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Climate-Crisis Landscapes in VR: Effects on Distance and Time Estimation

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Abstract

The Climate Crisis is reshaping not only ecosystems but also human cognition. While its psychological impact is increasingly acknowledged, little is known about how environmental degradation influences basic cognitive functions. Since spatial and temporal cognition provide the perceptual scaffolding for orientation and various decision-making processes, distortions in these dimensions may hinder adaptive responses to ecological change. This study examined whether simulated climate-related degradation affects spatial-temporal cognition and whether interoceptive awareness predicts variability in these effects. Using immersive Virtual Reality combined with an omnidirectional treadmill, participants walked along paths in verdant and arid landscapes and then estimated the duration and distance travelled on each path. The results showed that arid environments led to longer time and distance estimates than verdant ones, although there were no objective differences in path length or actual walking time. Furthermore, temporal judgements, but not spatial ones, were predicted by interoceptive attention regulation: participants with a higher capacity to regulate attention towards bodily sensations consistently provided shorter temporal estimates across all contexts. These findings demonstrate that spatial-temporal representations are sensitive to ecological quality and that interoceptive processes contribute to individual differences in temporal perception. This highlights the value of integrating cognitive processes and interoception into sustainability science, suggesting that environmental preservation supports not only ecological well-being but also the cognitive foundations through which humans perceive and adapt to their surroundings.

Keywords: climate crisis; climate change; environmental degradation; spatial-temporal representation; interoceptive awareness; verdant vs. arid environments; immersive virtual reality; omnidirectional treadmill

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1. Introduction

Climate change is one of the most complex crises of the 21st century, with cascading effects on ecosystems, societies, and public health [1–3]. Ecologically, it drives biodiversity loss, desertification, and glacial melting; socially, it exacerbates inequalities, affecting vulnerable populations; and at the health level, it contributes to rising respiratory, cardiovascular, and psychiatric disorders [4–7]. Beyond this, psychology and psychiatry have documented the mental health consequences of climate change. Climate anxiety, eco-distress, solastalgia,

and trauma responses to environmental disasters are recognized phenomena, particularly among young people and communities directly exposed to ecological instability [8–10]. These affective reactions raise the broader question of whether the same environmental conditions that generate distress may also impact cognitive processes. In particular, it is important to understand whether they may alter how people process space and time, that is, the basic cognitive dimensions through which human experience is organized [11–13].

Theories of embodied and situated cognition provide a framework for this possibility, emphasizing that mental processes emerge from continuous interactions between brain/mind, body, and environment [14,15]. Empirical research supports this view. For example, distances are perceived as longer when more physical effort is required [16,17]. Likewise, people who grow up in visually dense urban environments tend to perceive space by anchoring it closely to its surrounding context [18]. Finally, green natural environments help sustain attention, whereas degraded settings undermine it [19,20]. Within this broad picture, spatial and temporal cognition is particularly relevant. It allows individuals to orient themselves, navigate, plan actions [13,21] and also scaffolds higher-order functions such as autobiographical memory, prospection, and personal identity [12,22–24]. Research has shown that heavy loads make hills appear steeper and distances longer [16,25]. Similarly, targets look farther away when thrown with heavy rather than light balls [17]. In addition, sadness increases slope estimates [26], fear exaggerates perceived heights [27], and high-arousal emotions such as fear or anxiety lengthen perceived durations [28–30]. Taken together, these findings show that spatio-temporal representations are adaptive constructions that integrate ecological, bodily, and emotional information. They regulate action through an economy of effort, that is, by calibrating perception to the anticipated energetic costs of acting [11,31,32]. Consistent with this view, research in spatial cognition and cartography has shown that similar distortions in distance and direction estimation emerge across both real and representational spaces, including maps and virtual environments [33]. Such converging evidence suggests that these biases reflect general mechanisms of spatial encoding rather than task-specific artifacts. Since these representations serve essential adaptive functions, even relatively small and systematic distortions in perceived space and time may have cumulative cognitive consequences. Persistent distortions could affect orientation, effort appraisal, and decision-making, highlighting why studying their modulation under ecological degradation is theoretically and practically relevant [34–38].

