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Physical cognition in altered gravity: Link between sensorimotor and cognitive adaptability

Highlights

- Participants played basketball in virtual reality under altered physical rules
- Adaptability to new gravity was consistent within motor and cognitive domains
- Motor recalibration also corresponded to adjustments of abstract physical reasoning
- Findings support embodied theories linking low-level action and high-level cognition

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In brief

Psychology

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Physical cognition in altered gravity: Link between sensorimotor and cognitive adaptability

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SUMMARY

A hallmark of human intelligence is rapid adaptation to changing environments. Yet the link between sensorimotor recalibration to new physical conditions and cognitive updating of internal models remains unclear. We addressed this using altered gravity as a model system. In a within-subject study, 25 adults completed a virtual-reality task requiring motor adjustment to non-terrestrial gravities and an online problem-solving task requiring physical reasoning under matched gravity manipulations. Adaptability in each domain was computed relative to performance under terrestrial gravity. We reveal consistent individual differences in adaptability within the sensorimotor domain and the cognitive domain. We also found a significant correlation across the domains. Participants who better adjusted their movements under altered gravity also more effectively modified their reasoning strategies. Findings support embodied cognition theory, indicating a close coupling between physical interaction and high-level reasoning. The study raises the possibility that training sensorimotor recalibration may enhance abstract reasoning and vice versa.

INTRODUCTION

From the unpredictable landscapes of planet Earth to the unfamiliar physical laws in outer space, humans must learn to adapt to changes in local conditions.[1] This adaptability is critical for survival and proper function as even the most foundational and automatised actions (e.g., reaching or walking) should be modified to suit physical demands (e.g., obstacles in the path or changes in gravity). Adaptability underscores the interplay between humans' physical capabilities and the cognitive processes that enable them to thrive in diverse and sometimes adverse conditions.[2]

Adapting to new physical environments requires humans to recalibrate their sensorimotor behavior to deal with altered physical laws, unfamiliar terrains, and other environmental changes.[3–7] For example, adults and infants modify their locomotor strategies and gait patterns when crossing terrains with varied height, slant, width, deformability, and friction.[8–10] Similarly, when confronted with altered gravitational forces, adults use a sophisticated recalibration process, adjusting balance, muscle control, and coordination to maintain functionality.[4,11–13] This recalibration has been shown to rely on perceptual adjustments[14,15]

Nevertheless, adaptation extends beyond mere sensorimotor recalibration[13]; adaptability also encompasses a critical cognitive process of recalibrating the mental representation of the environment,[2,16–18] in which previous experiences are harnessed to predict the outcomes of potential motor acts.[19] Discrepancies between prediction and actual sensory feedback lead to motor adjustments.[20–22] For instance, when an individual learns to navigate different terrains, sensory receptors provide feedback on the body's movements, which the brain uses to modify motor output to maintain stability and prevent falling.[19,23–25] In this experience, humans also learn to recalibrate cognitively and recalibrate the internal representation of the environment to align with the alterations in local conditions,[25–29] although they occasionally perform poorly in such tasks.[30] Importantly, while "sensorimotor recalibration" refers to adjusting motor actions and control parameters in response to immediate sensory feedback and altered environmental constraints,[31,32] "abstract physical reasoning" involves using internal cognitive models to anticipate outcomes and solve problems without direct motor action. Thus, sensorimotor recalibration focuses on fine-tuning movement execution under novel physical conditions, whereas abstract physical reasoning engages higher-level cognitive processes thatoss represent and predict how objects will behave.[33–36]

Yet, despite the importance of adaptability in daily life, the question of the extent to which sensorimotor adaptations are linked to cognitive adaptations is still open. Are individuals

