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Research article

Cognitive processes and a centre-of-pressure error-based moving light-touch biofeedback

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ABSTRACT

Lightly touching an earth-fixed external surface with the forefinger provides somatosensory information that reduces the center of pressure (CoP) oscillations. If this surface were to move slowly, the central nervous system (CNS) would misinterpret its movement as body self-motion, and involuntary compensatory sway responses would appear, resulting in a significant coupling between finger and CoP motions. We designed a forefinger moving light-touch biofeedback based on this finding, which controls the surface velocity to drive the CoP towards a target position.

Here, we investigate this biofeedback resistance to cognitive processes. In addition to a baseline, the experimental protocol includes four main conditions. In the first, participants were utterly naive about the feedback. Then, they received additional reliable sensory information. The third condition ensured their full awareness of the external nature of the surface motion. Finally, the experimenter notified them that the external motion drives their balance and asked them to reject its influence.

Our investigation shows that despite the robustness of the proposed biofeedback, light-touch remains penetrable by cognitive processes. For participants to dramatically reduce the existing coupling between the finger and CoP motions, they should be aware of the external motion, how it impacts sway, and actively reject its influence.

The main implication of our findings is that light-touch exhibits the same cognitive flexibility as vision when artificially stimulated. This could be interpreted as a defense mechanism to re-weight these two sensory inputs in a moving environment.

1. Introduction

Independent artificial manipulation of sensory inputs evokes coupled postural responses. The strength of this coupling may depend on cognitive processes, including awareness, prediction of the forthcoming events, central multisensory integration, and voluntary control. When manipulating sensory inputs signalling only self-motion, the coupling remains strong regardless of the presence of cognitive processes. In contrast, cognitive processes can weaken or even preclude the coupling, during artificial manipulation of senses reporting both external and self-motions.

Vestibular and kinesthetic sensory inputs signal only body self-motion. A typical way of artificially manipulating the vestibular sensory modality is to apply galvanic vestibular stimulation (GVS) to the vestibular nerves [1,2]. Once applied, the participant experiences a virtual rotation and leans in the opposite direction. GVS stimulation is immune to cognitive processes [3]. The coupling remains high regardless of the awareness of the artificial nature of the stimulus, pre-cueing of its occurrence or even its self-triggering. Applying vibrations to neuromuscular spindles at the calves muscles' level is a usual way to manipulate kinesthetic channels artificially. It induces a false sensation of falling forward [4], and an automatic backward postural response is then triggered. This artificial stimulus is also immune to cognitive processes, as reported in [5]. Prediction or self-triggering could only delay the evoked response.

Vision signals both external and self-motions. People, standing in a room, whose walls are moving slowly, experience illusory self-motion. Postural reactions are then engaged in the same direction of the moving walls [6,7]. Unlike vestibular inputs and muscle spindles, if anything alerts participants about their misinterpretation of the visual information, the evoked sway may be strongly inhibited [8].

Lightly touching a stationary surface with the forefinger is a

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significant sensory input to postural balance. It diminishes dramatically sway without providing any mechanical support [9]. However, if the surface moves periodically and slowly, body sway shows an automatic coupling to the stimulus trajectory [10,11]. Like vision, a moving light touch leads, most of the time, to a perceptual ambiguity. The central nervous system (CNS) misinterprets the surface movement as self-motion [12]. We designed a forefinger moving light-touch biofeedback based on the finding of Jeka et al., which controls the surface's velocity to drive the CoP towards a target position [13]. Our control sets the surface speed proportional to the error between the current and the target CoP positions. We tuned the control to keep the speed low with the objective of increasing the pre-mentioned sensory ambiguity.

Due to sensory re-weighting mechanisms, providing participants with a reliable additional sensory input may decrease the evoked postural responses. For example, if participants could benefit from light-touch with a stationary surface, postural responses to visual stimuli [14,15], tendon vibration [16] and galvanic stimulation [17] would decrease significantly. Jeka et al. reported that the coupling strength is also subject to multisensory integration mechanisms [15] and that opening the eyes can reduce coupling for moving light touch.

This paper questions our biofeedback resistance to the following cognitive processes: the addition of reliable sensory information, the explicit awareness of the motion's external nature, and the understanding of the potential coupling associated with the instruction to reject it actively. Our investigation shows the robustness of the proposed feedback. For participants to dramatically reduce the existing coupling between the finger and CoP motions, they should be aware of the external motion, how it impacts sway, and actively reject its influence.

