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Research

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Visually simulated altered gravity modulates perceived object weight

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Gravity is a fundamental force acting on all objects on Earth. It is therefore unsurprising that the brain has internalized regularities associated with terrestrial gravity. An internal model of gravity is thought to arise from the integration of vestibular, visual, proprioceptive and visceral sensory cues. However, it remains unclear whether this internal representation of gravity contributes to the perception of physical object properties. Object weight is determined by the product of its mass and gravitational acceleration. Although previous studies have examined how an object's visual properties, such as its size, shape and texture, influence perceived weight, no study has investigated the effect of altered visual-gravitational information. Here, participants judged the weight of physical objects while they experienced virtual reality environments in which virtual objects accelerated according to either terrestrial gravity (Earth: 9.81 m s^{-2}) or partial terrestrial gravity (Mars: 3.71 m s^{-2}). Participants perceived the objects as lighter when viewing Mars gravity relative to Earth gravity. Our results suggest that participants incorporate visual-gravitational information when perceiving object weight, and that the internal model of gravity adapts to altered visually simulated gravitational environments.

1. Introduction

Gravity is the fundamental physical force by which objects with mass are drawn to one another. It is constant on Earth (9.81 m s^{-2}) and has remained stable throughout human evolution. It is therefore unsurprising that gravity shapes behaviour [1]. The way in which humans build a representation of gravity is multi-modal, integrating information from multiple sensory systems. Proprioceptive and somatosensory cues provide information about body position relative to the gravitational vector [2]; vestibular organs sense linear acceleration from gravity, signalling head position relative to the gravitational vector [3]; visual cues provide information about verticality [4,5] and gravitational acceleration of moving objects [6]. This multi-sensory information is integrated to form an internal model of gravity [7].

The internal model of gravity is essential for a wide range of interactions with the external environment. For example, we rely on terrestrial gravity to intercept objects that are thrown towards us. Accordingly, interception of moving objects is more accurate when their motion is consistent with terrestrial gravity than under simulated weightlessness [8,9]. Similarly, motion duration judgements are more precise for objects moving downward in accordance with terrestrial gravitational acceleration than for objects moving upward against gravity, a phenomenon known as the gravitational bias [6,10]. Importantly, the internal model of gravity may not be strictly tied to terrestrial gravity, but instead generalize across contexts on the basis of real-time sensory signals about the strength

of gravitational acceleration. Torok *et al.* [11] showed that the gravitational bias emerges not only for motion consistent with Earth gravity, but also for motion consistent with Mars gravity (3.71 m s^{-2} , which is about 38% of Earth's gravity). While this suggests that visual inputs can flexibly tune the internal model of gravity in the domain of motion perception, it remains unclear whether such cues extend to other aspects of gravitational processing, such as the perception of object weight.

According to Newton's laws, object weight is calculated as its mass multiplied by gravity. While objects therefore have an objective, physical weight, *perceived* weight may be influenced by a number of factors [12]. Visual properties, such as material [13], temperature [14] or size [15] can influence perception such that objects with the same physical weight are perceived as having different weights. One example of this is the well-known size-weight illusion in which smaller objects are perceived as heavier than larger objects even if they have the same physical weight [15].

Here, we explored whether altered visual cues about gravity influence perceived object weight. Participants viewed virtual reality (VR) objects falling under either terrestrial gravity (Earth: 9.81 m s^{-2}) or partial terrestrial gravity (Mars: 3.71 m s^{-2}), while judging the weight of physical objects placed on their hand. The physical objects were identical in both conditions and therefore exerted the same force on the hand. However, the Mars environment depicted a lower gravitational acceleration: virtual objects fell more slowly and thus provided visual information consistent with a world in which a given mass would weigh less. We hypothesized that, if the brain integrates this visual-gravitational context with haptic information, the same force experienced on the hand would be interpreted relative to the lower gravitational reference suggested by the Mars environment. Consequently, participants may judge the physical object as lighter in the Mars than in the Earth condition. Such a difference would indicate that visually simulated altered gravity contributes to the computation of felt object weight.

