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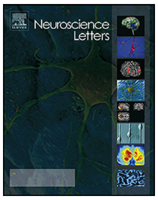

Word-induced postural changes reflect a tight interaction between motor and lexico-semantic representations

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HIGHLIGHTS

- Kinematic analyses reveal a coupling between lexico-semantic access and postural control.
- Listening to action verbs, but not mental-state verbs, disrupts the control of quiet standing.
- The results support overlap in neural processing of action words and whole-body motor functions.

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ABSTRACT

A tight coupling between lexico-semantic access and motor control has been established on the basis of neuropsychological, neurophysiological, and behavioral evidence. For example, sensory and motor cortices have been shown to be active when subjects listen to words denoting bodily actions. Kinematic analyses of participants' motor actions during the processing of linguistic stimuli provide further insights into the nature and time-course of this relationship. However, such studies have largely focused on individual body parts, in particular the upper limbs, thus neglecting the effect of language processing on lower or whole body representations. The present study bridges this gap by evaluating the interaction between linguistic processing and whole-body *postural* control during quiet standing. The results reveal a systematic influence of passive listening to action verbs, but not mental-state verbs, on measures of postural control, pointing to a clear and specific neural link between words conveying action concepts and whole-body motor functions.

1. Introduction

Psycholinguistic models positing that words acquire their meaning from somatosensory representations in the brain (i.e., "embodied cognition", [1]) have been subject to enthusiasm [1,2] and criticism [3,4]. Support for a link between language and action is based on neuropsychological, neurophysiological, and behavioral data. Reports of an inability to execute volitional actions following verbal commands despite preserved receptive speech [5] suggest that language mediates motor control. An inability to access the meaning of action verbs (e.g., "cutting" or "sailing") following lesions in the premotor cortex indicates that this phenomenon is bidirectional [6]. This correlation has been corroborated in neuroimaging studies, demonstrating that somatosensory cortices are active when subjects listen to words that denote bodily actions, such as "kick" (leg related) or "lick" (tongue related, [7,8]; Boulenger et al., 2009) either in single words [7] or in sentences [9].

Kinematic analyses of participants' motor control have further elucidated the nature and time-course of these correlates. For instance, Frak et al. [10] asked participants to hold a cylinder equipped with grip force sensors while listening to action verbs (e.g., "write") or non-action concrete nouns (e.g., "cliff"). Increased grip force was recorded approximately 260 ms after hearing action-related verbs but not after hearing non-action nouns. Similar effects of word type on arm movement have been observed in several other kinematic studies [11–13]. These results indicate that the link between language and motor control is sensitive to subtle manipulations of linguistic context.

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While these studies contribute to understanding the interaction between language and action, little is known about this link beyond goal-directed movements involving the upper limbs. The present study explores the nature of this relation in the context of whole-body *postural* control during quiet standing. The neural mechanisms of postural control involve a continuous processing of sensory data from the visual, proprioceptive and vestibular systems to rapidly detect self-movement (sway) and generate an appropriate motor changes to maintain balance [14]. This sensorimotor loop provides a sensitive context in which to examine transient modulations in neural sensory and motor processing. Interfering with any component of this system, even briefly, may result in subtle instability that can be readily measured (Sensory: [15,16]; Motor: [14,17]).

Our goal is to examine the specificity of the link between language and motor functions by contrasting the influence of verbs whose meaning relates to physical movement (e.g., *tomber* – "fall"; *courir* – "run") with verbs referring to mental states (e.g., *aimer* "love"; *decider* "decide"). Previous studies examining language–motor interactions have contrasted different word classes, such as action verbs and concrete nouns. However, it is of interest to understand the extent to which distinct classes belonging to an otherwise similar grammatical category may exert different effects on motor control. Prior neurophysiological studies have found differences in neural activity between action and mental-state verbs [18,19], which may differently influence motor control. Here, we observed a systematic influence of passive listening to action-oriented verbs, but not mental-state verbs, on measures of standing postural control, which reveals a clear and functionally specific neural link between the processing of words conveying action concepts and whole-body motor functions.

2. Materials and methods

2.1. Participants

Fourteen native French speakers were tested (9 women and 5 men, 22–32 years of age), with no history of language or hearing disorder (hearing status was verified immediately prior to testing using a pure-tone audiometric screener). Participants reported no history of motor or vestibular disorder, and all obtained the maximum possible score (56) on the Berg Balance Scale. Participants were all right-leg dominant, as verified by the Bruininks-Oseretsky test of motor proficiency.