Considering that the processing of spatial and temporal information is continuously recalibrated through the interplay of environmental conditions, bodily capacities, and affective states, the disruptions induced by the Climate Crisis are likely to reverberate onto spatio-temporal cognition. Degraded or arid environments may act as perceptual stressors, altering judgments of distance and duration. In addition to the perception of external signals, interoception, or the perception and regulation of internal bodily states [39], may also contribute to understanding these distortions. For example, interoception has been linked to time perception, with greater heartbeat detection accuracy predicting longer interval estimates [40]. More recently, interoceptive awareness has been conceptualized as encompassing attention to bodily sensations, emotion regulation, and bodily self-representation [41]. Although interoception is consistently associated with temporal experience [11,40], its role in spatial estimation remains largely unexplored.

In this study, we used immersive Virtual Reality in combination with an omnidirectional treadmill to recreate ecological qualities and simulate climate-related degradation under controlled conditions [42,43]. Unlike static or controller-based navigation, this setup enables natural locomotion, aligning proprioceptive and visual cues, and thereby enhances the feeling of presence and ecological validity [44–47]. We have reproduced arid and verdant landscapes to simulate some of the immediately visible effects of global warming

on the environment. We investigated whether arid landscapes, compared to verdant ones, influence spatial and temporal representations, and whether individual differences in interoceptive awareness predict the extent of these distortions. Participants walked along paths that were the same size and configuration, with the only difference being that they ran through the two types of environments. Afterwards, they had to provide estimates of the distance travelled and the time taken for each path. Interoceptive awareness was assessed with the Multidimensional Assessment of Interoceptive Awareness (MAIA) [41]. We hypothesized that arid environments would lead to longer distance and time estimates compared to verdant ones, and that higher interoceptive awareness would predict systematic individual differences in the extent of these distortions.

2. Materials and Methods

2.1. Participants

A total of 35 healthy adults (18 females, 17 males; M age = 25.23 years, SD = 2.52, range 23–33) participated in the study. Participants were recruited from the university community through mailing lists and online advertisements. Inclusion criteria required normal or corrected-to-normal vision, no self-reported history of neurological or psychiatric disorders. An a priori power analysis was conducted using GPower 3.1 [48] for repeated-measures ANOVA, with $\alpha = 0.05$, power $(1-\beta) = 0.80$, and an expected medium effect size (Cohen's f = 0.25). The analysis indicated a minimum required sample size of 34. In addition, a sensitivity analysis with the achieved sample ($N = 35$) indicated that, for $\alpha = 0.05$ and power = 0.80, the study could detect within-subject effects of $f = 0.23$, confirming adequate sensitivity for small-to-medium effects.

All participants provided informed consent prior to participation. The experimental procedure and participants' rights were explained orally before the session, after which written consent was obtained, in accordance with the Declaration of Helsinki [49]. The study was approved by the Ethical Committee of the University of Campania, Department of Psychology (num. 14/2025). Participants were informed about the procedure in advance, reminded of their right to withdraw at any time without penalty, and guaranteed anonymity and confidentiality. No financial incentives were provided; participants took part on a voluntary basis.

2.2. Materials

Virtual Environments: Participants experienced four immersive Virtual Environments (VEs) developed with Unity (version 2021.2.20f1; Unity Technologies, San Francisco, CA, USA), presented through HTC Vive Pro 2 HMD (HTC Corporation, Taoyuan City, Taiwan). Two scenarios represented verdant landscapes, and two scenarios represented arid landscapes (as an example, see Figure 1a,b). The environments were matched for structural features (e.g., global configuration, horizon line, environmental elements, size), differing only in ecological qualities (green vs. arid). In the verdant scene, the path was immersed in a dense forest, with tall coniferous trees extending on both sides. The ground texture consisted of green grass. On the horizon, a green mountain with snow-covered peaks was visible. In the arid scene, the environment surrounding the path was an arid landscape, with a ground texture of sandy, cracked soil, dry leafless trees on both sides, and a barren mountain on the horizon. In both scenes, a directional light was used with rotation: x = 50; y = −30; z = 0, hex color FFF4D6, in real-time mode, intensity 1, indirect multiplier 1, render mode = auto, culling mask = everything. Each environment included a short route and a long route that were the same length, had the same configuration and could be travelled in first person. The short paths measured 38 m (mean real walking time ≈ 30 s), while the long paths measured 48 m (mean real walking time ≈ 36.5 s). Path lengths (38 m and 48 m)

were selected based on pilot testing to ensure clear perceptual discrimination while keeping walking durations within a comfortable range for treadmill locomotion. Metric distances were identical across verdant and arid environments by design. For real walking times, independent-samples *t*-tests showed that there were no significant differences between verdant and arid short paths (M = 29.97 s, SD = 9.31 vs. M = 30.43 s, SD = 9.56; $t(33) = 0.35$, $p = 0.73$) nor between verdant and arid long paths (M = 37.24 s, SD = 12.23 vs. M = 35.97 s, SD = 10.88; $t(33) = 0.77$, $p = 0.44$). Thus, any differences in subjective estimates cannot be attributed to actual variations in walking time or different metrics.