The main implication of our findings is that light-touch behaves to a large extent, like vision when taking into account cognitive processes. Similarly to vision, participants could drastically reduce the coupling between a moving-light touch and the evoked postural responses.

2. Methods

2.1. Participants

The study, achieved at Sorbonne University, complied with the Helsinki declaration relative to research involving human beings and received the approval of the local ethical committee.

Forty-four healthy participants, divided into three groups, were involved in the experiments. Participants did not present any known neurological or postural history. Table 1 summarizes the descriptive statistics of the three groups.

2.2. Experimental setup

Fig. 1 shows a view of the experimental setup. It consists of a force plate (AMTI BP400600-1000) and one Degree of Freedom (DoF) translational device, which workspace is of 6 cm. A typical trial consists of a participant standing on the top of the force plate and lightly touching the translational device.

Table 1
Participants characteristics summary. GR1, GR2 and GR3 designate three separate groups. N indicates the sample size of each group. BMI stands for Body Mass Index. Quantitative data is presented as medians (interquartile ranges). N. S. means non-significant.

	GR1 ($N = 18$)	GR2 ($N = 13$)	GR3 ($N = 13$)	Statistical significance
Age (years old)	22 (10.5)	22 (3)	22 (2)	N.S.
BMI (kg m^{-2})	22.5 (4.7)	21.1 (3.3)	21.9 (4.1)	N.S.
Gender (f/m)	7/11	5/8	5/8	N.S.

The force plate measures forces and torques applied by standing participants, which allows the computation of the CoP position. The translational device encloses a force sensor which measures the applied finger's six force components (see top-left in Fig. 1). Participants hear an alarm sound each time the applied vertical force exceeds 1N. Two Light-Emitting Diodes (LED), are placed on the top of the translational device. The LEDs are either off or on to indicate the direction of movement of the translational device (see top-right in Fig. 1). Participants put their finger on a double-sided tape to avoid sliding on the translational device.

A DC motor drives the translational device motion, and thus participants' forefinger, with a linear motion resolution of 0.003 mm. Loudspeakers broadcast continuously pink noise in the experimental room to prevent hearing the sound from motor and associated mechanical parts. A white sheet, covering the experimental setup, prevents participants from guessing that a translational mechanism is in play. During the experiment, the translational mechanism was placed in front of participants and oriented to produce translation in the sagittal plane.

Custom software controls the motion of the translational mechanism (more specifically its velocity) and collects the data in real-time with a refresh rate of 500 Hz.

2.3. Moving light-touch Biofeedback design

In [13], we proposed moving-light touch biofeedback allowing an automatic displacement of the CoP to a new target position in the sagittal plane.

We controlled the lightly touched translational mechanism velocity to be proportional to the difference between the target and the current CoP positions (see bottom-left in Fig. 1). The translational device drives CoP along a smooth path CoP_{Ref}, until reaching the final spot.

The control law writes:

$$V_{\text{Finger}}(t) = K(\text{CoP}_{\text{Ref}}(t) - \text{CoP}(t)) \quad (1)$$

where V_{Finger} is the velocity of the finger (equal to the velocity of the translational mechanism) at sample time t, CoP_{Ref} is the reference trajectory, $\text{CoP}(t)$ is a 0.3 Hz Butterworth low-pass filtered current CoP position in the anteroposterior direction. In other words, biofeedback works as follows: if a participant leaned forwards and overreached the desired value of the reference trajectory (i.e. $\text{CoP} > \text{CoP}_{\text{Ref}}$), the translational mechanism would move backwards to bring back CoP toward CoP_{Ref}, and conversely.

The feedback gain K is equal to 0.96 s^{-1}. We tuned it empirically to maintain V_{Finger} low enough with an average of about 1 mm s^{-1} during our experimental session. This tuning aimed at increasing the ambiguity between external and self-motions.

The time-domain description of the reference trajectory (CoP_{Ref}) includes four-time intervals (in blue in Fig. 1):

0–10s: there is no control. The software computes the average of CoP.
10–20s: CoP_{Ref} is equal to the mean of CoP computed during the previous time interval.
20–30s: CoP_{Ref} is a smooth trajectory moving 8mm forward.
30–60s: CoP_{Ref} remains constant at its new value (8 mm away from the initial position).

2.4. Data collection and processing

For each experimental trial, we recorded CoP_{Ref} and raw CoP corresponding to the reference and the current CoP position (unfiltered) in the sagittal plane.

