Body into narrative: Behavioral and neurophysiological signatures of action text processing after ecological motor training

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Abstract

Embodied cognition research indicates that sensorimotor training can influence action concept processing. Yet, most studies employ isolated (pseudo)randomized stimuli and require repetitive single-effector responses, thus lacking ecological validity. Moreover, the neural signatures of these effects remain poorly understood. Here, we examined whether immersive bodily training can modulate behavioral and functional connectivity correlates of action-verb processing in naturalistic narratives. The study involved three phases. First, in the Pre-training phase, 32 healthy persons listened to an action text (rich in movement descriptions) and a non-action text (focused on its characters' perceptual and mental processes), completed comprehension questionnaires, and underwent resting-state EEG recordings. Second, in the four-day Training phase, half the participants completed an exergaming intervention (eliciting full-body movements for 60 minutes a day) while the remaining half played static videogames (requiring no bodily engagement other than button presses). Finally, in the Post-training phase, all participants repeated the Pre-training protocol with different action and non-action texts and a new EEG session. We found that exergaming selectively reduced action-verb outcomes and fronto-posterior functional connectivity in the motor-sensitive ~10-20 Hz range, both patterns being positively correlated. Conversely, static videogame playing yielded no specific effect on any linguistic category and did not modulate functional connectivity. Together, these findings suggest that action-verb processing and key neural correlates can be focally modulated by full-body motor training in a highly ecological setting. Our study illuminates the role of situated experience and sensorimotor circuits in action-concept processing, addressing calls for naturalistic insights on language embodiment.

Keywords: Embodied cognition, action concepts, exergaming, naturalistic texts, functional connectivity.

Introduction

Emerging findings suggest that action concept processing may be influenced by sensorimotor training (Yang, 2014). However, no study has combined naturalistic texts with real-life physical activity and relevant neural measures, creating a gap between embodiment research and ecological approaches to neurocognition. To tackle the issue, we investigated behavioral and functional connectivity (FC) signatures of action text (AT) and non-action text (nAT) processing before and after (i) an exergaming intervention and (ii) a static gaming intervention.

In healthy persons, processing of action concepts (linguistic units denoting physical movements) distinctly hinges on motor brain mechanisms (Pulvermüller, 2018, García et al., 2019, Birba et al., 2021, Moguilner et al., 2021a, b) and proves sensitive to individual bodily experience (Yang, 2014, Bidet-Ildei et al., 2017, Beauprez et al., 2020). For example, professional athletes outperform novices in processing sport-specific (as opposed to general) action sentences (Beilock et al., 2008), especially when motorically feasible movements are described (Tomasino et al., 2012, 2013). Similarly, sentence-picture congruency judgments are facilitated upon three weeks of complex manual action training (Locatelli et al., 2012). Yet, opposite effects have been documented following shorter motor stimulation periods. For instance, upon 20 minutes of displacing objects toward or away from one's body, semantic decisions on directionally congruent sentences become significantly slower (Glenberg et al., 2008). Compatibly, short-lived up-regulation of the primary motor cortex selectively reduces action-verb outcomes during lexical decision (Gijssels et al., 2018). Thus, action concept processing can be distinctly modulated by changes induced in the sensorimotor system, with briefer engagement periods seemingly involving interference effects. Yet, this evidence fails to tackle two outstanding questions for embodied language models: do similar effects emerge under ecologically valid conditions, involving naturalistic texts and real-life bodily activities? And, if so, what are their underlying neural mechanisms?

As regards the first question, emerging research shows that the motor system critically supports comprehension of actions described in naturalistic ATs, relative to nATs (Garcia et al., 2018, Birba et al., 2020a, 2020b, Birba et al., 2021, Moguilner et al., 2021b). Evidence from dyslexic children shows that a sustained exergaming protocol (playing full-body-immersion videogames over nine days, 90 minutes a day) selectively enhanced comprehension of AT verbs relative to nAT verbs and circumstantial information, there being no effects for static videogames (Trevisan et al., 2017). Yet, shorter modulations of the sensorimotor system may trigger opposite results, especially in neurotypicals. Indeed, hyper-excitation of the primary motor cortex via direct current stimulation selectively reduces comprehension of AT verbs –again, relative to nAT verbs and circumstantial information (Birba et al., 2020). Potentially, then, a short exergaming protocol in healthy persons may also selectively interfere with AT verb processing, as previously observed for action sentences following short-term manual training (Glenberg et al., 2008).

Concerning the second question, indirect evidence points to potential neural underpinnings of such effects. Motor training may either boost (Tan et al., 2016) or decrease (Di et al., 2012, Wang et al., 2016) FC between fronto-parietal regions subserving sensorimotor functions. Importantly, lower fronto-parietal connectivity has been associated to reduced AT verb outcomes (Moguilner et al., 2021b), highlighting the relevance of brain coupling measures to establish signatures of the domain. A critical metric is afforded by EEG-derived FC, a method that captures (de)coupling patterns across relevant oscillatory networks (Palva and Palva, 2012). Crucially, these include frontal and fronto-posterior FC modulations in low frequency bands (below 20 Hz) sensitive to motor activity/training (Orgs et al., 2008, Denis et al., 2017) as well as naturalistic AT reading (Birba et al., 2020a) and AT verb comprehension (Birba et al., 2021). Accordingly, the impact of bodily training on AT verb outcomes might be mediated by specific fronto-posterior FC patterns below 20 Hz.

Against this background, we investigated whether short-term bodily training modulates behavioral and neural signatures of AT and nAT processing. We quantified comprehension of action, non-action, and circumstantial information before and after a four-day exergaming protocol and evaluated associated EEG-derived FC patterns with the weighted symbolic mutual information (wSMI) metric (shown to capture non-linear information sharing associated with action concept processing) (Melloni et al., 2015, Birba et al., 2020a, Birba et al., 2021). To test for specificity, as a control condition, we replicated the experiment with a second group of participants who played static videogames (requiring no full body movement).

We raised three hypotheses. First, we predicted that exergaming would selectively affect AT verb outcomes. Second, we anticipated that no such effects would be observed in the non-motor videogame group. Third, we hypothesized that exergaming would modulate fronto-posterior FC in the ~10-20 Hz range. Finally, we predicted that AT verb outcomes following exergaming would correlate with training-induced FC changes. With this design, we aimed to bridge the gap between embodied and ecological neurolinguistic models.

Materials and Methods

We report how we determined our sample size, all data exclusions (if any), all inclusion/exclusion criteria, whether inclusion/exclusion criteria were established prior to data analysis, all manipulations, and all measures in the study.

Participants

The study comprised 38 healthy Spanish speakers (27 female) complying with the following inclusion criteria: (i) no history of psychiatric or neurological disease, (ii) normal or corrected-to-normal vision and hearing, (iii) minimal exposure to videogames at large (less than three hours per week), (iv) null exposure to exergames in the last three months, (v) low levels of physical activity (less than three hours of regular exercising per week in the last three months, upon exclusion of high-level athletes and persons with high exposure to sports practice in childhood and adolescence), and (vi) commitment not to play videogames at home or doing extra physical activity during the course of the study. Participants were randomly allocated to the exergaming (EG) group and the static gaming (SG) group. Upon exclusion of six subjects due to extremely low performance in the naturalistic text task (≤ 30% accuracy on any condition from any text before the gaming protocol), the final sample comprised 16 participants in the EG group and 16 in the SG group. All these participants completed the full protocol. Both samples were matched for sex, age, years of education, handedness, physical activity profile, vocabulary knowledge, and working memory skills (Table 1). A power estimation analysis showed that this sample size conferred sufficient statistical power to reach reliable effects (see Supplementary material 1). All participants read and signed an informed consent form in accordance with the Declaration of Helsinki. The study was approved by institutional ethics committee.