2.2. Stimuli

Two lists of French words were created for use in this study: one consisting of 24 verbs which clearly convey actions pertaining to the lower limbs, and a second list of 24 verbs associated with changes in mental state and connote no physical action (Table 1). The 24 action words were selected from a larger set of 45 candidate action verbs on the basis of a listening study in which 15 native French speakers (different from those involved in the present study of postural control) rated each word on a scale of 1–5, where 1 = no association with lower limb movement, and 5 = strong association with lower limb movement. The 24 words with the highest average scores on this rating scale were used in the present study. A list of 24 verbs connoting no physical action, but rather changes in mental state, was created such that it matched, on average, the list of action words in terms of usage frequency, number of letters, number of syllables, as well as the frequency of occurrence of 2- and 3-consonant clusters (see [10] for a similar procedure). The word lists were digitally recorded at 44.1 kHz (16-bit) by a single female French speaker and amplitude normalized. Average duration of the words was 0.64 s (SD: 0.11), with no reliable difference between the 24 action words and the 24 non-action words ($t[46] = 1.63$, $p > 0.05$). The words were presented to participants over loudspeakers (MSP7, Yamaha, Japan) in an audiometric testing booth at a volume of approximately 60 dB SPL.

Table 1
List of French verbs presented to subjects denoting bodily action (left column) and mental state (right column), along with their English translations.

Action		Non-action	
French	English trans.	French	English trans.
Agenouiller	to kneel	Accepter	to acknowledge
Asseoir	to sit	Adorer	to adore
Avancer	to move forward	Ambitionner	to covet
Balader	to stroll	Aspirer	to aspire
Boiter	to limp	Choisir	to choose
Bondir	to leap	Concevoir	to imagine
Cavaler	to gallop	Consentir	to consent
Cheminer	to walk	Daigner	to condescend
Chevaucher	to ride	Décider	to decide
Clopiner	to hobble	Désirer	to desire
Courir	to run	Détester	to detest/hate
Danser	to dance	Envisager	to envision
Enjamber	to step over	Essayer	to try
Escalader	to climb	Hésiter	to hesitate
Gambader	to skip	Préférer	to prefer
Glisser	to slip	Prétendre	to claim
Marcher	to walk	Prévoir	to foresee
Pédaler	to pedal	Projeter	to plan
Piétiner	to stamp	Renoncer	to give up
Promener	to walk around	Répugner	to be reluctant
Sauter	to jump	Rêver	to dream
Trébucher	to stumble	Songer	to think deeply
Trotter	to trot	Souhaiter	to wish
Valser	to waltz	Tenter	to attempt

2.3. Procedure

Each participant underwent two blocks of word-presentation trials involving the randomized presentation of all 48 words (24 action and 24 non-action words), with an inter-stimulus interval of 10 s. Participants were asked to maintain a quiet upright posture while standing on a force plate (see *data analysis*) with their eyes closed throughout the presentation of each block. Their feet were placed at hip width in a natural position and their arms were at their sides. Data collection began when the participant was stable on the platform. A 2-minute break was provided between the two blocks of trials.

To maintain attention to the auditory stimuli, participants were instructed to silently count the number of times a target word was presented throughout each block of trials. A different randomly selected target word was presented to subjects immediately prior to the onset of each block. The target word was then presented 10 times, at random intervals, throughout the stimulus block. Each participant carried out the listening task once with the target word selected from the list of 24 action words, and once with the target word selected from the list of 24 non-action words (order counterbalanced among participants).

2.4. Data analysis

Force in two dimensions (M-L, medio-lateral; A-P antero-posterior) was sampled at 100 Hz using a force platform (model ACG, AMTI, Watertown, MA) and digitally low-pass filtered at 6 Hz using a second-order Butterworth filter (Matlab v. 7.0, Mathworks, Natick, MA) prior to the calculation of the Center of Pressure (CoP) along each axis (M-L and A-P). CoP reflects, at each moment, the spatial position at which the sum of forces exerted by the body acts on the force plate, and variation in CoP is a commonly used