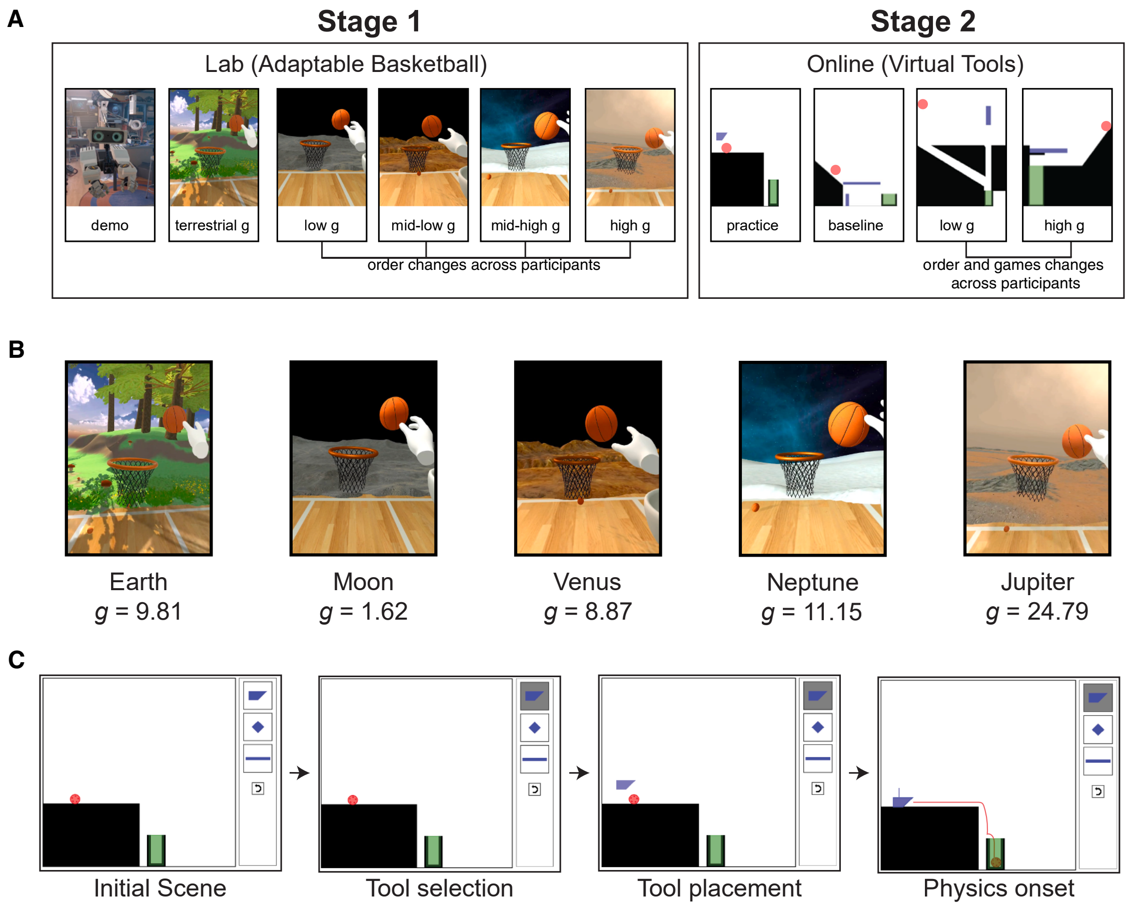

Figure 1. Experimental procedure and tasks

(A) Illustration of the experimental design, which included 2 stages. Participants first completed a lab session in which they completed the adaptable basketball task in a VR environment. Then, they completed the virtual tools task online at home.

(B) The adaptable basketball game (sensorimotor task). Participants wore a VR headset and played a game of throwing a ball into a basket on different planets with a variety of gravities: Earth (baseline), Moon (low gravity), Venus (mid-low gravity), Neptune (mid-high gravity), and Jupiter (high gravity). Adaptability was measured for each participant by comparing their performance in each planet to their baseline performance on "Earth."

(C) Virtual tools game (cognitive task). Participants played an online game in which they had to bring the red object into the green area using one of the three blue shapes on the top right side ("tools"). Once the initial scene appears (left box), the participant had to select a tool (second-left box), place it in the scene (third-left box). Once the tool was placed, all the objects in the scene would act according to the laws of physics based on a specific gravity. Therefore, to succeed in the task, participants must reason about the future outcome when they place the tool. Participants played games that included a variety of environments (see all in Figure S2) and in three different gravities—terrestrial gravity, low gravity (half terrestrial gravity), and high gravity (double terrestrial gravity).

who excel in recalibrating their motor actions to new physical environments also more adept at recalibrating their internal representations? The answer is important for understanding whether adaptation is a domain-specific process. If sensorimotor adaptability and internal representation are linked, it will support theories that advocate for an embodied, domain-general perspective on adaptability. These theories suggest that our knowledge about how the world works is deeply rooted in our physical experiences.[37–39] Alternatively, if sensorimotor adaptability and cognitive adaptability are not linked, it would suggest that the mechanisms underlying those two types of adaptability are independent within the human cognitive architecture. This would align with modular theories of mind, proposing a domain-specific model in which cognitive processes underlying adaptability are based merely on information processing.[40–42]

Here, we hypothesize that sensorimotor and cognitive adaptability are intertwined, so individual differences in the capacity to adjust movements physically match individual differences in the ability to mentally simulate actions in new environments (Figure 1A). To test this hypothesis, we used altered gravity as a model system to test motor and cognitive adaptations.[29,43] Adult participants completed two tasks. The first task aimed to test adults' ability to adjust their motor actions in "Adaptable Basketball"—a virtual reality (VR) task where they had to throw a ball into a basket on different virtual planets with altered gravities (Figure 1B). To succeed, participants must modify their movements from moment to moment—adjust throwing strength, release angle, release position, and hand gesture—to fit the demands of altered gravity. For example, if gravity is higher than terrestrial gravity, participants had to make more

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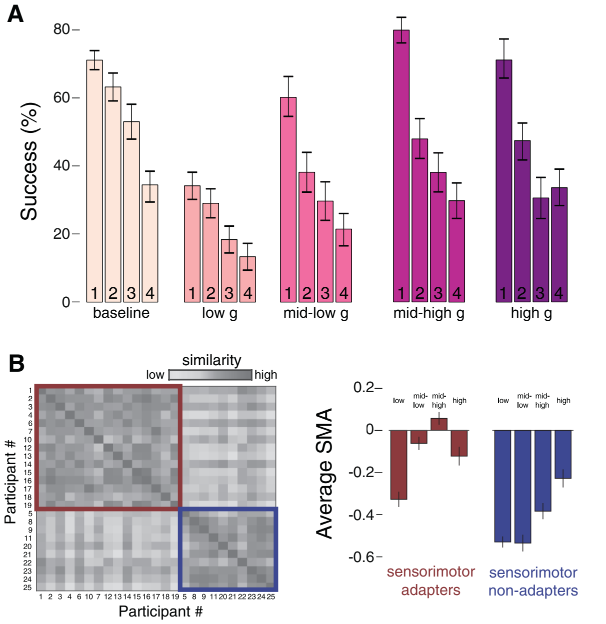

Figure 2. Sensorimotor adaptation

(A) Participants' overall percentage of successful trials in the adaptable basketball task for each gravity (planet), separated by different distances (1 – closest, 4 – furthest; see STAR Methods). For trial-by-trial performance, see Figure S1.