Table 1. Participants' demographic, physical, and cognitive profile.

	EG group	**SG group**	**EG group vs. SG group**	
	n = 16	*n* = 16	*p*-value[a]	Cohen's *d*
Demographic data				
Sex (F:M)	9:7	13:3	.25	-----
Handedness (R:L)[b]	12:4	13:3	1	-----
Years of age	22.06 (2.87)	23.69 (3.77)	.18	.49
Years of education	14.75 (3.02)	16.13 (3.56)	.25	.42
Physical activity profile				
Physical activity load at present	1.03 (1.44)	.97 (1.6)	.91	.49
Sports practice load in childhood and adolescence	3.47 (2.06)	4.3 (3.43)	.42	.29
Years of sports practice in childhood and adolescence	5.25 (3.84)	5.8 (4.26)	.71	.12
Cognitive profile				
Vocabulary knowledge[c]	151.5 (12.3)	150.9 (18.3)	.91	.04
Working memory skills[d]	36.6 (2.26)	36.13 (2.36)	.57	.2

Data presented as mean (*SD*), except for sex and handedness. a. Based on unpaired two-tailed *t*-tests (except for sex and handedness), based on a chi-squared test); b. Based on a Spanish version of Edinburgh Handedness Inventory (Oldfield, 1971, Bryden, 1977); c. Based on the Peabody Picture Vocabulary Test III (Dunn and Dunn, 1997); d. Based on a Spanish version (Rodrigo et al., 2014) of Siegel and Ryan's sentence-based working memory test (Siegel and Ryan, 1989). EG: exergaming; SG: static gaming.

Main condition: Exergaming group

Our main condition involved all 16 participants from the EG group. The protocol comprised three phases over a six-day period: a pre-training (Pre-T) phase, a training (T) phase, and a post-training (Post-T) phase (Figure 1). In the Pre-T phase (day 1), participants completed a naturalistic text task alongside sociodemographic and neuropsychological measures. The T phase (days 2 to 5) consisted of four sessions (one per day, in consecutive days) of motor training via exergames. Finally, in the Post-T phase (day 6), participants performed a new run of the naturalistic text task with materials different from those of the Pre-T phase.

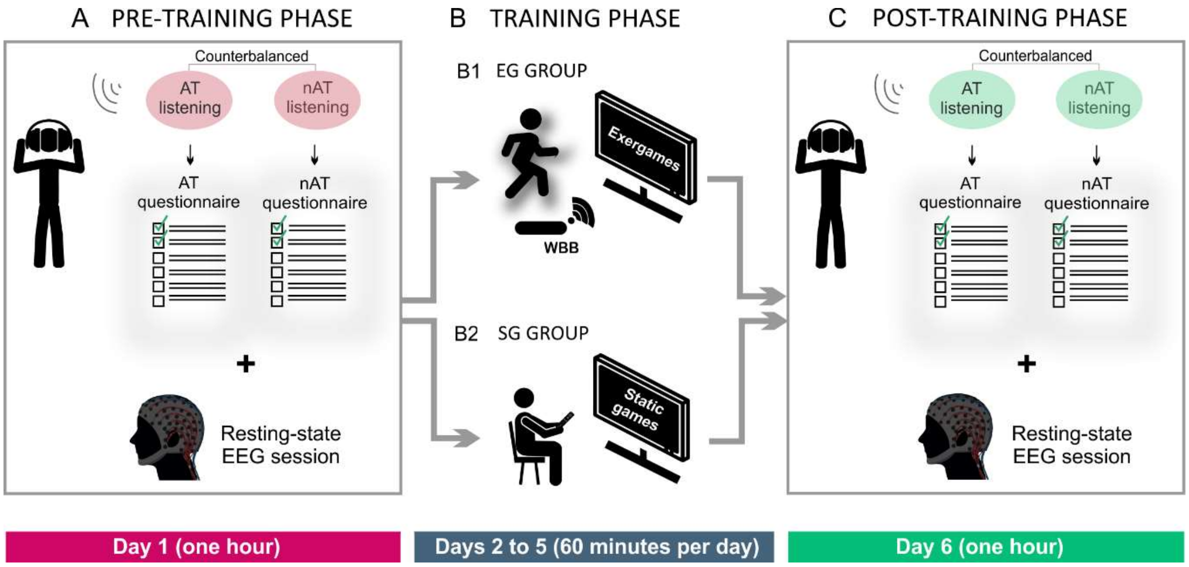

Figure 1. Study design. **(A)** Pre-training phase: on day 1, subjects first listened to an action text and a non-action text, and answered their corresponding multiple-choice questionnaires (read by the experimenter) after each recording. Then, they sat with eyes closed while EEG activity was recorded at rest. **(B)** Training phase: from days 2 to 5, subjects completed the videogame intervention using the Nintendo® console. **(B1)** Subjects in the EG group performed an exergaming protocol based on Wii Fit Plus software. Multiple bodily movements were required and captured via a Wiimote and a nunchuck while standing on a balance board. **(B2)** Subjects in the SG group played videogames that required minimal body movements, based on Wii Party software, totally controlled via button presses on the wiimote. **(C)** Post-training phase: on day 6, subjects first listened to a different pair of action and non-action texts, and answered their respective multiple-choice questionnaires after each recording. Then they completed the same resting-state EEG protocol administered on day 1. EG: exergaming; SG: static gaming.

Pre-training phase

Naturalistic text task

Narratives. The study involved four short narratives (two ATs, two nATs). These were composed through a validated procedure (Trevisan and García, 2019) capturing embodied effects in diverse settings (Garcia et al., 2018, Birba et al., 2020b, Birba et al., 2021, Moguilner et al., 2021b), including longitudinal (i.e., post vs. pre training) exergaming research (Trevisan et al., 2017). The ATs described multiple bodily movements of their characters, including physical interactions with people and objects (e.g., *Peter took his* *brother's hand and both ran towards the sea*). Conversely, the nATs focused on non-motoric events, such as the characters' feelings, thoughts, and perceptions (e.g., *Albert heard his favorite song and felt uplifted*). Each narrative abounded in details regarding the story's location, elements, and other setting details (collectively termed 'circumstances' in the present paradigm). The full texts and their approximate English translations are transcribed in Supplementary material 2.

All four narratives were built on the same set of 22 grammatical patterns, pseudo-randomly sequenced for each text and filled with strategic lexical items. Each text contained critical verbs manifesting the action versus non-action contrast, following semantic, syntactic, and distributional criteria (Halliday & Matthiessen, 2014). The texts were matched for (i) character count; (ii) and content-word-type counts; (iii) mean content-word frequency, familiarity, syllabic length, number of letters, and imageability; (iv) sentence and sentence-type counts; (v) reading difficulty; (vi) readability ratings; (vii) overall emotional content; and (viii) arousal level. Furthermore, the specific verbs targeted by each verb-related question in the questionnaires were matched for frequency, familiarity, syllabic length, number of letters, and imageability. See Table 2 for statistical details.

The texts were audio-recorded by a male native speaker of *rioplatense* Spanish, the participants' native dialect. A smooth narration pace was used in all cases. The files were recorded in .mp3 format with stereo output, and each of them lasted roughly 100 sec (all audio files and their scripts are available upon request). Analyses performed with Neuro-Speech (Orozco-Arroyave et al., 2018) confirmed that the four narratives did not differ significantly in terms of voiced segments, silence segments, average fundamental frequency, and average energy (Table 2).

Table 2. Linguistic features of the texts.

