing interests.

## Additional information

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