(B) Clustering based on SMAs' similarity among participants. Left panel shows the similarity matrix based on participants' SMA scores in all the gravities (see STAR Methods). The dark gray squares show high similarity among participants within clusters. Clusters represented by the red and blue squares. The right panel shows the average SMAs for each gravity per cluster. Individual data points represent individual subjects. Error bars represent standard error.

extreme movements and use a lot of strength to increase velocity so their ball would reach the basket. In contrast, if gravity is lower than terrestrial gravity, participants had to make small and delicate movements and use less strength to control the velocity so their ball would not "fly" beyond the location of the basket. We measured adaptability by calculating a sensorimotor adaptability index, which compares participants' success in altered gravities to their success in terrestrial gravity.

The second task tests adults' ability to modify their mental representation of their actions. The same participants completed an online reasoning task—"Virtual Tools."[33,35] The Virtual Tools task includes games that require participants to apply knowledge from their internal representation to anticipate changes in the environment and object-to-object interactions without performing physical movement (Figure 1C). We manipulated the gravity in these games to examine how participants adapt their internal representation. Similar to the VR task, we calculated a cognitive adaptability index, which compared success in altered gravity to success in terrestrial gravity. If our hypothesis is correct that motor and cognitive adaptabilities are linked, then individual differences in the sensorimotor adaptability index will correspond to individual differences in the cognitive adaptability index.

RESULTS

Participants completed $M = 91.08\%$ of the Adaptable Basketball task trials ($SD = 10.72$). Trials that were not completed were due to technical issues in grasping and throwing the ball. Participants completed all the Virtual Tools games. Preliminary analyses showed no effect of gender, $ps > 0.31$, so it was collapsed in subsequent analyses. In addition, one-way ANOVA across multiple Virtual Tools games confirmed no significant difference in performance across games, $F(25,39) = 2.05$, $p = 0.08$; therefore, we collapsed data across games in further analysis.

Individual differences in sensorimotor adaptability

Participants were successful in the Adaptable Basketball task in $M = 55.36\%$ ($SD = 25.07$) of the trials in terrestrial gravity (baseline block), and an average of $M = 39.39\%$ ($SD = 31.03$) in altered gravities (adaptability blocks). Figure 2A shows participants' percent of successful trials in each one of the planets and the different distances (for participants' performance trial-by-trial within each block, see Figure S1). A 4 (gravities) x 4 (distances) repeated-measures ANOVA confirmed main effect of gravity, $F(4, 240) = 16.56$, $p < 0.01$, main effect of distance, $F(3, 240) = 67.47$, $p < 0.01$, and near-significant interaction, $F(12, 240) = 1.79$, $p = 0.05$. Sidak-corrected pairwise comparisons on distance confirmed that the percent of successful trials significantly increased with shorter distances, $ps < 0.03$. In addition, Sidak-corrected pairwise comparisons on gravity confirmed lower success in the low- and mid-low gravities compared to the baseline, mid-high, and high gravities, $ps < 0.02$.

When examining the correlations between participants' sensorimotor adaptability indices (SMAs; see STAR Methods) across gravities, we found that SMAs were significantly correlated, $ps < 0.05$, except for the correlation between the mid-high gravity and high gravity, suggesting individual differences in sensorimotor adaptability are consistent across environments (see Table S1 for all correlations). We used a data-defined clustering procedure to group participants according to the similarity of their SMAs and identified two clusters (Figure 2B, left panel; see STAR Methods for procedure details). We labeled one cluster "sensorimotor adapters" ($n = 15$; 60% of the dataset) because those participants had relatively low SMAs across gravities, indicating a small difference in performance during the adaptability blocks compared to the baseline block. We labeled the second cluster "sensorimotor non-adapters" ($n = 10$; 40% of the dataset; Figure 2B, right panel) because participants in that cluster had high negative SMAs in all gravities, indicating a sharp decline in performance during adaptability blocks compared to baseline. Importantly, the groups did not significantly differ in their baseline performance ($M_{adapters} = 52.30\%$ $SD_{adapters} = 13.80$, $M_{non\text{-}adapters} = 58.69$, $SD_{non\text{-}adapters} = 16.70$; $t(23) = 1.04$, $p = 0.30$), suggesting that the differences between the groups are less likely to be driven by motivation.

Individual differences in cognitive adaptability

In the Virtual Tools task, participants succeeded in solving the games in $M = 73.79\%$ ($SD = 13.18$) of the baseline games, $M = 83.77\%$ ($SD = 16.67$) of the low-gravity games, and $M = 85.71\%$ ($SD = 16.49$) of the high-gravity games (Figure 3A). A one-way

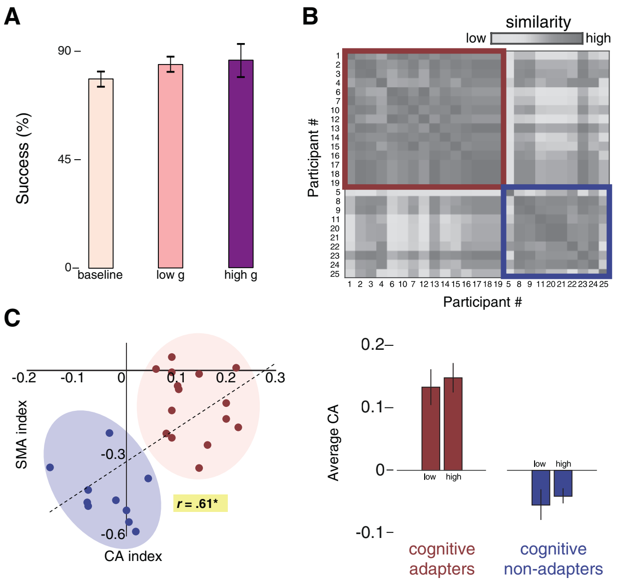

Figure 3. Cognitive adaptation

(A) Participants' overall percentage of successful trials in the Virtual Tools task for each gravity—baseline, low g, and high g (see STAR Methods). Error bars represent standard errors.