	AT 1	AT 2	nAT 1	nAT 2	*p*-values
Characters	941	908	976	934	.47[#]
Words	207	203	204	199	.98[#]
Nouns	48	48	44	43	.93[#]
Adjectives	7	8	9	10	.90[#]
Adverbs	6	8	8	8	.94[#]
Verbs	32	32	32	32	1[#]
Action verbs	24	28	1	2	$X^2 = 9.94$, $p < .001$. Tukey's HSD tests showed that each NT differed from both ATs (ps < .001), with no differences between NTs or ATs (all ps > .58)
Non-action verbs	8	4	31	30	
Content word frequency	1.64 (.08)	1.67 (.08)	1.79 (.08)	1.79 (.08)	.38*
Content word familiarity	6.17 (.08)	6.00 (.09)	6.28 (.08)	6.23 (.09)	.11*
Content word syllabic length	2.50 (.08)	2.50 (.09)	2.44 (.09)	2.52 (.09)	.88*
Content word imageability	5.17 (.16)	5.27 (.17)	4.96 (.16)	4.89 (.17)	.33*
Target verb frequency	1.08 (0.16)	1.48 (0.17)	1.10 (0.18)	1.43 (0.17)	.22*
Target verb familiarity	5.61 (0.36)	6.20 (0.28)	6.23 (0.34)	6.09 (0.30)	.58*
Target verb syllabic length	2.63 (0.19)	2.4 (0.18)	2.88 (0.19)	2.66 (0.17)	.35*
Mean target verb imageability	6.45 (0.42)	6.70 (0.44)	7.55 (0.46)	6.55 (0.46)	.31*
Complex sentences	7	7	8	8	.99[#]
Comprehensibility	4.5 (.20)	4.10 (.19)	4.38 (.19)	4.18 (.19)	.44*
Coherence	4.0 (.22)	3.52 (.21)	4.00 (.21)	3.73 (.21)	.32*
Grammatical Correctness	4.45 (.18)	4.14 (.17)	4.24 (.17)	4.36 (.17)	.28*
Reading difficulty[a]	79.38	79.93	77.9	75.09	.98
Readability[b]	Fairly Easy	Fairly easy	Fairly Easy	Fairly easy	-
Emotional valence[c] (main effect of text)	33.38 (1.40)	33.54 (1.40)	33.33 (1.40)	33.23 (1.40)	.99*
Arousal[d] (main effect of text)	2.02 (.12)	2.40 (.12)	2.14 (.12)	2.44 (.12)	*F* (240,3) = 2.82, $p = .04$. Tukey's HSD test (MSE = .43 $df = 240$) showed no differences among texts (all ps > .05)
Number of voiced segments	184	202	177	228	0.21[#]
Number of silence segments	61	61	60	64	0.23[#]
Fundamental frequency (Hz)	115.05 (27.24)	111.6 (27.09)	112.6 (26.1)	115.83 (26.36)	0.3871*

Energy (dB)	10.29 (12.29)	11.61 (13.48)	9.5 (12.02)	10.03 (12.19)	0.3893*

a. Measured through the Szigriszt-Pazos Index; b. Measured through the Inflesz scale; c. Overall emotional content was established by 31 Spanish-speaking readers who rated each sentence in each text as positive, neutral, or negative; d. Arousal level was established by the same panel of raters as the intensity of the chosen emotion on a scale from 1 (null arousal) to 7 (high arousal). The hashtag (#) denotes *p*-values calculated with chi-squared test. The asterisk (*) denotes *p*-values calculated with independent measures ANOVA, considering text as a factor.

Questionnaires. Each text was accompanied with a 20-item multiple-choice questionnaire, previously used with healthy adults (Birba et al., 2020b). In each questionnaire, 10 questions referred to verb-related information while the other 10 pointed to circumstantial (locative, causal, temporal or modal) information, realized by adverbial or prepositional phrases. All verb-related questions in the AT questionnaires referred to action verbs, and those in the nAT questionnaires pointed to non-action verbs. Questions were presented following the sequence of the corresponding events in the texts, alternating between verb-related and circumstantial items. Five answer options accompanied each question: one correct option, three subtly incorrect options, and an ‘I don't remember’ option. Sequencing of the options was randomized, except for the ‘I don't remember’ option, which always appeared last. Correct responses were given one point. Incorrect answers and the ‘I don't remember’ option were given zero points. Therefore, each questionnaire had a maximum score of 20 points (10 for verb-related questions and 10 for circumstantial questions).

Procedure

The assessment was carried out in a noiseless, dimly lit room. First, participants were informed about the study’s protocol and materials. They were then asked to listen attentively to each text (AT, nAT) with their eyes closed. The recordings were presented through professional, high-definition headphones (Sony MDR-XB950B1). At the end of each recording, an experimenter (the same for all participants) read each questionnaire item and its corresponding options. No time limit was established for participants to choose their option, and they could ask for one repetition (items for which more than one repetition was requested obtained zero points). The examiner marked the selected option on a scoring sheet. After a short break, this procedure was repeated with the next audio. The AT and the nAT were counterbalanced across participants considering which text of each type was used and the order in which they were presented.

Training phase

All training sessions were conducted in a separate customized room under supervision of an examiner. Participants were invited to play energetically, aiming to achieve the highest scores possible. Each session totaled 60 minutes of actual exergaming, with an optional ten-minute break after the first half. Participants played all games on their feet, standing at about 2 meters from a 50-inch ultra HD smart TV. Game audio was delivered through wireless professional headphones (Sony MDR-XB950B1). We used the Nintendo Wii Fit Plus gaming software, used to modulate sensorimotor-system activity in neuro-rehabilitation (Goble et al., 2014), sport rehabilitation (Baltaci et al., 2013), and training of healthy elderly persons (Toulotte et al., 2012). The system involves two haptic sensor-based manual controllers (Wiimote and Nanchuck) and a force platform (Wii balance board, WBB).

The exergaming protocol encompassed 14 games from Wii Fit Plus, chosen by a physiotherapist to maximize neuromuscular engagement through a combination of mobility, coordination, and balance demands. All games required moving an avatar that reflects the participant's three-dimensional movements, via accelerations of the controllers and displacement of the center or pressure over the WBB. The games were classified into three categories, namely: aerobic games (e.g., 'Obstacle Course,' which involves running, jumping, and dodging obstacles), high-precision balance games (e.g., 'Table Tilt Plus,' which requires shifting the body weight to tilt a moving platform and insert balls into holes), and fast-reaction games (e.g., 'Snowball Fight,' which involves quick movements for throwing snowballs while avoiding incoming ones). Two games from Wii Party software, taxing oculo-manual coordination skills, were added to complement the motor training.

We created four game sets of five different games each, aiming for maximal within-session variability and between-session homogeneity (see videogame list in Supplementary material 3). A different game set was administered randomly in each of the four sessions.

Each game was played for 10 minutes and then the participant could choose which game to replay in order to complete the 60 minutes of training.

Post-training phase

The post-T phase consisted in the very same naturalistic text protocol used in the pre-T phase, except that the texts employed here were those not employed in the pre-T phase. The order of the texts in this phase was counterbalanced across participants.

Control condition: Static gaming group

To assess whether potential effects in the EG group were due to video-gaming at large, as opposed to exergaming in particular, we included a control condition involving all 16 participants from the SG group. The protocol was identical to that of the main condition, except that the games used during the T phase were characterized by a low degree of dynamic bodily engagement.