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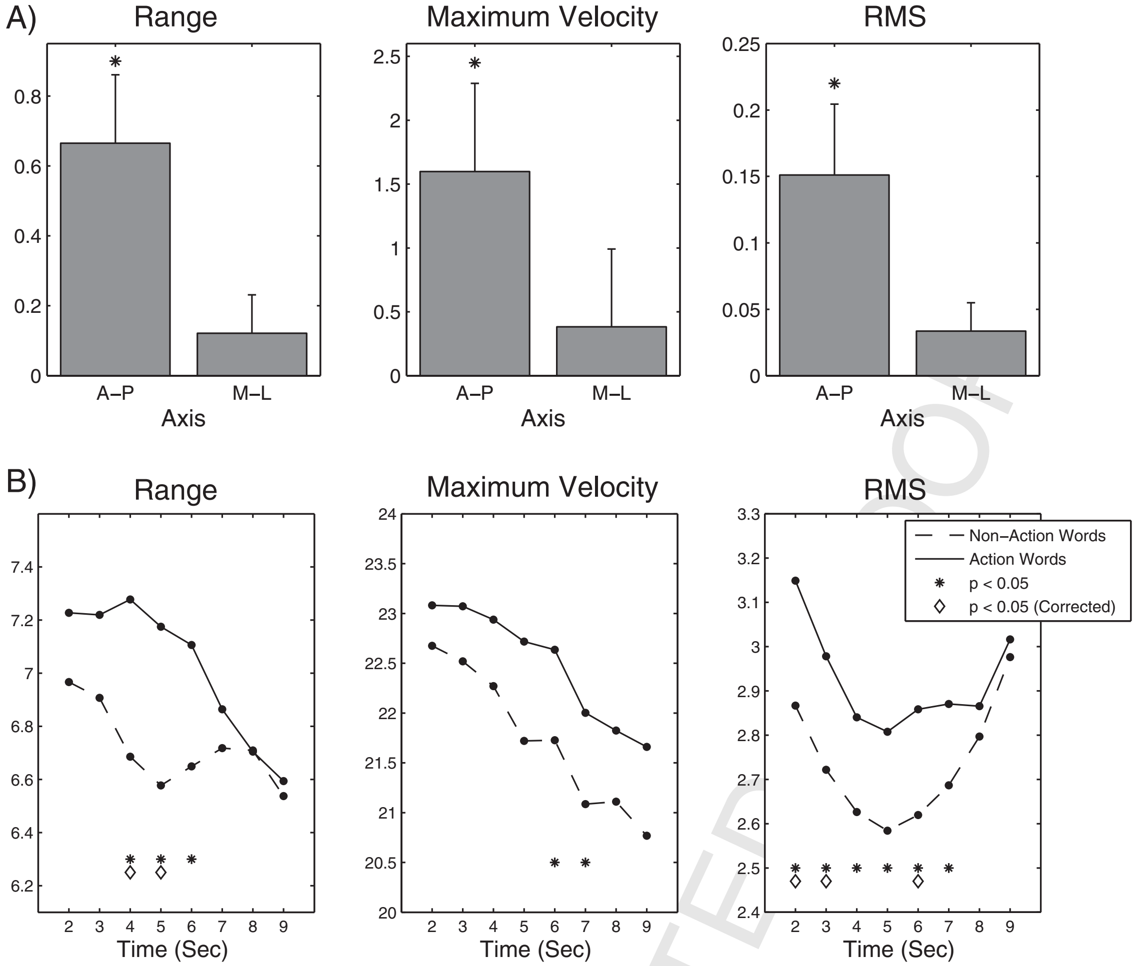

Fig. 1. (A) The mean difference between action and non-action word conditions for measures of CoP Range (mm), maximum velocity (mm/s) and RMS (mm). Positive difference scores reflect a larger mean value for the action words relative to the non-action words. Stars indicate difference scores that differ significantly from zero ($p < 0.05$) (M-L: Medio-lateral; A-P: Antero-posterior). (B) Average time series of CoP range (mm), maximum velocity (mm/s) and RMS (mm) measures, averaged over trials containing action words (solid lines) or non-action words (dashed lines). Times are relative to word presentation onset. Stars (*) and diamonds (◊) indicate time points during which the conditions differ reliably (* = uncorrected $p < 0.05$; ◊ = Holm–Bonferroni corrected $p < 0.05$; see text for details).

index of postural instability in standing [14]. Three previously validated kinematic measures of postural variation involving CoP (see e.g., [20–22]) were computed in M-L and A-P directions for the 9-s period following the presentation of each word: (1) *range*, reflecting the total excursion of CoP, (2) *peak velocity*, reflecting the largest sudden change in CoP, and (3) *root-mean square* (RMS), reflecting the average magnitude of variation. The analysis did not include the time during which the stimulus was being presented in order to reduce the influence of low-level effects of auditory input, such as the acoustic startle response. For each participant, the three postural measures were separately averaged across all presentations of the action-words and all presentations of non-action words. Trials involving the target stimulus for the word matching/counting task were excluded from the average. For each of the kinematic measures, the difference between the two word conditions (action vs. non-action) was evaluated using a paired-samples *t*-test.