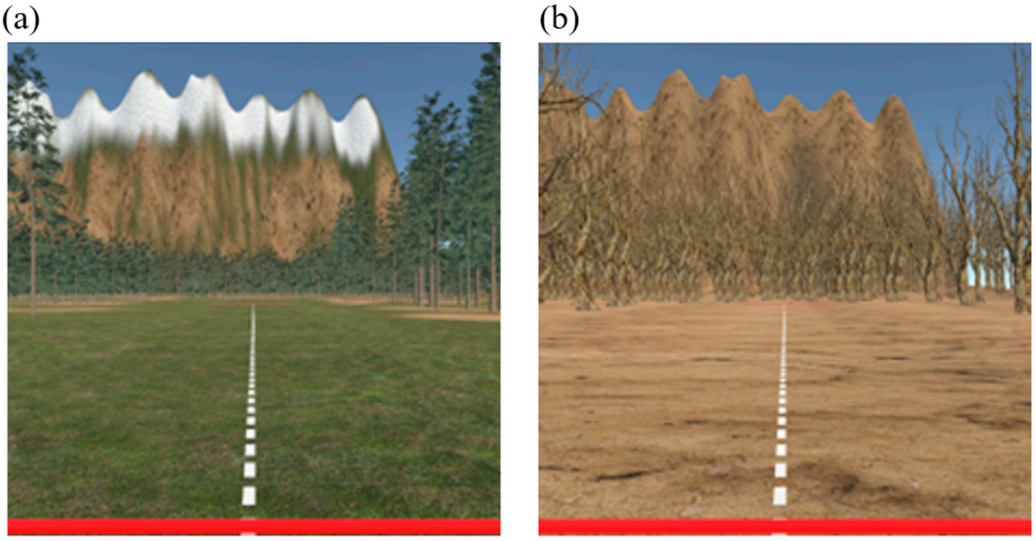


Figure 1. Examples of the immersive Virtual Environments used in the experiment. Panels (**a**,**b**) depict verdant and arid natural landscapes, respectively. Each landscape featured a straight path marked by a red start line, a purple finish line, and a central dotted white line to guide movement. The verdant scenes included green grass, trees, and a snow-capped mountain on the horizon, while the arid scenes included dry ground, bare trees, and a barren mountainous backdrop. Apart from these visual differences, the number and configuration of the simulated elements were the same.

Navigation System: Locomotion in the virtual environments was implemented using an omnidirectional treadmill (Virtuix Omni Pro, Virtuix Inc., Austin, TX, USA), which enabled participants to walk naturally while remaining in place (Figure 2). The use of this system ensured a realistic correspondence between bodily motion and visual flow, providing natural proprioceptive feedback. The simulated trajectory was linear by design, allowing us to preserve ecological realism in locomotion while maintaining a simple and well-controlled navigation task.

Questionnaire: Interoceptive awareness was assessed using the *Multidimensional Assessment of Interoceptive Awareness* (MAIA-1) [41], Italian validation [50], which currently represents the only version with established psychometric validation in Italian. The MAIA is a 32-item self-report instrument comprising eight subscales—Noticing, Not-Distracting, Not-Worrying, Attention Regulation, Emotional Awareness, Self-Regulation, Body Listening, and Trusting. Participants rated each statement on a six-point Likert scale (0 = "never," 5 = "always").



Figure 2. A participant navigates a virtual scenario using an HMD and an omnidirectional treadmill for movement.

2.3. Procedure

The experiment took place in the Laboratory of Cognitive Sciences and Immersive Virtual Reality (CS-IVR) of the University of Campania "L. Vanvitelli" (Caserta, Italy). Upon arrival, participants were welcomed into the laboratory and informed about the study. They signed a written informed consent form in accordance with the Declaration of Helsinki and subsequently completed a computer-based version of the Multidimensional Assessment of Interoceptive Awareness (MAIA) [41] to assess their level of interoception awareness.