Specifically, we selected 16 games from the Wii Party software that induced amusement while minimizing movement demands (Supplementary material 3). All of them were played using only the Wiimote. Three games involved mental prediction tasks (e.g., in ‘Walk-off,’ the player keeps a button pressed to keep an avatar running, at a given speed, and must release it when she estimates a predefined distance has been reached). In five games, the player had to aim at the target (the avatar or an object) with the Wiimote’s infrared sensor in order to select it or move it (e.g., in ‘Garden Gridlock,’ the player must place the avatar on the right point of a maze to reach the goal). In the other eight games, the player had to control a character by pressing buttons (e.g., in ‘Zombie Tag,’ correct button presses are required to elude zombies). All these games were played in sitting position. Most of them required solely two-finger movements to press buttons, and some required aiming the Wiimote at the screen to select an option. None of the games required movements of the arms, legs, trunk or head.

Behavioral data analysis

Following a previous report of this paradigm (Trevisan et al., 2017), questionnaire scores from each condition (main condition: EG group; control condition: SG group) were analyzed with a 2x2x2 factorial ANOVA including the factors Text type (AT, nAT), Information type (verb-related, circumstantial), and Time point (Pre-T, Post-T). Given our moderate sample sizes and the highly specific nature of our hypotheses (i.e., selective Post-T modulations for AT verbs but not for nAT verbs or circumstances from either text), significant main and interaction effects were further analyzed via planned pairwise comparisons through paired two-tailed *t*-tests. Effect sizes were calculated through partial eta square (η_p^2) for ANOVA results and Cohen's *d* for pairwise comparisons (Cohen, 1988). All analyses were performed on R 4.0.3.

EEG data acquisition and preprocessing

Resting-state EEG data were recorded for 10 consecutive minutes while participants sat comfortably on a reclining chair in a Faraday cage with a Biosemi Active Two 64-channel system (Amsterdam, NLD). Participants were instructed to keep their eyes closed and to think about nothing in particular (Dottori et al., 2017, Birba et al., 2021b). Signals were originally sampled at 1024 Hz and then down-sampled to 512 Hz. During recording, the reference was set as default to link mastoids and re-referenced offline to the average of all electrodes. Signals were band-pass filtered offline between 0.1 and 100 Hz. We also applied a digital bandpass filter between 0.5 and 40 Hz offline to remove unwanted frequency components. Bad channels were replaced via means of the statistically weighted spherical interpolation (based on neighboring sensors) method (Courellis et al., 2016). Clean resting-state recordings were then segmented into 4-second trials (Amoruso et al., 2022). A two-tailed paired *t*-test showed that the number of trials for the EG group did not significantly differ [$t(14) = -0.82$, $p = .43$] between Post-T (mean = 248.67, *SD* = 41.06) and Pre-T (mean = 256.73, *SD* = 21.97) sessions. The same analysis revealed non-significant differences in the SG group [$t(15) = -0.89$, $p = .39$] between the Post-T (mean = 235.75, *SD* = 22.57) and Pre-T (mean = 243.44, *SD* = 22.68) sessions. Preprocessing was performed with the EEGLAB toolbox (Delorme and Makeig, 2004) and custom-made scripts.

EEG resting-state functional connectivity analysis

EEG resting-state FC analyses were performed for the EG and SG groups separately (one participant from the EG group was excluded as he lacked EEG recordings in the Pre-T phase). We employed the weighted Symbolic Mutual Information (wSMI) metric (King et al., 2013), which proves robust against artefactual coupling and has been used to examine specific lexico-semantic categories in different tasks (Hesse et al., 2019, García et al., 2020), including AT processing (Birba et al., 2020a, Birba et al., 2021). This metric quantifies the amount of information shared by two signals over a given time interval (King et al., 2013). First, the signals are reduced into a set of discrete symbols, defined by a number of points ($k = 3$), separated by a fixed temporal interval τ. This τ determines the frequency bands for which the index becomes most sensitive. Here, we focused on $\tau = 16$ ms, sensitized for the motor-sensitive ~10-20 Hz range. Mutual information coefficients were obtained based on the entropies of each transformed signal and their joint entropy. Finally, binary weights are applied to discard pairs of symbols likely arising from common source artifacts (e.g., blink artifacts or volume conduction).

Cluster-based permutation statistics (Maris and Oostenveld, 2007) were performed on the wSMI topographical metrics (Perez et al., 2021) to test for potential training-induced FC changes in each group separately. Specifically, we ran a permutation test on the wSMI coefficient matrices obtained for each subject in each experimental condition (i.e., Pre-T vs. Post-T), to obtain clusters of connections based on neighboring criteria (measured through Euclidean distance). Two connections were considered neighbors if both electrodes in one connection were neighbors of the electrodes in the other connection. For each cluster obtained in a given permutation, we quantified its size as the number of intervening connections. The largest cluster size was used as cluster-level statistic in each permutation. As in previous works on AT processing (Birba et al., 2020a), we estimated the *p*-value of each cluster ($p_{cluster}$) in the actually observed data (i.e., before the permutation test was performed) as the proportion of 2,000 random permutations of the wSMI matrices that yielded a cluster-level statistic greater than the size of the given cluster. To identify connections with significant differences between conditions, we ran two-tailed *t*--tests at $p_{connection} < .05$. Only those who surpassed this test would be considered part of clusters. Finally, clusters with $p_{cluster} < .05$ were deemed significant. This method circumvents the multiple comparisons problem, as $p_{cluster}$ thus obtained do not need to be corrected in further steps.

Brain-behavior correlations

Given the normal distribution of the data we used Pearson correlations to explore potential associations between resting-state FC and behavior. We calculated mean connectivity wSMI values for each participant across the electrodes encompassed in any significant cluster upon subtracting the Post-T and Pre-T sessions, and masked activity within those electrodes in each session separately. Mean connectivity values for each participant within the cluster were correlated with an action-verb index. As in previous work (Birba et al., 2020b), we calculated, for each participant, AT scores in each category adjusted for the corresponding nAT scores (namely, AT verbs minus nAT verbs, and AT circumstances minus nAT circumstances). To further reduced data dimensionality we adjusted performance by text type and category (namely, adjusted AT verbs minus adjusted nAT circumstances). This yielded one action-verb index value per participant, adjusted for all relevant factors in the naturalistic text task.

Data and code availability

All experimental data, as well as the scripts used for their collection and analysis, are fully available online at: https://bit.ly/3zMIBBS

Results

Main condition: Exergaming group

Results from the EG group revealed that all main effects and double interactions were not significant (all *p*-values > .09). Critically, however, a significant triple interaction emerged among Text type, Information type, and Time point [$F(1,105) = 4.81$, $p = .03$, $\eta_p^2 = .04$]. Post-hoc comparisons revealed that AT verb outcomes were significantly lower in the Post-T than in the Pre-T phase ($t = -2.8$, $p = .01$, $d = .71$), there being no significant differences between phases in any other condition (nAT verbs: $t = 1.8$, $p = .10$, $d = .44$; AT circumstances: $t = 1.5$, $p = .17$, $d = .36$; nAT circumstances: $t = .5$, $p = .64$, $d = .12$). Also, whereas all four conditions yielded similar scores in the Pre-T phase (all *p*-values > .20), Post-T scores for AT verbs were significantly lower than those of AT circumstances (*t* = 2.7, *p* = .02, *d* = .68) and marginally lower than those of nAT verbs (*t* = -2.1, *p* = .05, *d* = .53). For full results, see Supplementary material 4.