We introduced an evaluation criterion called ϵ that quantifies the closed-loop performance, and consequently the strength of the coupling between the finger and CoP motions:

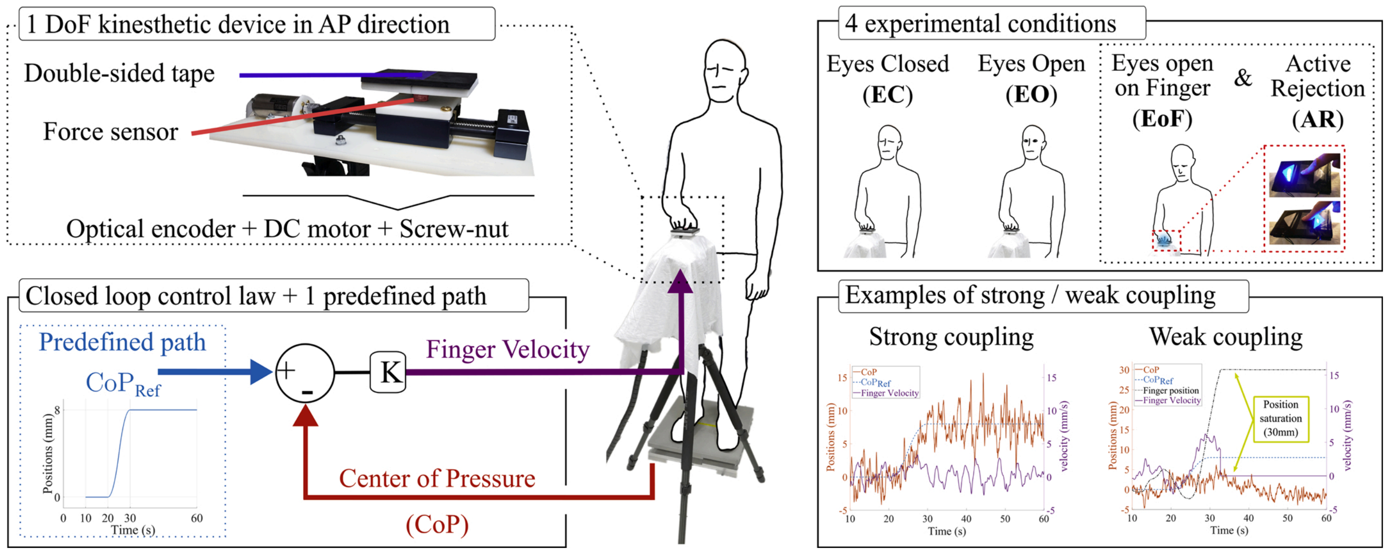

Fig. 1. In the figure center, a participant is standing on the top of a force platform and lightly touching the translational device. From top to bottom and from left to right: (1) a close view on the translational device composition, (2) a block diagram of the closed loop, with a time domain description of CoP_{Ref}, (3) the four experimental conditions, with a highlight on the illuminating LED, (4) two temporal representations of a closed-loop results. The first illustrates a strong coupling: the CoP in red follows the predefined path in blue, the velocity plot in purple is low. The second illustrates a weak coupling: the CoP is far from the predefined path, the moving plate reach its mechanical limits (saturation) and thus the velocity is equal to zero.

$$\epsilon = \frac{1}{N}\left|\sum_{N}(\mathrm{CoP}_{\mathrm{Ref}} - \mathrm{CoP})\right| \quad (2)$$

N designates the number of samples of the experiment when the biofeedback was on (i.e. the [10–60]s time interval). This tracking error qualifies the efficiency of the closed-loop performances. The higher the tracking error is, the weaker is the coupling. A high ϵ indicates a failure in driving the CoP around the reference trajectory. An upper-bound of 8 was assigned to the error.

2.5. Experimental procedure

All participants were utterly naive about the goal of the experiment. For all the conditions, participants stood on the top of the force platform and touched the double-sided tape, located on the top of the translational mechanism, lightly with the index of their dominant hand. As soon as normal force exceeds 1N, an alarm sound is emitted and participants are asked to release the pressure. They held the other arm along the body. The experimenter adjusted the height of the translational device for each participant. Fig. 1 illustrates the experimental protocol. The experimenter controlled visually the participants' upper limb configuration, which they kept almost the same during the whole experiment. We also checked that the upper limb configuration was far from all joint limits.

We instructed participants to keep a neutral upright standing.