(B) Clustering based on CAs' similarity among participants. Similar to Figure 2B, the left panel shows the similarity matrix based on participants' CA scores in low and high gravity (see STAR Methods). The dark gray squares show high similarity within clusters, which are represented by the red and blue squares. Clusters were identical to the clusters found based on the SMA analysis. The right panel shows the average CAs for each gravity per cluster. Individual data points represent individual subjects. Error bars represent standard error.

(C) Individual differences in adaptability correlated across domains. The cross-domain adapters are marked in red dots, and the cross-domain non-adapters are marked in blue. Error bars represent standard errors.

repeated-measures ANOVA confirmed a main effect of gravity, $F(2, 48) = 6.68$, $p < 0.01$. Sidak-corrected pairwise comparisons confirmed a significant difference between the baseline gravity and the altered gravities, $ps < 0.04$, but not between the two altered gravities, $p = 0.92$.

Similar to sensorimotor adaptability, we found that participants' cognitive adaptability indices (CAs; See STAR Methods) were correlated across gravities $r(23) = 0.46$, $p < 0.02$, suggesting that individual differences in cognitive adaptability as consistent across simulated environments. We took a similar clustering approach and grouped participants by using their CA indices in low- and high-gravity as input to the clustering procedure (see STAR Methods). We identified two clusters (Figure 3B, top panel). One cluster was labeled as "cognitive adapters" (n = 15; 60% of the dataset) because participants in this cluster had high CAs in the low and high gravities, indicating strong cognitive adaptability skills. The second cluster was labeled "cognitive non-adapters" and included participants with difficulties in adapting (n = 10; 40% of the dataset; Figure 3B, right panel). Similar to the groups we identified based on the SMAs, the CA-based groups did not significantly differ in their baseline score ($M_{adapters}$ = 81.01% $SD_{adapters}$ = 11.04, $M_{non\text{-}adapters}$ = 69.12%, $SD_{non\text{-}adapters}$ = 14.01; $t(23) = 1.91$, $p = 0.08$), suggesting that the differences between the groups are less likely to be driven by motivation.

Sensorimotor adaptability is associated with cognitive adaptability

To test cross-domain adaptability, we compared the overlap between the sensorimotor clusters and the cognitive clusters. We found 100% overlap between the sensorimotor adapters and the cognitive adapters, and between the sensorimotor non-adapters and the cognitive non-adapters (see participant numbers in Figures 2B and 3A).

Participants' average SMA (averaged across low, mid-low, mid-high, and high gravities) was significantly correlated with their average CA (averaged across low and high gravities), $r(23) = 0.61$, $p < 0.01$. Figure 3C shows the correlation between adaptability in the two domains and participants' labels according to their sensorimotor/cognitive groups.

DISCUSSION

In this study, we used altered gravity to investigate the link between sensorimotor adaptability and cognitive adaptability. Gravity profoundly affects motor behavior because it dictates the basic parameters within which physical forces operate. Consequently, when engaged in motor tasks under conditions of altered gravity, participants must recalibrate their movements to meet the specific demands of their environment, as the altered dynamics challenge their habitual motor patterns.[20,21] Gravity is also an important component in our cognitive reasoning about physical interactions.[28] In environments where gravitational norms are disrupted, the usual cues used to predict object behavior become unreliable, requiring individuals to adapt their mental representations to maintain accurate predictions and effective problem-solving strategies.[44] Our findings suggest that individual differences in adaptability are similar across environments within the sensorimotor and cognitive domains (participants who adapted well to one gravity also adapted well to another gravity). Findings also show a significant correlation between the two domains. In other words, participants who adeptly adjusted their motor actions to the altered gravitational forces also demonstrated a superior ability to adapt their cognitive strategies under similar conditions.

The effects of variation in gravity

One unexpected finding in this study was that participants performed better in the altered gravity conditions compared to the baseline terrestrial gravity in the Virtual Tools task. While our primary focus was on measuring adaptability, we recognize that the improved performance in altered gravity may be influenced by factors other than cognitive adaptability to new gravitational environments. Possible explanations include practice effects, as participants became more familiar with the task mechanics over time, potentially enhancing their performance in the later blocks. Additionally, the novelty and increased engagement associated with the altered gravity environments may have heightened participants' interest and motivation, positively affecting their performance. There may also be other contributing factors. However, this study was designed to examine individual differences in adaptability, not to compare overall group performance between terrestrial and altered gravity conditions. The terrestrial gravity condition served as a baseline for each participant, allowing us to measure adaptability relative to their own performance under familiar conditions. Therefore, while the overall improvement in performance under altered gravity is noteworthy, it does not detract from our primary findings regarding the relationship between sensorimotor and cognitive adaptability at the individual level. Our results emphasize the consistency of individual adaptability across different domains and conditions, supporting the notion of a linked underlying mechanism.