3. Results

The mean difference between action and non-action word conditions is shown for each of the postural control variables in Fig. 1a. Positive difference scores reflect a larger mean value for the action words relative to the non-action words. Statistically reliable differences were observed in the A-P direction for CoP Range ($t[13] = 3.27$, $p < 0.05$; Cohen's d: 0.17), maximum velocity ($t[13] = 2.23$, $p < 0.05$; Cohen's d: 0.19) and RMS ($t[13] = 2.73$, $p < 0.05$; Cohen's d: 0.17). No reliable difference was observed for any of the measures in the M-L direction ($p > 0.05$).

To examine the evolution of the reliable effects in postural control throughout the 9-s period following word presentation, the CoP measures in the A-P direction were re-calculated as a time-series using 2-s time windows centered at each second of each trial. For each participant, an average time-series was computed across all action-word and non-action word trials, permitting a comparison between conditions at successive moments in time using pair-wise repeated-measures *t*-tests. As traditional corrections for multiple comparisons will be overly-conservative for time-series data such as these because they cannot account for the autocorrelated nature of the data, we present results corrected for multiple comparisons using the Holm–Bonferroni method [23], as well as uncorrected results.

Fig. 1b shows the evolution of the three CoP measure for trials involving action words (solid lines) and non-action words (dashed lines). On average, CoP range showed a transient difference between the two word conditions that was statistically reliable (corrected $p < 0.05$) 4–5 s following word onset (or 4–6 s using uncorrected p values), at which point the two curves converge once again. The CoP maximum velocity measure was not found to deviate reliably between the two conditions (corrected $p > 0.05$) at any single time window, however a reliable difference

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was observed 6–7-s following word onset using uncorrected p values ($p < 0.05$). The RMS measure shows a robust difference between word conditions (corrected $p < 0.05$) that begins earlier (2 s) and is observed up to 6 s following word onset (or 2–7 s using uncorrected p values). Taken together, these time-series indicate that the influence of word meaning on postural control manifests reliably within 2 s following word presentation, on average, and that the effect is transient, becoming non-significant within 6–7 s.

4. Discussion

The present study aimed to gain further insights into the relationship between lexical access and motor control. Contrary to mental state verbs, verbs denoting physical movement were found to induce small but systematic transient changes in whole-body posture. This complements existing evidence supporting a tight coupling between the lexico-semantic processing of words – particularly those denoting physical action – and the neural control of motor function.

Verbs denoting body movement appear to be associated with increased neural activity of their respective somatotopic loci ([7,8]; Boulenger et al., 2009) and interfere with task execution [10–13]. Our own results extend these findings by pointing to a linkage between lexical and bodily representations that also encompasses whole-body experience.

Our results differ from previous behavioral studies in terms of the time course of the influence of word processing on motor control. Changes in grip force, for example, have been observed approximately 100 ms following the onset of the target word, with the effect diminishing after 400 ms (e.g., [10]). While not studies of word processing, the integration of auditory-sensory input in the planning of limb motor actions has also been shown to occur at latencies of less than 1 s (see e.g., [24]). In contrast, the variables in the present study were shown to exhibit changes that began within the first 2-s period following word onset and lasted up to 6–7 s. This difference is likely related to the nature of the motor behavior being measured. Unlike grip force and upper limb movement, changes in standing posture result from the aggregate activity of numerous muscle groups distributed throughout the body. As a result, while changes in orientation may be sensed rapidly, changes in whole-body posture – reflecting the activity of spatially distributed muscles – are typically observed after several seconds [15,16]. Postural sway, which includes oscillatory components in the range of 0.5–2.5 Hz [25,26], lends itself to an analysis of variability as an index of postural control. Because of the long latency of these whole-body oscillations, kinematic measures of postural control require a time window on the order of seconds to avoid instability. It is possible that the onset of changes in postural muscle activity occurred earlier than 1 s following stimulus presentation. Incorporating physiological measures of motor behavior, such as EMG, may provide a more detailed understanding of the time-course of these effects.

To our knowledge, only one study to date has tested the effect of language processing on postural control [27]. In this study, participants' CoP measures were monitored as they produced nouns evoking motor control (e.g., tools) or nouns devoid of any such meaning (e.g., cities). Producing words from the former category yielded greater CoP changes, demonstrating an interaction between postural control and word production. While this result is consistent with those of the present study, its interpretation is complicated by the fact that the semantic manipulation may have interacted directly with kinematic parameters of the speech behavior (including head motion), and thus indirectly with postural control via those parameters [28]. Such difficulties are readily avoided in the present study.