2. Methods

(a) Participants

A total of 16 participants (11 female, mean age = 22.69, s.d. = 3.75) took part in the study, although two participants were excluded from analysis (see below), leaving a final sample of 14 participants. This sample size was chosen on the basis of similar experiments [6,11,16]. A post hoc sensitivity analysis with $\alpha = 0.05$, power = 0.8 suggested a sample size of 14 was sufficient to detect medium effect sizes ($f = 0.244$). All participants were right-handed according to their Edinburgh Handedness Questionnaire [17]. Participants were recruited from the Royal Holloway University of London subject pool, and were paid £5 for their participation.

(b) Experimental procedure

Participants were instructed to place their head on a chin rest, position their left hand palm up on a pillow, and rest their right hand on the armrest of the chair. Participants were asked to maintain this posture throughout each block of the task.

Participants viewed a virtual environment consisting of the surface of a planet, with sand dunes and a night sky (figure 1). A red dot was placed at the centre of the environment. Participants were instructed to fixate on this red dot throughout the block. Two black tubes extended from the sky and ground, between which a black and white football accelerated downwards. The acceleration matched Earth (9.81 m s^{-2}) or Mars (3.71 m s^{-2}) gravity in the respective conditions, such that the kinematics of the objects were equivalent to free fall under the respective gravitational environments. The virtual environment was created in Unity 3D (version 2017.3.0f3; Unity Technologies, 2018) and presented using an Oculus Quest DK2 virtual-reality head-mounted display. Example videos are available at <https://osf.io/5jg8m>.

Participants passively viewed the VR environment for approximately 2 minutes before beginning the weight-judgement task. Five visually identical three-dimensionally printed spheres served as experimental stimuli, with weights ranging from 20 to 40 g in 5 g increments. Although this range was constrained by the size of the spheres, it was comparable to that used in previous studies of the size-weight illusion [16]. The spheres' weights were concealed from participants throughout the experiment. Before each block, participants were presented with a 10 g reference weight. They were informed that this weight fell outside the range of experimental stimuli and were asked to use it to calibrate their estimates, thereby reducing extreme or implausible responses. Participants were instructed to estimate the exact weight of each experimental object in grams. During each trial, a sphere was placed on the participant's left hand at the onset of an auditory beep and removed after 2 s. Participants then provided a verbal weight estimate in grams. They were instructed to keep their hand still throughout the task, ensuring that weight was perceived passively. Each of the five weights was presented three times per block, yielding 15 trials per block; presentation order was randomized.

The VR environment remained visible throughout the weight-judgement task. At the end of each block, the head-mounted display was removed before the alternative VR environment was presented and the task repeated. Each block lasted approximately 5 minutes, comprising 2 minutes of passive VR exposure followed by 3 minutes of weight judgements. Participants completed two blocks, one for each simulated gravitational acceleration, with block order counterbalanced across participants. Weight order was randomized within blocks. At the end of each block, the head-mounted display was removed before the next VR environment was presented, and the weight-judgement task was repeated.