Importantly, not all Virtual Tools games may be equally influenced by variations in gravity. Some tasks may rely heavily on gravitational forces to alter object trajectories, timings, or impacts, while others may be solved effectively with strategies less sensitive to changes in gravity. In the current study, we analyzed all games collectively, but we acknowledge that future research could benefit from classifying tasks based on their gravity sensitivity. By identifying and focusing on the subset of games that show the greatest differences in solutions across gravitational conditions, it may be possible to reveal even stronger relationships between sensorimotor and cognitive adaptability. Such an approach could help confirm that our observed findings are indeed rooted in a shared adaptive mechanism rather than being diluted by tasks in which gravity exerts minimal influence.

The role of embodied cognition in adaptability

We propose that adaptability arises from the synergistic interaction of the body, brain, and environment, and therefore, it is rooted in the capacity to plan and control motor actions. This stands in contrast to information-processing perspectives of cognition,[42,45,46] which focus on how mental representations function as discrete constructs within the mind and control how information is received, processes, and stored internally.[47] Therefore, it largely disregards how the environment or bodily states might influence or integrate into cognitive processes.[29]

Our findings support the framework of embodied cognition, which argues that cognitive processes are fundamentally intertwined with the body's interactions with the physical environment.[48] For example, the way humans physically interact with objects affects their understanding of objects' properties and shapes their exploration, planning, and problem-solving strategies.[34,35,37,49–52] Additionally, gestures during conversations do more than accompany speech—they actively shape humans' thoughts and the way they communicate.[53] Research further shows that embodied sensation and experience affect cognitive processes such as understanding abstract concepts, emotion connotation, language comprehension, or sense of agency and ownership.[54–56]

Within the embodied cognition framework, the association between the motor adaptability index and the cognitive adaptability index raises the possibility that sensorimotor adaptation may enhance abstract reasoning capabilities or vice versa. In both tasks, participants were required to process visual information, make decisions about the required responses, and carry out those responses. However, the adaptable basketball task required a full embodied, whole-body motor calibration to the altered virtual environment, whereas the virtual tools game required an abstract, high-level reasoning calibration to the altered gravity. While few studies showed that experts do not necessarily have performance advantages in gravity-related sensorimotor tasks,[57] the question of directional influence between motor and cognitive adaptation remained open. Our study did not directly explore such causal effects. Future research should use longitudinal designs or experimental interventions to manipulate sensorimotor experiences and observe subsequent changes in cognitive adaptability. Such research should include longer training and retention sessions, which will inform the development of integrated physical and cognitive training programs that optimize human adaptability.

That said, while we have used the terms "sensorimotor adaptability" and "cognitive adaptability" to distinguish between our two tasks, this dichotomy oversimplifies the complex interplay between sensorimotor and cognitive processes. As pointed out by Morton and Bastian[58] in their work on prism adaptation, there can be significant generalization between seemingly distinct domains of adaptation. Our VR basketball task, while primarily focused on motor adaptation, undoubtedly involves cognitive components such as strategy formation and error detection. Conversely, the Virtual Tools task, while more explicitly cognitive, still involves sensorimotor interaction through the user interface. The link between adaptability indices across these tasks suggests a shared underlying mechanism of adaptability, which may transcend traditional boundaries between sensorimotor and cognitive domains. This perspective challenges the theoretical stove-piping of sensorimotor and cognitive concepts, and aligns with more integrated views of human adaptation and learning.[44] We suggest that future research will explore whether training in one domain (e.g., abstract problem-solving) can enhance performance in another (e.g., sensorimotor tasks), and to what extent the cognitive processes involved in different adaptive tasks need to be equivalent for such transfer to occur.

Relevance to embodied artificial intelligence

This study holds significant relevance for the AI and robotics communities, which are keen on developing embodied models that mimic human cognition. Previous research has introduced computational models that encapsulate elements of cognitive physical reasoning.[36,45,59] However, a critical question remains: Can such cognitive reasoning effectively translate to adaptive behavior in AI systems?

We propose that by engaging with the environment in a manner akin to human interaction, AI systems can learn and adapt their behaviors in response to dynamic physical laws, much like humans adjusting to altered gravity. Building AI systems that adjust like humans could lead to more intuitive and context-aware robotic systems capable of more naturally navigating and manipulating their environments.[60,61] Taking such a computational approach can also shed light on the mechanisms underlying our findings. For example, one crucial factor that could explain the observed correlation between sensorimotor and cognitive adaptability is the shared underlying process of learning from errors.[61,62] Both motor and cognitive adaptation likely rely on the ability to recognize discrepancies between expected and actual outcomes, judge why there was a failure, and recalibrate accordingly. Perceptual adaptation and motivation may also play roles in this correlation. Incorporating computational models that simulate these processes, alongside experimental approaches, could help disentangle the contributions of these various factors and provide a clearer picture of the mechanisms driving adaptability in both domains.

Limitations of the study

While our findings support a link between sensorimotor adaptability and cognitive adaptability, they do not inherently rule out alternative theoretical positions. While we have interpreted the results through an embodied cognition framework—suggesting that cognitive adaptability is intimately linked to one's capacity for motor planning and control—other interpretations remain plausible. For example, a modular perspective could argue that abstract physical reasoning is largely encapsulated within a cognitive system that can inform sensorimotor responses downstream. In this view, the observed correlation might reflect a shared learning signal or error-detection mechanism, where cognitive representations adapt first and guide motor behavior, rather than a direct, bidirectional coupling between motor and cognitive processes. Thus, our findings invite further inquiry regarding the definitive distinction between embodied and modular accounts. Future studies that manipulate training in one domain and measure transfer to the other, or that use neuroimaging to identify overlapping neural substrates of adaptability, will be necessary to clarify the causal relationships and the mechanistic nature of the observed association.