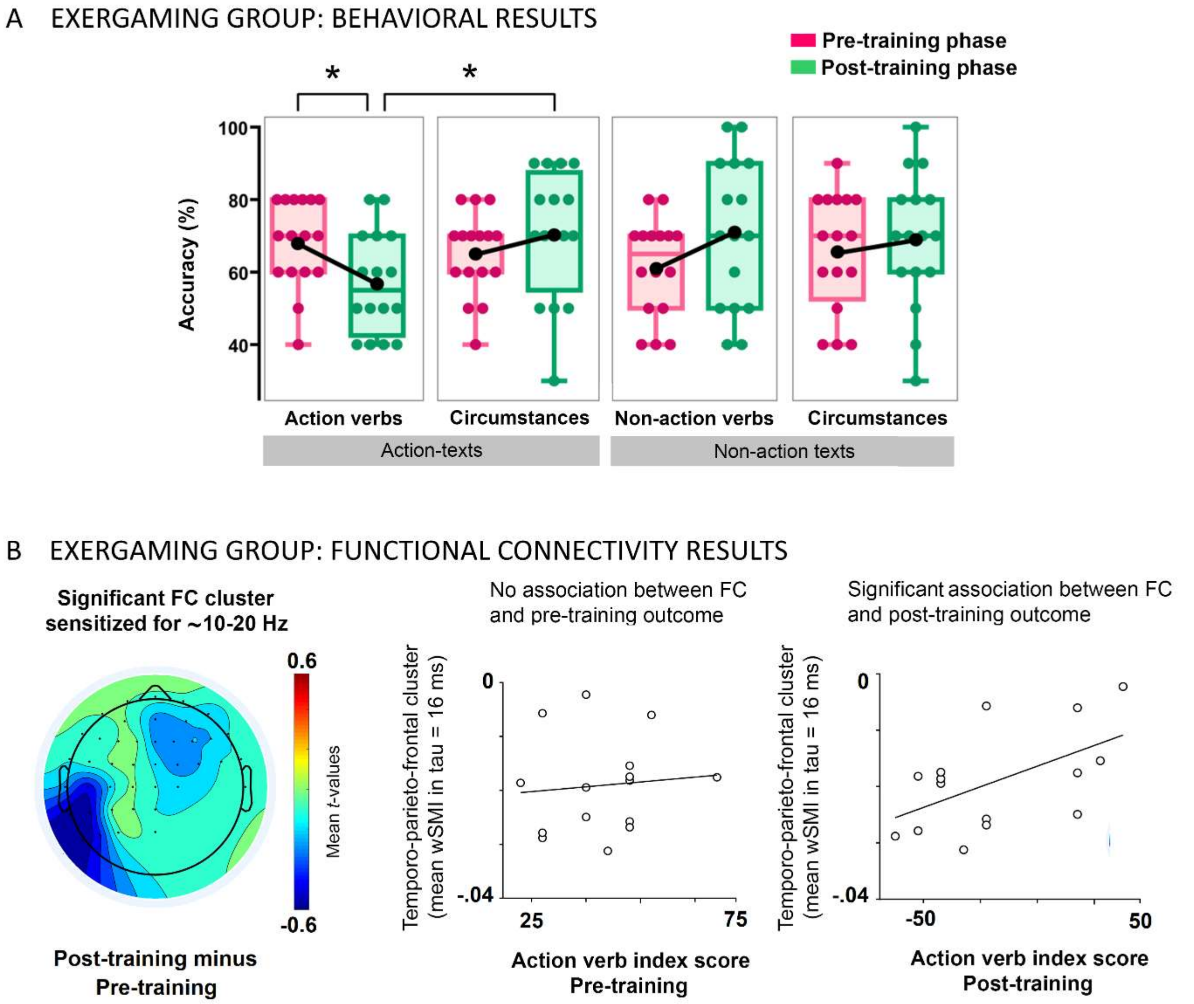

Figure 2. Behavioral and functional connectivity results in the exergaming group. **(A)** Significant triple interaction among Text type, Information type, and Time point. Post-hoc tests revealed that, while no pairwise comparison was significant in the Pre-T session, Post-T AT verb outcomes were significantly lower than Pre-T AT verb outcomes and Post-T circumstance outcomes. No other pairwise comparison yielded significant differences. Values on the Y-axes indicate percentage of scores. Asterisks (*) indicate significant differences. AT: action text; nAT: non-action text; Pre-T: pre-training; Post-T: post-training. **(B)** Significant lower connectivity (sensitized for the ~10-20 Hz range) after training over a cluster spanning left temporo-parieto-frontal electrodes. Color bar indicates *t*-value scaling. Correlation results showed no significant associations between Pre-T FC in the significant cluster and the action-verb index.

Conversely, Post-T FC in the significant cluster was positively correlated with the action-verb index. Color bar indicates mean wSMI. FC: functional connectivity.

Control condition: Static gaming group

Results from the SG group revealed a main effect of the Time point [$F(1,105) = 7.51$, $p = .007$, $\eta_p^2 = .07$], with better performance on the Post-T than the Pre-T phase ($p = .01$, $d = .77$). The main effects of Text type [$F(1,105) = 1.2$, $p = .28$] and Information type [$F(1,105) = .08$, $p = .78$] were not significant. A significant interaction emerged between Text type and Information type [$F(1,105) = 4.80$, $p = .031$, $\eta_p^2 = .04$], with lower performance for AT verbs than nAT verbs ($p = .04$, $d = .55$) and no differences between other condition pairs (all p-values > .14). No significant differences emerged between Text type and Time point [$F(1,105) = 1.88$, $p = .17$] nor between Information type and Time point [$F(1,105) = 1.88$, $p = .17$]. The triple interaction was not significant [$F(1,105) = 2.71$, $p = .10$]. For details, see Supplementary material 5.

Functional connectivity results

The EG group exhibited significantly lower FC after training over a cluster spanning left temporo-parietal electrodes and bilateral frontal electrodes, at $\tau = 16$ ms (~10-20 Hz) ($p_{connection} < .05$; $p_{cluster} = .03$). No significant differences were observed between time points in the SG group (all $p_{connection}$-values > .05).

Correlation results

In the EG group, a significant positive correlation ($r = 0.54$, $p = .03$) emerged between the action-verb index and Post-T FC at $\tau = 16$ ms (~10-20 Hz) –i.e., the lower the connectivity, the lower the accuracy on the action-verb index. No correlations were observed between behavioral performance and Pre-T FC ($p = 0.9$). To further understand this pattern, we explored whether Pre-T connectivity levels were associated with pre-training physical activity. To this end, we performed a correlation between physical activity load (weekly hours of physical activity over the preceding three months) and the mean connectivity of the significant cluster. No significant correlation emerged ($r = -0.33$, $p = 0.22$).

Discussion

We examined whether short-term motor training, via exergaming, modulates processing of action concepts evoked by naturalistic texts. This intervention selectively reduced action-verb outcomes and fronto-posterior connectivity in the ~10-20 Hz range, with both patterns being significantly correlated. Conversely, static videogame playing yielded no specific effect on any linguistic category, nor did it modulate FC in the frequency range under consideration. These findings illuminate the role of bodily experience and sensorimotor circuits in action concept processing, as discussed below.

Exergaming selectively reduced AT verb outcomes, whereas raw scores for every other condition actually increased after the intervention. This category-specific effect aligns with evidence of less efficient action-verb processing following short-lived motor system modulations via physical action training (Glenberg et al., 2008) and non-invasive brain stimulation (Gijssels et al., 2018). In particular, the absence of similar effects on nAT verbs rules out an unspecific impact on processing of verbs as a broad lexical category. In this sense, differential motor-system engagement for action relative to abstract concepts has been reported in word-level (García et al., 2019, Moguilner et al., 2021a) and text-level (Moguilner et al., 2021b) tasks, reinforcing the view that semantic processing hinges on embodied reactivations of modality-specific experiences (García and Ibañez, 2016, Zwaan, 2016, Birba et al., 2017, Pulvermüller, 2018)

AT circumstances were also unaffected by exergaming, corroborating the intervention's focal effects on action concepts, rather than on ATs at large. Note that circumstantial adjuncts conveyed temporal, locative, or logical aspects that are neither semantically nor syntactically required by the regime of action verbs (Halliday & Matthiessen, 2014). It would seem, then, that training-induced simulations did not percolate beyond the semantic reenactment of movements proper. Accordingly, the effects of bodily training seem to be conceptually and grammatically specific to action-related units.