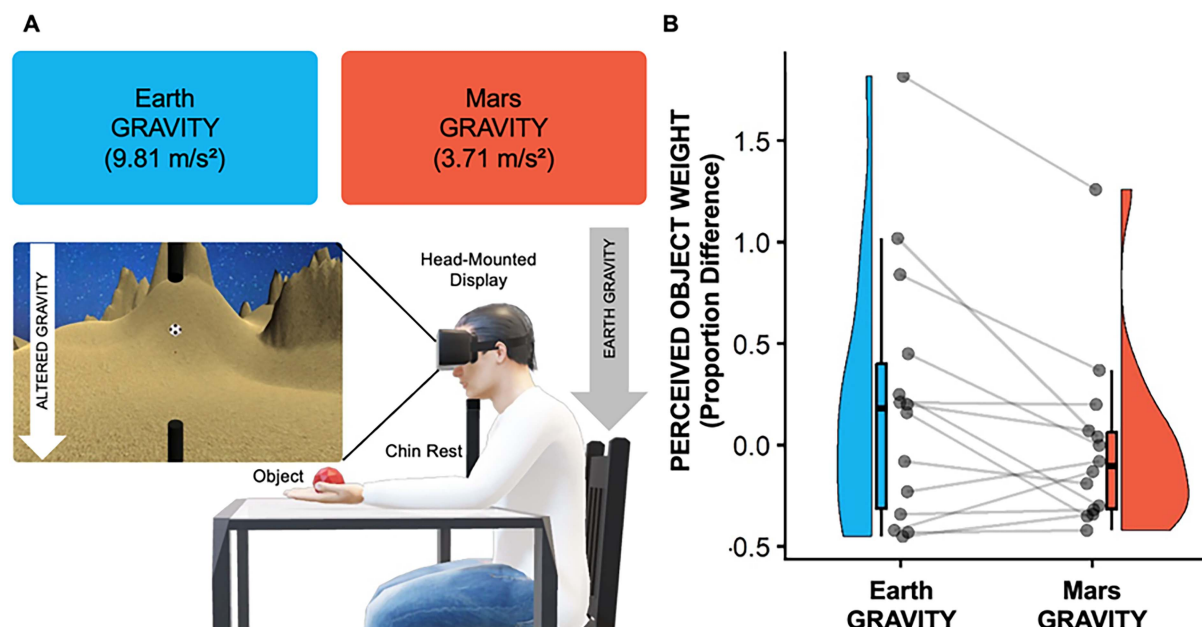


Figure 1. Experimental set-up and perceived weight across gravity conditions. (A) Participants sat with their head supported by a chin rest, their left hand resting palm up on a pillow, and their right hand on the chair armrest. While wearing a head-mounted display, participants viewed a virtual environment containing a centrally positioned red fixation point and a football falling between two vertical tubes. The football's motion simulated free fall under either Earth gravity (9.81 m s^{-2}) or Mars gravity (3.71 m s^{-2}). During the task, one of five three-dimensionally printed spheres (20–40 g) was placed on the participant's left hand for 2 s, after which participants verbally estimated its weight in grams. (B) Raincloud plot showing proportional differences between perceived and actual object weight in the Earth and Mars gravity conditions. Individual points represent participant means. Objects were perceived as significantly lighter in the Mars than in the Earth condition.

Table 1. Mean (SE) perceived weights. Perceived weights are expressed as a proportional difference relative to the actual weight.

gravity	actual weight				
	20 g	25 g	30 g	35 g	40 g
Earth	0.26 (0.14)	0.30 (0.17)	0.17 (0.18)	0.15 (0.19)	0.18 (0.24)
Mars	0.06 (0.08)	0.05 (0.10)	0.003 (0.13)	−0.08 (0.12)	−0.10 (0.18)

3. Data analysis

The difference in reported and actual weight was expressed as a proportional difference relative to the actual weight, such that positive values corresponded to an overestimation of weight and negative values corresponded to an underestimation (i.e. $\text{prop} = (\text{estimate} - \text{actual}) \div \text{actual}$). A 5 (weight: 20, 25, 30, 35 and 40 g) $\times$ 2 (gravity: Earth versus Mars) repeated measures analysis of variance (ANOVA) was conducted on the proportions. Greenhouse–Geisser correction was applied where Mauchley's test indicated violations of the sphericity assumption.

A paired t -test was conducted on Mars estimates versus 37% of Earth estimates (reduced gravity estimate = average Earth estimate $\times$ 0.37) to assess whether any changes in perceived weight were equivalent to the physical reduction in gravity between Earth and Mars. A two one-sided tests (TOST) analysis was also conducted to assess whether the difference in Mars and reduced Earth estimates fell within $\pm 10\%$ to assess equivalence.

Analysis was conducted in Jamovi (version 2.7.17.0). Bayes factors were obtained with the Jamovi jsq package, version 1.2.0, and the TOST analysis conducted using the TOSTER package, version 0.8.4 [18,19]. Two participants were excluded from analysis as their responses were two standard deviations away from the mean in at least one gravity condition. Specifically, while most participants' estimates ranged from approximately -0.4 to 2 across all individual weight conditions, these two participants' estimates were between 4.6 and 14.25 indicating a substantial variation in response strategy from other participants, questioning the reliability of their data.