Another potential explanation is that "sensorimotor adapters" were simply more motivated or attentive participants. If this were the main reason for their adaptability, we would expect these individuals to outperform others uniformly, including on the baseline terrestrial gravity trials. However, the defining feature of these participants was their ability to adjust effectively to altered conditions, not just their baseline performance. Moreover, their consistent adaptability across multiple distinct gravities suggests a stable underlying capacity rather than momentary engagement. Because we did not include direct measures of motivation (e.g., physiological indicators, self-reported effort), we propose that follow-up studies would employ such methods to more definitively separate motivational influences from genuine sensorimotor-cognitive integration. By doing so, we can ensure that observed individual differences in adaptability are not merely a product of differences in effort or attention.

Moreover, our measure of sensorimotor adaptability focused on within-session recalibration rather than the longer-term learning processes often associated with sensorimotor adaptation.[31,32,63] Long-term paradigms involve repeated sessions to demonstrate persistent adaptation and subsequent after-effects when returning to baseline conditions. In contrast, our experiment utilized a relatively small number of trials (20 per gravity condition) and did not include a return-to-baseline test, making it less suited to assess long-term adaptation or retention. Thus, our study design cannot completely disentangle sensorimotor recalibration and sensorimotor adjustments. Nevertheless, our aim was not to capture the entirety of the sensorimotor adaptation process, but rather to measure individual differences in the ability to recalibrate actions in the face of novel and transient physical constraints. Therefore, our current interpretation of the results does not rely on whether the adaptability we are capturing is a rapid adjustment or slower recalibration. Future research should employ longer training periods, retention tests, and return-to-baseline assessments to more fully characterize the time course and durability of sensorimotor adaptations across changing physical conditions.

RESOURCE AVAILABILITY

Lead contact

Requests for further information and data resources should be directed to and will be fulfilled by the Lead Contact, Ori Ossmy (ori.ossmy@bbk.ac.uk).

Materials availability

This study did not generate new reagents.

Data and code availability

- Data are shared via Databrary and GitHub platforms. With participants' permission, their Adaptable Basketball identifiable videos, demographic data, and coding spreadsheets are shared in Databrary with authorized investigators. Raw and processed data of the virtual tools and adaptable basketball tasks are publicly shared on GitHub. Accession numbers are listed in the key resources table.
- All analysis codes are publicly shared on GitHub. Accession numbers are listed in the key resources table.
- Other materials, including the stimuli of the Adaptable Basketball game code in Unity, are shared on GitHub. Accession numbers are listed in the key resources table.

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AUTHOR CONTRIBUTIONS

M.C. and O.O. provided the initial idea. M.C., D.H., and O.O. designed the experiments. O.O. and M.C. carried out computer programming. M.C., D.H., and O.O. carried out the experiments. M.C., O.O., and M.H. analyzed data. O.O. drafted the initial versions of the article. M.C., D.H., M.H., and O.O. completed writing the article. All contributed to the conceptual analysis of the results. All authors approved the final article for submission.

DECLARATION OF INTERESTS

The authors declare no conflict of interest.

STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

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SUPPLEMENTAL INFORMATION

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STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Deposited data		
Virtual Tools data	This study	https://github.com/Physical-Cognition-Lab/Physical-Cognition-in-Altered-Gravity/tree/main/Data
Adaptable basketball video data	This study	databrary.org/volume/1524
Stimuli	This study	https://github.com/Physical-Cognition-Lab/Physical-Cognition-in-Altered-Gravity/tree/main/AdaptableBasketbal_Unity
Software and algorithms		
MATLAB 2019b	Mathworks, Inc	Mathworks.com
SPSS 29.0	SPSS Software	https://www.spss.com
Scripts for analysis	This study	https://github.com/Physical-Cognition-Lab/Physical-Cognition-in-Altered-Gravity/tree/main/Analysis

EXPERIMENTAL MODEL AND STUDY PARTICIPANT DETAILS

Participants

Twenty-seven participants (7 males; mean age = 25.63 years; age range = 20.9–34.6 years) naive to the purpose of the experiment were recruited through word of mouth. All participants provided written informed consent to participate in the study and received a photo magnet and tote bag for participation. All participants had normal (or corrected to normal) vision. The study was approved by the ethics committee of New York University. Two participants were excluded because they did not complete the Virtual Tools tasks. Two participants were left-handed.

The central statistical test in our manuscript is the association between adaptability scores across domains. Based on previous research examining relationships between motor and cognitive skills e.g.,.[64,65] Using G*Power 3.1 (Erdfelder et al., 1996), we calculated that a sample size of 26 participants would be required to detect this effect with 80% power at $\alpha = 0.05$ (two-tailed).

METHOD DETAILS

Procedure

The experiment has within-subject design and was split into two stages (Figure 1A). In the first stage, participants arrived at the NYU Infant Action lab for a VR session to play the 'Adaptable Basketball' game. The study began by showing the VR headset to participants. To motivate participants to wear the VR and allow them to get used to the VR experience, they played with the Oculus 'First Contact' tutorial demo which was designed as the entryway for the headset (https://www.youtube.com/watch?v=KKT3Z8LBn6s&ab_channel=MetaQuest). The entire procedure for each participant can be found at Databrary: nyu.databrary.org/volume/1524. After playing with the demo, participants completed the 'Adaptable Basketball' task where they threw a virtual ball into a virtual basket in different 'planets' with altered gravity (Figure 1B). The study lasted for about 60 min.