After the questionnaires, participants were fitted with motion sensors attached to their shoes and instructed to step onto the omnidirectional treadmill. They were then equipped with a head-mounted display (HMD), which provided access to the immersive virtual environments.

Before exposure to the experimental conditions, participants underwent a training session in a neutral virtual scene. The layout of the training path was identical to the experimental ones, but the surrounding environment was minimal and devoid of ecological cues. During this phase, participants practiced walking straight along the dashed central line until they reached the arrival marker. They were allowed to repeat the training path as many times as they needed to feel comfortable with the treadmill and the VR system.

The experimental phase then began. Each participant experienced four virtual scenes: verdant–short, verdant–long, arid–short, and arid–long. The order of presentation was counterbalanced across participants to control for sequence effects. Each path was traversed twice, and at the end of each traversal, participants provided a distance and a duration judgment, with counterbalanced order (distance first in half the trials, duration first in the other half). Thus, each path yielded two distance and two duration estimates. For each trial, the same sequence of steps was followed:

1. Immediately after immersion, participants were asked to look around and briefly describe the environment in which they found themselves.
2. They were then instructed to walk straight across the entire path, at a self-paced speed, following the dashed line until they reached the arrival marker.
3. Once they crossed the arrival line, the scene was paused, and participants were asked to provide a verbal estimate of either the duration of the walk (in seconds) or the length of the path (in meters), depending on the trial type.

For each condition, the two judgments per variable (time and distance) were subsequently averaged and used for statistical analyses.

At the end of the four scenes, participants removed the equipment, were debriefed and thanked for their participation.

2.4. Data Analysis

We used a within-subjects design, with Environment (Verdant vs. Arid) and Path Length (Short vs. Long) as factors. The dependent variables were the mean distance estimates (meters) and the mean time estimates (seconds), obtained by averaging the two judgments provided for each condition. Preliminary checks showed that skewness values of the dependent variables ranged from 1.10 to 1.65 and kurtosis from 0.67 to 2.05, all within the limits conventionally regarded as acceptable for parametric analyses [51–53]. No extreme outliers (> | 3 *SD* |) were detected, and the assumption of sphericity was satisfied. Therefore, for each dependent variable, a 2 × 2 repeated-measures ANOVA was carried out, testing Environment, Path Length, and their interaction. Where relevant, post hoc pairwise comparisons were conducted with Tukey's adjustment.

Moreover, to assess associations between interoceptive awareness and spatial-temporal judgments, Pearson correlations were computed between the eight MAIA subscales and both distance and time estimates. Correlations were computed for each scene (verdant-short, verdant-long, arid-short, arid-long).

Finally, to examine unique contributions of interoceptive dimensions, we fitted multiple linear regressions with the MAIA subscales as predictors of distance and time estimates (for each scene).

3. Results

3.1. ANOVA

Distance estimation: Results revealed a significant main effect of Environment, $F(1, 34) = 5.64$, $p = 0.023$, $\eta^2_p = 0.14$ (Cohen's $f = 0.40$), with paths in the arid environment estimated as longer ($M = 36.99$, $SE = 4.21$) than those in the verdant environment ($M = 31.05$, $SE = 3.5$). There was also a significant main effect of Path Length, $F(1, 34) = 13.89$, $p < 0.001$, $\eta^2_p = 0.29$ (Cohen's $f = 0.64$), with long paths estimated as longer ($M = 38.55$, $SE = 3.15$) than short ones ($M = 29.49$, $SE = 3.15$). The Environment × Path Length interaction was not significant, $F(1, 34) = 0.11$, $p = 0.743$, $\eta^2_p = 0.003$. See Figure 3.

Time estimation: Results revealed a significant main effect of Environment, $F(1, 34) = 4.46$, $p = 0.042$, $\eta^2_p = 0.12$ (Cohen's $f = 0.37$), with arid paths judged as taking a longer time ($M = 49.13$, $SE = 5.60$) than verdant paths ($M = 42.66$, $SE = 4.65$). There was also a significant main effect of Path Length, $F(1, 34) = 19.19$, $p < 0.001$, $\eta^2_p = 0.36$ (Cohen's $f = 0.75$), with long paths estimated as taking more time ($M = 39.71$, $SE = 4.79$) than short ones ($M = 52.09$, $SE = 5.42$). The Environment × Path Length interaction was not significant, $F(1, 34) = 0.09$, $p = 0.766$, $\eta^2_p = 0.003$. See Figure 4.