Interestingly, raw scores showed similar Pre/Post changes in the SG condition across all categories. Crucially, however, the magnitude of the difference between Post-T and Pre-T AT verbs was markedly smaller in the SG condition than in the EG condition. This raises the possibility that exergaming *amplified* proto-effects associated with action perception in videogames at large. This view is consistent with the notion that action semantics may be modulated by movement observation, as claimed in previous exergaming research (Trevisan et al., 2017), while accounting for the condition-specific effect observed in the EG group. Yet, this remains speculative. Future studies should be run with larger samples to disentangle the specific contributions of action execution and observation to the observed effects. Be that as it may, our findings reinforce models which posit direct links between situated experiences and germane conceptual domains (Barsalou, 2003, García and Ibañez, 2016).

The direction of this selective effect might seem surprising. Indeed, Trevisan et al. (2017) found that a nine-day exergaming protocol selectively *enhanced* AT verb processing (Trevisan et al., 2017). Importantly, however, such an experiment involved children with dyslexia, a population with known motor system alterations (Fawcett and Nicolson, 1995, Chaix et al., 2007, Marchand-Krynski et al., 2017) –for a meta-analysis, see Obeid et al. (2022). In such a population, we surmise, exergaming may boost *impaired* motor-system dynamics, facilitating semantic processes that hinge on such resources. Contrariwise, in healthy individuals, the same intervention may boost *normal* motor-system dynamics, reaching supra-threshold activation levels that render those circuits unavailable for concomitant processes. This view is consistent with previous findings. In fact, following anodal M1 stimulation, action-verb processing has been shown to *improve* in patients with motor-system deficits (Suárez-García et al., 2021) and to *decrease* in healthy individuals (Birba et al., 2020b). Such patterns may be interpreted in terms of the Hand-Action-Network Dynamic Language Embodiment (HANDLE) model (García and Ibañez, 2016). Indeed, building on dozens of experiments, HANDLE posits that action-verb processing can be primed if motor networks are excited following low baseline activation, but that the same category be interfered with if such excitation follows higher baseline activation.

In addition, the different directionalities of these embodied effects might also be influenced by motor training duration. Whereas the studies yielding action-concept facilitation tended to be considerably long (ranging from nine to 20 days and up to several years) (Beilock et al., 2008, Locatelli et al., 2012, Tomasino et al., 2012, 2013, Trevisan et al., 2017), those resulting in category-specific decrements were substantially briefer (ranging from minutes to only a few days) (Glenberg et al., 2008, Gijssels et al., 2018, Birba et al., 2020b) –note, however, that facilitation may also be attained following shorter practice periods if these involve familiarization with unusual actions (Beauprez et al., 2020) or sustained practice of highly specific actions (Lyons et al., 2010). Our exergaming protocol was considerably short (four 60-minute sessions), especially vis-à-vis that of Trevisan et al. (nine 90-minute sessions), and the texts did not focus on the specific actions elicited by the exergaming protocol. These differences might also partly account for the studies' discrepant findings. In fact, due to their distinct impact on cortical excitability, brief periods of motor training may be typified by cross-skill interference, whereas longer periods are typically associated with behavioral improvements (Luft and Buitrago, 2005, Dayan and Cohen, 2011, Cantarero et al., 2013). Reduced action comprehension could be further promoted by the lack of effector-specific relations between the actions described by the texts and performed by participants (Lyons et al., 2010). Briefly, motor-system integrity at baseline, training duration, and the absence of limb-specific action-semantic couplings may have jointly shaped the behavioral decline observed in the EG group.

Of note, this behavioral effect was mirrored by EEG results. Whereas the SG group showed no FC changes after training, the EG group exhibited reduced temporo-parieto-frontal connectivity. Previous studies showed that specific sensorimotor networks including fronto-parietal hubs may become decoupled following brief training periods (Floyer-Lea and Matthews, 2005). Left temporal and fronto-parietal networks, indeed, become jointly recruited during initial stages of motor training, possibly indexing an early reliance on conscious verbal control (supported via temporal structures) during the acquisition of new visuo-motor patterns (Haufler et al., 2000, Kerick et al., 2001, 2004). In particular, training-dependent motor system modulations seem to be distinctly indexed by alpha and beta activity, including mu rhythms (Orgs et al., 2008, Denis et al., 2017, Amoruso et al., 2022). This evidence aligns with our finding that reduced fronto-parietal connectivity after exergaming occurred exclusively within the ~10-20 Hz frequency range. Importantly, recruited brain mechanisms keep reverberating at rest following exposure to new experiences (Lewis et al., 2009, Jolles et al., 2013), suggesting that training-induced effects may have remained operative until the Post-T EEG recording took place.

Crucially, this post-training FC reduction was positively correlated with action-concept outcomes (controlling for other lexical categories), showing that the lower the connectivity, the lower the performance on AT verbs. Other text-level studies (on patient populations) have linked lower outcomes in this category with reduced connectivity along fronto-parietal (Moguilner et al., 2021a) and other sensorimotor (Birba et al., 2021a) networks, without comparable effects in non-action categories. In line with embodied views of language (Gallese and Sinigaglia, 2011, Pulvermüller, 2013a, 2013b, Gallese and Cuccio, 2018, Cervetto et al., 2021), this association speaks to a direct link between action semantics and sensorimotor systems, as bodily training would induce proportional changes in their behavioral and FC signatures, respectively. In this sense, our study extends previous evidence on athletes, showing that the neural signatures of action verb processing are shaped by individual experience (Lyons et al., 2010).

Importantly, a complementary analysis showed that Pre-T connectivity was not associated with pre-training physical activity. This suggests that baseline connectivity and exergaming-induced changes were not primarily driven by previous physical activity, reinforcing the generalizability of our results. More particularly, the direction of the significant behavioral and FC effects indicates that connectivity changes induced by newly encoded motor behaviors either *interfered* with linguistic processes supported by this network (Bays et al., 2005, Krakauer et al., 2005, Gagne and Cohen, 2016) or rendered this network *insufficiently engaged* to optimally subserve such processes (García and Ibáñez, 2016). Future studies with strategic designs could disentangle between these competing views.

Finally, it is worth stressing that present findings came from a highly ecological setting, involving naturalistic texts and real-life bodily engagement. Most action-language studies, including motor-training protocols, involve responding to (pseudo)randomized sequences of isolated words or sentences with basic and repetitive single-effector actions (Yang, 2014, García and Ibañez, 2016, Kogan et al., 2020). While such evidence is fundamental to capture embodied phenomena, it fails to inform their deployment in everyday scenarios, which often involve rich, coherent, cohesive texts alongside full-body dynamics. Our study bridges this gap with its combination of naturalistic narratives and immersive movements, extending evidence that action-concept processing in naturalistic texts can be selectively impaired due to motor-network disruptions (Garcia et al., 2018, Birba et al., 2021a, Moguilner et al., 2021b), decreased upon non-invasive M1 neurostimulation (Birba et al., 2020b), and influenced by linguistic experience (Birba et al., 2020a). Further efforts in this direction are vital to address the plea for more ecological insights in neurolinguistics (Desai et al., 2016, Hasson et al., 2018).