The second stage of the experiment was conducted online after the VR session in the lab ($M = 14 \pm 3$ days after the first stage). We sent all participants a link to an online physical reasoning task Virtual Tool Use; Figure 1C; https://www.bbk.ac.uk/psychology/e/xp/269/258/1/,[33–35] which they completed in their homes. After accessing the experiment link, participants were refreshed with information about the experiment, an online consent form for conducting the second stage, and instructions on playing the game. Then, participants completed all the games in a single session of approximately 45 min.

Recording device

We used Meta Oculus Rift headset and three external Oculus sensors as our virtual reality system (https://www.oculus.com/rift-s/; released 2017). The VR session was also recorded using two external HD cameras at 30 fps from the right and left side views (Figure 1B;[66,67]). Videos of all participants are shared via Databrary (nyu.databrary.org/volume/1524) upon their approval of the consent forms.

Adaptable basketball task

The Adaptable Basketball game consisted of 6 blocks. In each block, participants were asked to throw a virtual ball into a virtual basket under different gravitational conditions (Figure 1B). A virtual stand holding a ball was positioned close to participants' dominant hand, and they were shown virtual hands that mirrored the movements of their real hands. Participants interacted with the virtual ball by physically grasping the controller using a power grip, simulating a natural grasp. However, unlike a real ball, they did not release the controller to throw the virtual ball. Instead, to simulate the act of releasing the ball, participants opened their palms while the controller was still being held (using a strap), effectively mimicking the gesture of letting go of a real object. The complete throwing action required participants to extend their arms and perform a full throwing motion as if they were holding an actual ball. Importantly, if participants did not open their palms or if their arm movement was minimal, the virtual ball would not have been thrown. Thus, the motion replicated the experience of throwing a physical ball, despite the controller remaining in their hand throughout the process. Moreover, the size of the virtual basketball was intentionally designed to be smaller than a standard basketball, approximating the size of a child's ball. This decision was based on several factors including ergonomics (the smaller size allowed for comfortable one-handed grasping, crucial for natural throwing mechanics in VR), integration with the VR Controller (the ball size was calibrated to be more aligned with the VR controller dimensions than a standard basketball, enhancing the congruence between the physical and virtual interactions), and object perception (objects in VR often appear smaller than in reality. Our chosen size compensated for these perceptual discrepancies).

Besides practising with the tutorial demo, participants underwent a brief practice session in the adaptable basketball game before starting the main task. During this practice, they were introduced to the mechanics of the VR environment and were explicitly informed about the unique gravitational conditions of each virtual planet. Visual cues and instructions emphasised the need to adapt to varying gravitational forces. As a result, participants were aware of the altered conditions from the start, and they had the necessary context to begin recalibrating their movements immediately, even on the first trial. Therefore, all trials, including the first, were included in our analysis as they reflect the full process of motor recalibration.

We used 5 different 'planets' and their real gravities (from low to high gravity): Moon ($g = 1.62$; low-gravity), Venus ($g = 8.87$; mid-low gravity), Earth ($g = 9.81$; terrestrial gravity), Neptune ($g = 11.15$; mid-high gravity), Jupiter ($g = 24.79$; high gravity). Each gravity requires participants to adapt their throwing to achieve the goal. For each participant, the first block—'baseline block'—was on Earth, to evaluate their baseline skills in the game. Then, participants played four additional blocks—'adaptability' blocks—on different virtual planets with altered gravities (Figure 1A). Each block consisted of one planet and the order of planets was counterbalanced across participants. Participants were informed about the gravity of each planet (before and during the block), and the planets were visually different in the virtual environment (Figure 1B).

The baseline block consisted of 50 trials, systematically arranged to assess performance across varying distances. Participants played the first 15 trials with the virtual basket positioned at a 1-meter distance. This was followed by sets of 15, 10, and 10 trials at distances of 2 m, 3 m, and 4 m, respectively. The adaptability blocks consisted of 20 trials each, with five trials per distance, identical to the order of the baseline block. The rationale for this design was 2-fold: the increased trial count in the baseline block aimed to establish a robust baseline of participant performance, while the subsequent reduction in trials sought to minimize fatigue, ensuring the integrity and reliability of the data. We did not interleave the distances because we did not want to add more variability to the motor adjustments.

Virtual tools task

Our physical reasoning task is based on the 'Virtual Tools' framework[33]—a digital gaming platform featuring a collection of two-dimensional virtual environments, containing various virtual objects and shaded areas (Figure 1C). Although the design of the environment differs from game to game, the objective for each game remained the same: participants were asked to select and place a shape ('tool') to bring a red object into the green goal area (see Figure S2 for all games). The environment—initially static—becomes dynamic once the tool is placed as the world physics gets activated (e.g., gravity).

Participants were allowed up to 12 attempts per game, without time constraints, to achieve this goal. Each game automatically reverted to its starting configuration following an unsuccessful try. Successful completion advanced the participant to the subsequent game. We recorded the selected tool, its placement, timing, and the outcome of each attempt. Feedback on their performance was provided to the participants visually through a green tick for success or a red cross for failure.

Participants started with two practice games under terrestrial gravity conditions to familiarize themselves with the gameplay mechanics. Following this, participants completed a 'baseline' block of twelve games with terrestrial gravity to evaluate their baseline performance. Those were followed by two 'adaptability' blocks, each including seven games. One block included seven games with low gravity (half terrestrial gravity) and the second block included seven games with high gravity (double terrestrial gravity). We selected the games based on previous work[33–35] and our recent experiences[68,69] using Virtual Tools. Drawing on these diverse datasets, we evaluated game difficulty in both altered and non-altered gravity conditions and selected sets of games that maintained similar difficulty across baseline and adaptability blocks.