While a numerical increase in magnitude for the three dependent measures was observed in both A-P and M-L directions following presentation of the action-words (see Fig. 1a), statistically reliable changes in postural kinematics were only observed in the A-P direction. The reason for this is likely biomechanical in nature. In quiet standing, with feet placed parallel at hip width, the body is considerably more stable in the M-L direction than in the A-P direction. As a result, M-L CoP displacements are typically much smaller (e.g., [29]). This was reflected in the three dependent measures of CoP variability in the present study, with all three showing average magnitudes in the A-P direction (Range: 12.71, Max velocity: 31.60, RMS: 2.92) that were more than twice as large as those in the M-L direction (Range: 5.89, Max velocity: 17.00, RMS: 1.26). As postural adjustments during quiet standing are primarily observed in the A-P direction, it is in this axis that differences between conditions are also most readily observed.

A concern that may be raised in studies of lexical–motor interactions is that action-words, by virtue of their being associated with physical behavior, may also be more concrete and imaginable. At issue here is the possibility that subjects may have in fact experienced some sort of "motor imagery" (i.e., covert simulation of the motor action) immediately following the presentation of action words, consequently inducing a postural change in response to the imagined movement. In the present study, participants were instructed to stand quietly while carrying out a secondary task (identifying and counting the number of times a target word was played). No mention of motor action or motor imagery was made, hence the idea that this may have played a role presumes that subjects spontaneously (and involuntarily) performed such imagery while carrying out the secondary task.

There are several factors indicating that motor imagery was not the source of the observed changes in postural variability. Neuroimaging studies have shown that the earliest functional changes in cortical motor areas following the passive presentation of action-words are observable at latencies under 200 ms, indicating that such motor activation is linked with lexical processing and not due to post-lexical processes such as motor imagery (see e.g., [2]). As noted above, changes in postural control are slow by their physical nature. In the present study, we observed systematic changes in postural control for action words within 2 s following word presentation. This latency, while slow in relation to non-postural behaviors, is consistent with observed kinematic (CoP) and physiological (EMG) adaptations of postural control in response to simple changes in sensory input. For example, Sozzi et al. [16] observed postural adaptations to the presence or absence of visual and haptic input at a latency of 0.5–2.2 s. Hence the timing of the postural effects observed in the present study is not longer than that expected for simple sensory-mediated adjustments.

In contrast, changes in postural control due to motor imagery might reasonably be presumed to require longer latencies than those observed here. There is no data on the timing of postural responses to motor imagery of whole-body action, and in fact it remains unknown whether mental imagery of movement would induce any measurable changes in postural kinematics at all. However, if we consider the possibility that subjects did carry out such imagery involuntarily, it would presumably require time for postural adjustments in addition to lexical-semantic access (determining the meaning of the word, observed at latencies as long as 400 ms for words presented without contextual cues; e.g., [30]), as well as the time to initiate a mental simulation of the motor behavior (believed to be temporally similar to real physical action; see e.g., [31]).

The postural changes in the present study following the presentation of action verbs were observed to continue for approximately 6–7 s (Fig. 1b). It is thus possible that motor imagery played a role at a later point during this period. The idea of motor effects arising

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from different sources (lexical-semantic representation in motor areas as well as motor imagery) has been raised previously in studies showing prolonged effects of action-word presentation on limb motor function [10], and is a possibility in the present study as well. Identifying these different possible sources in future studies will likely require neuroimaging techniques with good spatial and temporal resolution, such as MEG.

In the present study, subjects stood with their eyes closed during quiet standing in order to minimize possible interference from the visual system. Postural control without vision may have increased reliance on proprioception, and hence may have enhanced interactions with lexical representations of whole body movement. Future studies contrasting postural control with and without visual input may further elucidate the role of different sensory modalities in the observed lexico-motor interactions.

Despite evidence that lexico-semantic processing "infiltrates" sensory and motor structures in the brain, why and how this phenomenon takes place remains elusive. Some researchers have speculated that such interactions reflect the use in humans of brain areas that originally evolved for the perception and production of action (e.g., the mirror-neuron system) for the processing of language, thus preserving a link between the perception and planning of goal directed actions and their related lexical representations (see e.g., [32]).

A major challenge remains to devise methods that can demonstrate a *causal* link between these functions. Until then, it remains a valuable endeavor to delineate as precisely as possible the domains of language that share a common semantic organization with sensorimotor representations.

Q3 Uncited references

[33–36]

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