Limitations and further research

This study is not without limitations. First, our sample size was moderate. Although power estimation results attested to its adequacy for present analyses, replication studies should be conducted with more participants. Second, behavioral measures were restricted to 20 items per questionnaire. While other works with similar materials obtained strong findings with even fewer questions (Trevisan et al., 2017, Birba et al., 2021), it would be useful to extend this research line with materials offering an even longer range of possible scores. Third, examination of neural correlates was limited to offline recordings. Despite its usefulness to capture embodied signatures in text-level paradigms (Birba et al., 2021, Moguilner et al., 2021b), such an approach fails to reveal ongoing modulations as meaning is built on-the-fly during language processing. Future works should strive to include real-time EEG measures as participants process both ATs and nATs, as done elsewhere (Birba et al., 2020a). Finally, our design cannot disentangle the relative contributions of action execution and observation to the observed effects. Granted, the SG group exhibited no category-specific effects even though their games' characters did perform bodily movements, suggesting that action observation may not be the primary driver of results in the EG group. Still, given that embodied motor mechanisms can be recruited by virtue of action imagery and visualization (Eaves et al., 2016), future studies should implement strategic designs manipulating the role of both self-initiated and visualized movements during exergaming.

Conclusion

Unlike static videogames, a brief exergaming protocol can selectively undermine action-verb processing in narrative texts. This effect correlates with reduced resting-state FC over left temporo-parieto-frontal electrodes in the ~10-20 Hz range, a pattern implicated in motor activity. Jointly, such findings reveal direct neurocognitive links between situated bodily experience and germane semantic categories, while meeting the imperative of ecological validity. Further work along these lines can would be crucial to consolidate a naturalistic neurolinguistic agenda.

Conflicts of interest

The authors declare no conflicts of interest.

Credit author statement

Sabrina Cervetto: Data acquisition, Methodology, Formal analysis, Data curation, Writing - Original draft. **Agustina Birba:** Methodology, Formal analysis, Writing - Original draft, Writing - Review & Editing. **Gonzalo Pérez:** Formal analysis, Writing - Review & Editing. **Lucía Amoruso:** Formal analysis, Writing - Original draft, Writing - Review & Editing. **Adolfo M. García:** Conceptualization, Validation, Methodology, Writing - Original draft, Writing - Review & Editing, Supervision, Funding acquisition, Project administration.

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Supplementary material

1. Power estimation analysis

To determine the sample size required for our study, we ran a power estimation analysis using MorePower 6.0 (Campbell and Thompson, 2012). Given our statistical design, based on a 2x2x2 factorial ANOVA, we considered an α level of $p = .05$, a power of 0.80 and, following (Trevisan et al., 2017) a Cohen's effect size of $f > 0.5$. This analysis showed that a total sample size of 16 is adequate to detect the estimated effects.

2. Full texts and approximate English translations

2.1. Action text 1

Spanish original: ¡La playa, el lugar preferido de Pedro en todo el universo! Pedro tomó a su hermano de la mano y corrieron hacia el mar. Ya en la orilla, se sacó la remera, los zapatos y los anteojos y se metió al agua. Sumergió la cabeza y buceó bajo las olas. Al llegar al fondo, Pedro agarró un caracol de abajo de un par de piedras. Un caracol exótico. Luego, su hermano nadó hasta él y lo retó a una carrera. ¡Era el momento de nadar hasta el muelle! Pedro nadaba adelante y... ¡ganó! Se sentía muy cansado. ¡Había nadado un montón! Luego, se acercó hasta el muelle y se agarró de una columna. Se subió de un salto. ¡Qué linda vista del horizonte! Era un hermoso atardecer. Mientras, su hermano seguía jugando en el mar. Pedro se levantó rápidamente y corrió hasta el otro lado del muelle. Luego, agarró una piedra y la arrojó hacia el agua con fuerza. Finalmente, su hermano salió del agua. Ambos se acercaron a un grupo de chicos que armaban castillos de arena y se agacharon para ayudarlos. Luego, todos caminaron hasta la casa de los hermanos, donde comieron una gran torta de chocolate. Fue una tarde muy divertida.

English translation: The beach, Peter's favorite place in the entire universe! Peter took his brother's hand, and they both ran towards the sea. By the shore, he took off his T-shirt, shoes, and glasses, and dove into the water. He submerged his head and swam under the waves. When he reached the bottom, Peter took a snail from underneath a couple of rocks. An exotic snail. Then, his brother swam towards him and challenged him to a race. It was time to swim all the way to the dock! Peter swam ahead… and won! He felt very tired after swimming so much! Then, he made his way to the dock, and he held onto a column. He jumped onto it. What a lovely view of the horizon! It was a beautiful sunset. Meanwhile, his brother was still playing in the sea. Peter quickly stood up and ran to the other side of the dock. Then, he grabbed a rock and vigorously threw it into the water. Finally, his brother came out of the water. They both approached a group of kids building sandcastles and crouched to help them. Then, they all walked together to the brothers' house, where they ate a big chocolate cake. It was a most amusing afternoon.

2.2. Action text 2

Spanish original: Sábado por la tarde. ¡El momento favorito de Juancito en toda la semana! Tomó a sus padres de la mano y juntos corrieron hasta la plaza. Al lado de las hamacas, un grupo de niños aplaudía las piruetas de un colorido payaso. Juancito corrió velozmente hacia el lugar donde el payaso saltaba y bailaba sin cesar. Al terminar el espectáculo, el payaso escribió su nombre en el pavimento. ¡Qué sorpresa! ¡También se llamaba Juan! Luego, entre toda la muchedumbre, Juancito caminó hacia el lugar donde se sentaron sus padres. Abrazó a su padre con mucha fuerza y le jaló la camisa para que se levantara. ¡Era hora de jugar al fútbol! Juancito tomó la pelota y la puso en el pasto. Su padre se movía de izquierda a derecha, en posición de arquero. Juancito pateó y… ¡gol! Repentinamente salió el sol. Juancito se sacó el abrigo y lo apoyó en el asiento. Luego, su madre se acercó y le entregó un chocolate. Se lo comió de un bocado. Como siempre, al terminarlo, arrojó el paquete en el basurero. Había sido una intensa jornada. Se sentía muy cansado. Ya en la falda de su madre, mientras se limpiaba los restos de chocolate de la boca, se quedó dormido.

English translation: Saturday afternoon. Johnny's favorite time of the week! He took his parents' hands and ran with them to the park. Next to the swings, a group of children were clapping to the antics of a colorful clown. Johnny quickly ran to the place where the clown was jumping and dancing non-stop. When the show was over, the clown wrote his name on the pavement. What a surprise! He was also called John! Then, walking through the crowd, Johnny went towards the bench where his parents were sitting. He hugged his father tightly and pulled him by the shirt to make him stand up. It was time to play soccer! Johnny grabbed the ball and placed it on the lawn. His father moved from left to right, acting as the goalkeeper. Johnny kicked the ball and… goal! Suddenly, the sun appeared. Johnny took off his sweater and laid it on the bench. Then, his mother approached him and gave him some chocolate. He ate it in one bite. As usual, after finishing it, he threw the wrapper in a trash can. It had been a very intense day. He felt very tired. Once on his mother's lap, while wiping traces of chocolate off his mouth, he fell asleep.