4. Results

Mean perceived weights by condition can be seen in table 1. The 5×3 ANOVA revealed a significant main effect of gravity ($F(1,13) = 5.58$, $p = 0.034$, $\eta_p^2 = 0.30$, $\text{BF} = 18.22$). Participants perceived the objects as significantly lighter when viewing Mars gravity

($M = -0.01$, $SE = 0.12$) relative to Earth gravity ($M = 0.21$, $SE = 0.17$) (figure 1). No significant main effect of weight was found ($F(1.16, 15.06) = 1.30$, $p = 0.28$, $BF = 0.0003$). No significant interaction between gravity and weight was found ($F(4, 52) = 0.76$, $p = 0.55$, $BF = 0.81$).

The paired t -test revealed that there was no significant difference between the perceived Mars weights ($M = -0.01$, $SE = 0.12$) and one-third of Earth gravity weight ($M = 0.08$, $SE = 0.06$) ($t(13) = 1.35$, $p = 0.20$, $BF = 0.57$), suggesting that participants perceived the weights as close to 37% of the equivalent Earth weight perception. However, the TOST paired samples t -tests with $\Delta L = -0.1$ and $\Delta U = 0.1$ found no evidence of equivalence, with differences not significantly different from the lower boundary (lower $t(13) = 0.103$, $p = 0.46$, upper $t(13) = -2.794$, $p = 0.008$).

5. Discussion

Gravity is a fundamental, ubiquitous physical force. The brain builds up an internal model of gravity from multi-modal sensory signals, as well as prior knowledge of gravitational laws [1,7]. This internal model supports a wide range of perceptual and behavioural tasks, including verticality perception [4,7], object interception [20,21] and motion duration estimates [6,10]. Although gravity is constant on Earth (9.81 m s^{-2}) and has remained stable throughout human evolution, the internal model appears to be flexible, capable of adapting to novel gravitational contexts [11]. While previous studies have explored the impact of visually altered gravity on visual motion, the wider influence of such altered gravity is not known. Here, we investigated whether viewing objects falling under simulated Martian gravity alters the perceived weight of physical objects. Participants judged identical objects as lighter in the Mars than in the Earth gravity condition. This finding suggests that visually simulated gravitational cues can influence the internal model of gravity used to form expectations about object weight.

Perceived object weight is influenced by several factors, including an object's material properties, size and shape, as well as individual factors such as mood and prior experience [22–26]. Accordingly, systematic deviations from veridical weight judgements are common in the object-weight perception literature, consistent with the biases observed in the Earth condition of the present study [24]. Crucially, our VR scenario did not depict the physical object being judged. Instead, it manipulated visual-gravitational context alone. Thus, the present study was not designed to assess absolute accuracy in weight judgements, but rather the relative difference between the Earth and Mars conditions, which isolates the contribution of visual-gravitational cues to perceived object weight. Nevertheless, the discrepancy between perceived and actual object weight is an interesting question for future research.

To our knowledge, no previous study has systematically examined the influence of visual-gravitational signals on perceived object weight. Observations from altered-gravity environments, including parabolic flight, show that perceived weight scales with actual gravity: objects and the body feel heavier during hypergravity and lighter during microgravity [27,28]. Our findings extend this evidence by showing that visual-gravitational cues alone, in the absence of changes to the physical weight of an object, are sufficient to modulate perceived weight.

Our findings demonstrate that visual-gravitational information modulates perceived object weight: identical objects were judged as lighter when visual cues simulated the partial gravity of Mars rather than terrestrial gravity. These results provide novel evidence that the internal model of gravity is flexible and context-dependent, extending beyond motion perception to influence the perceived weight of objects. This flexibility may be important for adaptation to environments with altered gravitational forces, including spaceflight and planetary exploration.

Ethics. The study procedure was approved by the local research ethics committee of Royal Holloway University of London. The study was conducted in accordance with the Declaration of Helsinki. Participants gave written informed consent before participating.

Data accessibility. Data are available on the Open Science Framework [29].

Declaration of AI use. We have not used AI-assisted technologies in creating this article.

Author's contributions. M.G.: conceptualization, data curation, formal analysis, investigation, methodology, project administration, visualization, writing—original draft, writing—review and editing; M.R.L.: conceptualization, methodology, resources, supervision, visualization, writing—review and editing; E.R.F.: conceptualization, data curation, formal analysis, investigation, methodology, project administration, resources, supervision, writing—review and editing.

All authors gave final approval for publication and agreed to be held accountable for the work performed therein.

Conflict of interest declaration. We declare we have no competing interests.

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