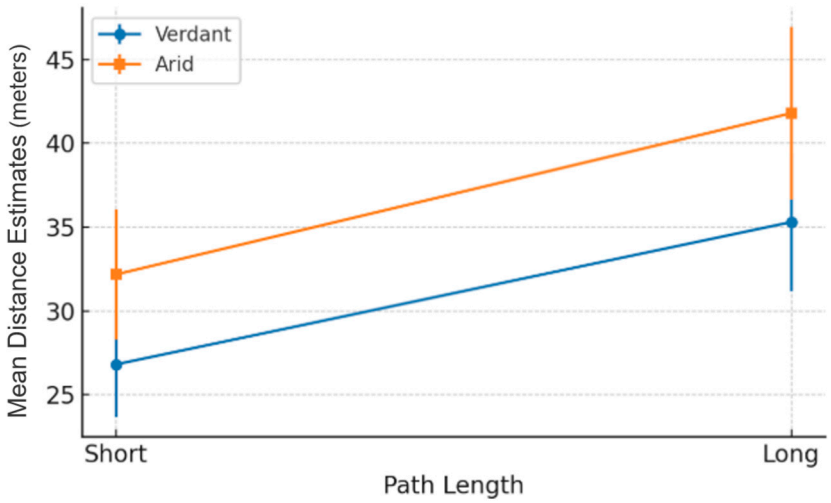


Figure 3. Mean distance estimates (±1 SE) as a function of Path Length (short vs. long) and Environment (verdant vs. arid). Participants judged paths as longer in arid than in verdant environments and in long compared to short paths. Error bars represent standard errors of the mean.

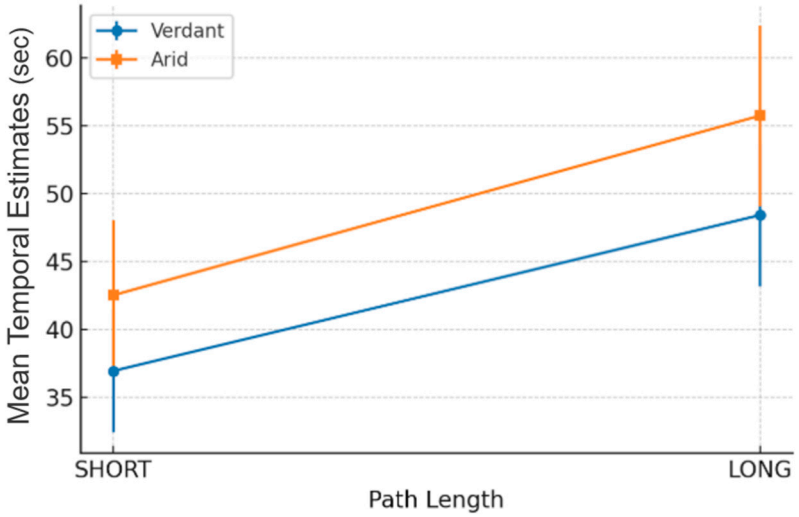


Figure 4. Mean temporal estimates (±1 SE) as a function of Path Length (short vs. long) and Environment (verdant vs. arid). Participants judged durations as longer in arid than in verdant environments and in long compared to short paths. Error bars represent standard errors of the mean.

3.2. Correlations

Distance estimation: No significant correlations emerged between distance estimates and the MAIA subscales (all *p*s > 0.05).

Time estimation: Correlation analyses revealed a consistent association between the Attention Regulation subscale of the MAIA and time estimation across all environmental conditions. This subscale reflects the ability to voluntarily sustain and redirect attention toward bodily sensations, even when distractions are present. Higher scores on this dimension were significantly related to shorter duration judgments on the verdant short ($r = -0.49$, $p = 0.006$, 95%CI [−0.71, −0.19]), verdant long ($r = -0.51$, $p = 0.004$, 95%CI [−0.72, −0.21]), arid short ($r = -0.54$, $p = 0.002$, 95%CI [−0.74, −0.25]), and arid long ($r = -0.52$, $p = 0.003$, 95%CI [−0.73, −0.23]) paths. In other words, participants who reported being better at staying focused on their bodily sensations tended to judge the walks as lasting less. No other MAIA subscale showed significant correlations with time judgments. Effect size interpretation based on Cohen's [54] benchmarks indicated large effects for all significant correlations.