2.3. Non-action text 1

Spanish original: ¡Qué felicidad, estaban de viaje! Clara estaba entusiasmada por haber invitado a su amiga con ella. Iban en el auto para el bosque y los paisajes eran hermosos. ¡Hora de disfrutar de las vacaciones! En un momento, Clara vio un animal en la ruta. No lo había visto nunca y tenía curiosidad. A su amiga, quien conducía, no le interesaban los animales, y menos uno raro en la ruta. Clara sabía que no era común y quería sacarle una foto. Al lado de la ruta, un grupo de autos detenidos fotografiaban y admiraban la belleza del animal. ¡Qué afortunados! Clara insistía, pero su amiga no se detenía por nada. Clara imaginaba historias de la criatura y se las contaba a su amiga, que se divertía. Luego de tanto insistir, Clara decidió disfrutar del paisaje a través de la ventanilla del auto. ¡Qué hermosa vista! Sacó un par de fotos a las montañas. Luego, impaciente, cerró los ojos y se quedó dormida. Se despertó un rato después. Sólo había dormido unos minutos. ¡Qué bien! En ese tiempo habían avanzado un montón. ¡Ya llegaban! Una hora más tarde, ya en el bosque, Clara disfrutaba del paisaje y del olor de las flores.

English translation: What a joy! They were on a trip! Clara was thrilled to have invited her friend. They were driving by car to the forest and the scenery was beautiful. Time to enjoy their vacation! At one point, Clara saw an animal on the road. She had never seen it before and was curious about it. Her friend, who was driving, was not interested in animals, let alone an exotic one on the road. Clara knew that it was rare and wanted to take a picture of it. On the side of the road, a group of people parked their cars to take pictures and admire the beauty of the animal. How lucky! Clara insisted, but her friend would not stop for anything. Clara imagined stories about the animal and told them to her friend, who enjoyed them. After insisting so much, Clara decided to enjoy the scenery through the car window. What a beautiful sight! She took some pictures of the mountains. Then, impatient, she closed her eyes and fell asleep. She woke up a little later. She had just slept for a couple of minutes. Great! During that time, they had made a lot of progress. They were almost there! One hour later, deep into the forest, Clara enjoyed the view and the smell of the flowers.

2.4. Non-action text 2

Spanish original: La noche recién comenzaba. Alberto estaba contento. ¡Gracias a Dios por los fines de semana! A unas pocas cuadras, la discoteca. Sus amigos lo esperaban allí y juntos compartirían un buen momento. Al cruzar la calle, Alberto leyó el nombre de la discoteca en un cartel: "Ni jefe ni reloj". Siempre lo ponía de buen humor. Una vez adentro, lo enceguecieron las luces. Sintió calor y se encontró muy transpirado. Al lado del bar, un grupo de mujeres se entretenía con las historias de su amigo, Mario. Las muchachas se reían sin pausa junto a ese joven que bromeaba e inventaba personajes. Luego, entre toda la gente, Alberto reconoció a su novia, Elsa. Ella lo esperaba en una silla. Desde atrás, Alberto le preguntó si le gustaba la música. "¡Por supuesto!", respondió Elsa. Aunque ella tenía sueño, Alberto le insistió para que lo acompañara a la pista. ¡Era hora de disfrutar la música! Como siempre, al decidirse, Elsa se olvidó la cartera en la silla. Alberto escuchó su canción favorita y se entusiasmó mucho. Elsa, fiel compañera, lo ayudó a recordar la letra. ¡Qué buen equipo! De regreso en su casa, mientras sentía el sudor y el cansancio en el cuerpo, se quedó dormido.

English translation: The night was just starting. Albert was happy. Thank God for weekends! The night club was just a few blocks away. His friends were waiting for him there, and they were going to have a good time. While crossing the street, Albert read the name of the club on a sign: “No boss, no clock”. It always put him in a good mood. Once inside, he was blinded by the lights. He felt hot and very sweaty. Next to the bar, a group of women were amused by the stories that his friend Mark was telling. The girls were laughing non-stop with that young man, who joked and made up characters in his stories. Then, among the crowd, Albert recognized his girlfriend, Elsa. She was waiting for him sitting on a chair. Coming from behind, Albert asked her whether she liked the music. “Of course!” replied Elsa. Although she was sleepy, Albert insisted that she join him on the dance floor. It was time to enjoy the music! As usual, after deciding to go with him, Elsa forgot her purse on the chair. Albert heard his favorite song and got very excited. Elsa, ever the good sport, helped him remember the lyrics. What a good team! On the way back home, as he felt the sweat and tiredness all over his body, Albert fell asleep.

3. Videogame lists

The videogames used with the exegarming and the static gaming groups are listed in Supplementary Table 1.

Supplementary Table 1. List of videogames used in our protocol.

Exergaming group (Wii Fit Plus software)	**Static gaming group** (Wii Party software)
	Garden Gridlock
Rhythm Kung-Fu	Colour Coordination
Rhythm Boxing	Banana Blockade
Step Basics	Maze Daze
Perfect 10	Follow Your face
Obstacle Course	Fruit Focus
Hula Hoop	Commuter Count
Table Tilt Plus	Stop Watchers
Balance Bubble	Walk-off
Snowboard Slalom	Face Flip
Tilt City	Friendly Face-Off
Snowball Fight	Zombi Tag
Soccer Heading	Hammer Heads
Delivery Duel	Back Attack
Poppin’ Pilots	Teamwork Temple
	Rodent Rundown

4. Supplementary results (exergaming group)

Results from the exergaming group revealed non-significant main effects of Text type [$F(1,105) = .28$, $p = .59$], Information type [$F(1,105) = 1.55$, $p = .22$], and Time point [$F(1,105) = .43$, $p = .52$]. All double interactions were non-significant [Text type by Information types: $F(1,105) = .59$, $p = .44$; Text type by Time point: $F(1,105) = 2.95$, $p = .09$; Information type by Time point: $F(1,105) = 1.02$, $p = .32$]. For further details, see Supplementary Table 2.

Supplementary Table 2. Relevant pairwise comparisons for results from the exergaming group.

Comparison	***p*-value[a]**	**Cohen's *d***
Pre-T vs. Post-T phase | Action texts		
Action verbs $_{\text{Pre-T}}$ vs. Action verbs $_{\text{Post-T}}$	**.01**	.71
Circumstances $_{\text{Pre-T}}$ vs. Circumstances $_{\text{Post-T}}$	.17	.36
Action verbs $_{\text{Pre-T}}$ vs. Circumstances $_{\text{Pre-T}}$	.44	.20
Action verbs $_{\text{Post-T}}$ vs. Circumstances $_{\text{Post-T}}$	**.02**	.68
Pre-T vs. Post-T phase | Non-action texts		
Non-action verbs $_{\text{Pre-T}}$ vs. Non-action verbs $_{\text{Post-T}}$	.10	.44
Circumstances $_{\text{Pre-T}}$ vs. Circumstances $_{\text{Post-T}}$	.64	.12
Non-action verbs $_{\text{Pre-T}}$ vs. Circumstances $_{\text{Pre-T}}$	.36	.23
Non-action verbs $_{\text{Post-T}}$ vs. Circumstances $_{\text{Post-T}}$	.76	.08
ATs vs. nATs | Verb-related information		
Action verbs $_{\text{Pre-T}}$ vs. Non-action verbs $_{\text{Pre-T}}$	.23	.31
Action verbs $_{\text{Post-T}}$ vs. Non-action verbs $_{\text{Post-T}}$	.05	.53
ATs vs. nATs | Circumstantial information		
Circumstances $_{\text{Pre-T}}$ vs. Circumstances $_{\text{Pre-T}}$	.89	.03
Circumstances $_{\text{Post-T}}$ vs. Circumstances $_{\text{Post-T}}$	.72	.09

[a] Based on two-tailed paired *t*-tests. Pre-T: pre-training phase; Post-T: post-training phase.

Supplementary references

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Ethical statement

All participants signed an informed consent, and all experimental protocols were performed in accordance with the Declaration of Helsinki. This study was approved by the institutional ethics committee.