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QUANTIFICATION AND STATISTICAL ANALYSIS

Sensorimotor adaptability

To measure participants' sensorimotor adaptability, we calculated a Sensorimotor Adaptability index *SMA* per altered gravity *g* (low, mid-low, mid-high, and high gravity) according to the following formula:

$$SMA_g = \frac{\sum_{d=1}^{4} \frac{SR_{gd} - SR_{Td}}{SR_{gd} + SR_{Td}}}{4}$$

Where SR_{gd} is participants' percentage of successful trials at distance *d* and altered gravity *g* (that is, the percentage of trials they successfully threw the ball into the basket from the overall throws in the specific distance and gravity). SR_{Td} is the participants' percentage of successful trials at distance *d* in terrestrial gravity. In other words, sensorimotor adaptability was measured as the ratio between participants' success in scoring a basket in altered gravity and their success in scoring a basket in terrestrial gravity averaged across distances.

We recognize the importance of capturing the dynamic nature of sensorimotor adaptability. However, given that participants were prepared for the altered gravity from the first trial onward, our approach of including all trials focuses on providing a *valid measure of recalibration* across the entire session, and not *trial-by-trial motor adjustment*, which was shown in the literature to be a distinct process.[32,70] Moreover, because the visual system is notoriously insensitive to accelerations downwards accelerations as gravities are no exception,[22]; we performed extensive pilot studies to address concerns about participants' perception of gravity differences. Therefore, perceptual judgment of the altered gravity was not the primary focus of this study. Instead, our sensorimotor adaptability measure inherently incorporated the participants' recalibration to the altered environment, without isolating perceptual processes from the broader sensorimotor response.

Cognitive adaptability

Additionally, similar to the Adaptable Basketball game, the order of the adaptability blocks and their altered gravities were random across participants. Participants were informed about the gravity before and during each game. See Figure S2 for all the game environments.

To measure participants' cognitive adaptability, we assessed participants' performance in each game by calculating their percentage of successful trials in the game. After determining participants' performance, we calculated a Cognitive Adaptability index *CA* per altered gravity *g* (low or high gravity), according to the following formula:

$$CA_g = \frac{\frac{\sum_{e=1}^{5} S_{ge}}{7} - \frac{\sum_{e=1}^{10} S_{Te}}{12}}{\frac{\sum_{e=1}^{5} S_{ge}}{7} + \frac{\sum_{e=1}^{10} S_{Te}}{12}}$$

Where S_{ge} is participants' success at game environment *e* and altered gravity *g*. S_{Te} is the participants' success in the game environment *e* in terrestrial gravity. In other words, cognitive adaptability was measured as the participants' average performance across games in altered gravity relative to their average performance across games in terrestrial gravity. Because the games were different across gravities, we averaged the percentage of successful trials in each gravity separately.

Clustering analysis

To test consistency within each domain and its relation to performance across domains, we took a multivariate approach by examining whether participants could be sorted into groups based on their sensorimotor adaptability (measured by their SMA indices, one for each gravity in the adaptable basketball task—low, mid-low, mid-high, and high), and cognitive adaptability (measured by their CA indices, one for each gravity in the Virtual Tools task—low and high). To that end, we used an unsupervised machine-learning procedure based on k-means clustering.[71–73] With this procedure, the number of clusters is derived from the data, and we made no assumptions about the number of clusters or the number of participants per cluster. More than one cluster of participants would suggest multiple patterns of adaptability and that the adaptability of participants within a cluster is more similar to each other than the adaptability of participants in other clusters.

To calculate the measures used for clustering, we first calculated the four SMAs (for clustering sensorimotor adaptability) and two CAs (for clustering cognitive adaptability) in each gravity and each participant. Using the adaptability indices, we calculated the four-dimensional (in case of sensorimotor adaptability) or two-dimensional (in case of cognitive adaptability) Euclidean "distance" between each pair of participants. If the distance between participants is low, the similarity between them is high, and vice versa.

Next, we ran a k-means clustering algorithm with the adaptability data as input. K-means clustering requires a pre-defined number of clusters. Therefore, we ran the algorithm in multiple iterations with a number of clusters equal to 2 to 25. For each iteration, we calculated the ratio between the average distance within clusters and the average distance across clusters (see Figure S3). The iteration with the maximal ratio determined the number of clusters identified. We visualised similarity among participants using a 25 x 25 similarity matrix in which cell i,j is the "distance" between participant i and participant j based on the input adaptability (either sensorimotor or cognitive).

Our motivation for using clustering analysis was to gain additional insights into the structure of our data beyond correlation analysis. This multivariate approach allowed us to consider multiple dimensions of adaptability simultaneously, potentially revealing patterns that might not be apparent in univariate analyses. Clustering can identify distinct subgroups within the sample with different adaptability profiles across tasks, providing a more in-depth examination of individual differences in adaptability across both domains.

Statistical analysis

Statistical analyses were conducted using SPSS and MATLAB. Prior to performing statistical tests, we checked the data for normality (Shapiro-Wilk test) and homogeneity of variances (Levene's test). In cases involving multiple comparisons, we employed the Sidak correction in post-hoc analyses to control for the family-wise error rate. Adjusted *p*-values are reported, and the significance level was set at $\alpha = 0.05$ for all statistical tests unless otherwise specified. For correlation analyses that involved multiple comparisons, we used the Bonferroni correction to adjust the significance threshold, ensuring that the probability of a Type I error remained controlled across tests.