3.3. Multiple Regressions

Verdant short: The overall model was significant, $F(2, 27) = 5.49$, $p = 0.009$, $R^2 = 0.29$. Attention Regulation emerged as a significant negative predictor, $\beta = -0.56$, $t(27) = -3.28$, $p = 0.003$, indicating that higher ability to regulate attention toward bodily sensations predicted shorter time estimates. Not-Worrying did not reach significance ($p = 0.17$).

Verdant long: For the verdant long condition, the regression model was significant, $F(2, 27) = 6.23$, $p = 0.006$, $R^2 = 0.31$. Within this model, Attention Regulation was again a significant negative predictor, $\beta = -0.58$, $t(27) = -3.50$, $p = 0.002$, whereas Not-Worrying was not significant ($p = 0.15$).

Arid short. In the arid short condition, the model including Attention Regulation as a predictor was significant, $F(3, 26) = 4.73$, $p = 0.001$, $R^2 = 0.35$. Attention Regulation negatively predicted time estimates, $\beta = -0.63$, $t(26) = -3.63$, $p = 0.001$, again indicating that participants with higher interoceptive attentional regulation reported shorter durations. Self-regulation and Not-Distracting were not significant (all *p*s > 0.10)

Arid long. Finally, in the arid long condition, the regression model was significant, $F(3, 26) = 5.12$, $p = 0.006$, $R^2 = 0.37$. Attention Regulation was again a significant negative predictor, $\beta = -0.69$, $t(26) = -3.90$, $p = 0.0006$. Other MAIA subscales (Not-Worrying, Self-Regulation) were not significant (all *p*s > 0.10).

For all models, interpretation of the effect sizes following Cohen's [54] conventions indicated large and consistent associations. Table 1 reports the whole results.

Table 1. Multiple regression analyses predicting time estimates from MAIA subscales across experimental conditions.

Condition	Predictor	β	95% CI	T	*p*	R^2
Verdant short	Attention Regulation	−0.56	[−0.91, −0.21]	−3.28	0.003	0.29
	Not-Worrying	0.24		1.41	0.17	
Verdant long	Attention Regulation	−0.58	[−0.92, −0.24]	−3.50	0.00	0.31
	Not-Worrying	0.24		1.46	0.15	
Arid short	Attention Regulation	−0.63	[−0.99, −0.27]	−3.63	0.001	0.35
	Self-Regulation	0.31		1.59	0.12	
	Not-Distracting	0.20		1.11	0.28	
Arid long	Attention Regulation	−0.69	[−1.00, −0.33]	−3.90	0.0006	0.37
	Self-Regulation	0.25		1.47	0.15	
	Not-Worrying	0.22		1.38	0.18	

4. Discussion

This study examined whether an arid landscape, reflecting climate-related environmental degradation, influences spatial-temporal cognition and whether interoceptive awareness contributes to this effect. We compared green landscapes, as an example of an optimal climate environment, with arid landscapes that simulated some of the immediately visible effects of global warming. Using immersive Virtual Reality combined with an omnidirectional treadmill, participants walked through both landscapes and estimated the distance and duration of travelled paths. The results showed that environmental degradation biased spatio-temporal judgments: arid landscapes led to longer estimations of both travelled time and distance compared to verdant ones. These distortions showed that spatial and temporal representations are sensitive to the ecological quality of the environment.

This finding can be interpreted in line with literature on action-based perception, according to which increased energetic costs, such as carrying loads or climbing slopes, make layouts appear longer or steeper [16,24]. In this case, participants did not expend more energy due to different metrics because the distances travelled were the same in both environments but presumably perceived the arid environment as requiring more effort. The effect therefore cannot be reduced to biomechanical load: ecological degradation itself acted as a cue of hardship, operating as a perceptual stressor.

Beyond perceived effort, the affective valence of the environment may also contribute to the observed distortions. Emotional qualities such as threat, beauty, or hope have been shown to systematically influence spatial and temporal perception. Negatively valenced or arousing scenes tend to expand subjective duration and perceived distance, whereas positive or aesthetically pleasing environments often produce the opposite effect [55,56]. Recent studies have demonstrated that emotionally laden environmental cues can modulate how routes and spatial layouts are mentally represented. For example, routes containing negative or threatening landmarks lead to overestimation of distances and slower mental navigation, while positive landmarks enhance positional accuracy and configurational recall [30,57]. From this perspective, the arid landscape used in our study may have implicitly conveyed affective meanings of threat, scarcity, or discomfort, which could have amplified participants' spatial–temporal estimates.

It is important to note that these two interpretations are not mutually exclusive. Indeed, judging paths and durations as longer in hostile settings may serve an adaptive role, discouraging unnecessary effort and biasing individuals toward caution in contexts associated with scarcity of natural resources. This interpretation resonates with affect-as-information theory [31,32], which emphasizes that affective signals act as heuristics for judgment under uncertainty. However, further studies are needed to clarify the origin of the effect.

Another contribution of this study lies in the integration of immersive VR with an omnidirectional treadmill. Unlike controller-based navigation, this setup enables more natural locomotion by aligning proprioceptive and visual cues, thus enhancing presence and ecological validity [47,58]. This movement likely made participants more sensitive to ecological qualities, allowing spatio-temporal effects to emerge more clearly than would have been the case in less immersive virtual scenarios [46,47]. Previous research has shown that distortions in distance estimation in VR often arise from the absence of real locomotion and the limited proprioceptive feedback of controller-based movement [33,59]. By overcoming these constraints, our paradigm suggests that the distortions observed here are unlikely to stem from the virtual medium itself but rather reflect the ecological properties of the environment.

The practical significance of the large effects observed in this study can be considered in light of established benchmarks in psychological research. According to Cohen [54], a "large" effect is one "visible to the naked eye of a careful observer" (p. 25), implying that it produces an observable and functionally relevant change in human behavior or experience. This notion has been refined by Funder and Ozer (2019) [38], who noted that effects explaining approximately 10–20% of variance ($r \approx 0.30$–0.45) "are already consequential for everyday functioning, social interactions, and decision-making" (p. 160). The present effects, accounting for 29–37% of the variance and corresponding to perceptual biases of about 15–20% in estimated distance and duration, may therefore be interpreted as relatively substantial within this empirical framework. As Abelson [36] pointed out, even effects of modest statistical magnitude can have meaningful practical implications when they accumulate across perceptual or behavioral events, a principle referred to as the "variance explanation paradox." In this regard, consistent overestimations of spatial

and temporal magnitude in degraded environments could gradually influence how individuals evaluate effort, plan movement, or respond to environmental challenges. This interpretation is consistent with Cumming's [37] view that practical importance arises not solely from effect size magnitude but also from the consistency and precision of observed patterns—characteristics that were evident across the present analyses. Comparable levels of perceptual distortion have been described as functionally meaningful in the literature on embodied and action-based perception. For example, Proffitt [34] reported that increases in perceived energetic cost, such as carrying a load or walking uphill, tend to produce perceptual overestimations of slope and distance in the range of 10–15%. Likewise, Stefanucci and Geuss [35] found that bodily states can modulate perceived spatial metrics to a similar extent. Within this context, the distortions observed here appear consistent with previously documented embodied effects, suggesting that ecological degradation may influence spatial–temporal perception in measurable and cognitively relevant ways.

Interoceptive awareness added an additional layer of variability. One dimension consistently predicted temporal estimations across contexts: Attention Regulation. Participants who reported a higher ability to focus on bodily signals provided shorter time estimates, both in verdant and arid environments. This pattern was supported by correlational analyses and by multiple regressions, where Attention Regulation emerged as the most consistent predictor of temporal judgments. By contrast, no reliable associations were found between interoceptive dimensions and distance estimations, suggesting that interoception may be more tightly linked to temporal than spatial processing. These findings align with models linking interoception to the subjective flow of time [11,39] and suggest that attentional control over bodily cues may buffer against distortions induced by degraded environments. Functionally, this means that individuals with higher interoceptive attention regulation produced lower temporal overestimations across both verdant and arid environments, indicating that this dimension reflects an individual trait operating independently of contextual conditions.

Taken together, these results support the view that cognition is recalibrated by environmental affordances, bodily states and affective signals. The distortions observed in arid landscapes exemplify how perception adapts to context: by amplifying costs in arid environments, it biases behavior toward caution and conservation. In this sense, spatio-temporal cognition can be seen as a regulatory system, where distortions serve functional purposes rather than reflecting error [60,61].

Beyond theory, these results speak to the Climate Crisis as a psychological and cognitive challenge. If degraded environments alter estimations of time and space, climate change jeopardizes not only ecosystems and mental health but also what may be termed cognitive sustainability: the capacity to maintain adaptive cognitive functions under unstable or deteriorating conditions [62,63]. The present findings provide empirical evidence on the impact of climate change on cognitive functions, showing that ecological degradation affects the spatio-temporal scaffolding that supports, among others, orientation, planning, and episodic future thinking. Implications extend to both prevention and intervention. Preserving and restoring natural landscapes may stabilize not only emotional well-being but also the cognitive clarity needed for decision-making. Cultivating interoceptive awareness, through practices such as mindfulness or body-based therapies, may help individuals resist perceptual distortions in degraded settings, reinforcing resilience at the bodily–cognitive interface [64,65]. Virtual Reality also emerges as a translational platform: it enables systematic investigation of how environmental qualities shape cognition and offers opportunities for training adaptive skills in safe simulations.

These conclusions must be tempered by limitations. First, the sample was culturally homogeneous, restricting generalizability. Cultural and linguistic factors might also

have a role. For example, our Western European participants could be less accustomed to navigating or estimating distances in open landscapes. In addition, linguistic systems encode spatial references differently across cultures, some preferring egocentric ("left–right") and others absolute ("north–south") coordinates, leading to distinct ways of representing space [66,67]. In addition, individuals from Western cultures tend to focus more on salient objects, whereas those from East Asian cultures pay greater attention to spatial context and background relations [68]. Second, interoceptive awareness was assessed through self-report (MAIA) rather than physiological indices, and the VR scenarios, while immersive, lacked multisensory realism (e.g., heat, dryness, smell) that may intensify real-world effects. Emotional reactions to environments were not measured independently. Future research should integrate objective physiological measures, assess emotional reactions, and employ multisensory or mixed-reality simulations. Third, although a within-subjects design was adopted and a sensitivity analysis confirmed that the achieved sample (N = 35) provided adequate statistical power, the overall sample size could be enlarged. Studies using virtual environments typically show differences in presence, simulator adaptation, and susceptibility to motion-related discomfort [69,70]. Consequently, larger samples would help capture this variability more accurately and enhance the generalizability of the findings. Fourth, the visual fidelity of virtual environments could have limited ecological realism. Future studies employing higher-fidelity or photorealistic scenes could evaluate whether visual realism affects the magnitude of the observed distortions.

In sum, recruiting culturally diverse and larger samples and adopting longitudinal designs would help clarify how exposure to environmental degradation reshapes spatio-temporal cognition and whether interoceptive training can mitigate such effects.

Future work could also explore the translational potential of immersive VR. Recent studies have shown that VR-based biofeedback and mindfulness protocols can successfully enhance interoceptive awareness and self-regulation in both clinical and non-clinical populations [71–73]. Parallel research demonstrates that climate-themed VR experiences foster environmental engagement and pro-environmental behavior [74–76]. Building on these findings, the present paradigm could be adapted to develop embodied VR micro-trainings that combine locomotion, interoceptive monitoring, and ecological context. Such interventions may help evaluate whether strengthening interoceptive skills reduces spatio-temporal distortions and supports cognitive sustainability under environmental change. Furthermore, the use of an omnidirectional treadmill provides promising opportunities for future research. This setup enables the simulation of more complex and naturalistic navigation patterns, including curved and multi-directional trajectories, while preserving precise control over sensory contingencies. Such extensions could help examine how ecological degradation affects real-time spatial updating, route planning, and embodied navigation across different path lengths, thereby further enhancing the ecological validity and scalability of this line of research.

5. Conclusions

This study provides experimental evidence that climate-degraded environments bias spatio-temporal representations and identifies interoceptive attention regulation as a consistent predictor of temporal judgments. Simulated climate degradation inflated estimations of time and distance, and individual variability in temporal distortions was systematically related to interoceptive attention regulation. These findings suggest that climate change reshapes not only how people feel about the world but also how they perceive and represent it. The emerging notion of cognitive sustainability points to a promising approach: one in which the resilience of cognitive functions themselves is recognized as a critical dimension to be safeguarded in the Anthropocene.

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Abbreviations

The following abbreviations are used in this manuscript:

VEs	Virtual Environments
HMD	Head-mounted display
VR	Virtual Reality
MAIA	Multidimensional Assessment of Interoceptive Awareness

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