The experiment, consisting of providing participants with our moving light-touch biofeedback, included a baseline and four main conditions:

- **W/O feedback**: In each trial, we considered the [0–10]s time lapse where the moving-light touch feedback was off. We computed the average CoP position during the first 5 seconds, and we considered a hypothetical 8 mm forward reference for the remaining time to obtain a baseline score ϵ. This condition is the baseline.
- **EC**: Participants kept their eyes shut. The LEDs were off.
- **EO**: Participants kept their eyes open and looked at a cross drawn on a wall located 50 cm in front of them. The LEDs were off, and the moving plate was outside their field of view. This condition consists of *adding reliable sensory input*.
- **EOF**: Participants kept their eyes open and looked at the translational device. The experimenter told them that the translational device is moving. The LEDs were on and indicated the direction of motion of the plate (i.e. forward or backward). This condition consists of *adding the awareness about the external movement.*
- **AR**: Participants, aware of the external motion, are always looking at their finger, with the LEDs indicating the direction of movement of the plate. The experimenter informed them about the existing coupling between their finger motion and their postural sway. The instruction changed: in this condition, they should try to reject the coupling. This condition corresponds to *a change from a neutral standing to voluntary rejection of the coupling.*

Participants achieved each condition three times. We thus computed three tracking errors, and the average is denoted ϵ.

Participants of **GR1** took part in the five conditions. The W/O feedback condition was always the first presented one. Then, the two second conditions (**EC** and **EO**) were presented randomly. The two remaining conditions took place in the same order: **EOF** and then **AR.** No further randomisation was possible since participants were gaining awareness progressively.

In order to check that participants of **GR1** did not benefit from learning or habituation, two other Groups were involved. In addition to the W/O feedback, participants of **GR2** and **GR3** were involved respectively in the **EOF** and **AR** conditions.

2.6. Statistical analyses

Taking into account the relatively small sample sizes of the groups included in the study, we present the descriptive statistics describing the data as medians (Inter-Quantile-Range), i.e. *Mdn (IQR)*, and we use non-parametric methods for analyses.

We investigated the null hypothesis validity for gender ratio, BMI, and age between Groups using a χ^2 and two Kruskal–Wallis tests.

A Kruskal–Wallis test allowed checking the rejection of the null hypothesis for the **W/O feedback** condition between the three groups.

The investigation of the null hypothesis between the tracking error during the different conditions (**W/O feedback**, **EC**, **EO**, **EOF**, and **AR**) for **GR1** relied on a Friedmann test analysis. If the test rejected the null hypothesis, Post hoc paired Wilcoxon tests, with a Bonferroni correction, is used.

Two Wilcoxon signed-rank tests allowed checking the existence of a significant difference between the **W/O feedback**, **EOF** and **AR** respectively for groups **GR2** and **GR3**.

A Mann–Whitney *U* test allowed the comparison of the tracking error between Groups (**GR1/GR2**), and (**GR1/GR3**) for the **EOF** and **AR** conditions, respectively. A final Mann–Whitney *U* test allowed the comparison of the tracking error between **GR2** in the **EOF** condition and **GR3** in the **AR** condition.

The statistical level of significance has been set at $p = 0.05$.

3. Results

3.1. Participants

Table 1 summarises the three groups characteristics. The groups did not differ by gender, χ^2 (2, $N = 44$) = 0.001, $p = 1$. Two Kruskal–Wallis tests rendered no significant difference between groups for age (H(2) = 0.1, $p = 0.95$) and BMI (H(2) = 3.89, $p = 0.143$).

3.2. The tracking error ϵ

Fig. 2 shows a Tukey outlier boxplot of the tracking error score ϵ.

Between groups comparisons. A Kruskal–Wallis indicated no significant difference (H(2) = 2.21, $p = 0.33$) for the **W/O feedback** conditions between the three groups **GR1** (*Mdn* = 7.99), **GR2** (*Mdn* = 7.81), and **GR3** (*Mdn* = 7.14).

A first Mann–Whitney *U* test indicated no significant difference in the **EOF** condition between **GR1** (*Mdn* = 2.14) and **GR2** (*Mdn* = 0.85), $U = 90$, $p = 0.293$. The second Mann–Whitney *U* test indicated no significant difference in the **AR** condition between **GR1** (*Mdn* = 4.3) and **GR3** (*Mdn* = 3.3), $U = 87.5$, $p = 0.242$. The final Mann–Whitney *U* test indicated a significant difference between **GR2** (*Mdn* = 0.85) and **GR3** (*Mdn* = 3.3) involved in the **EOF** and **AR** conditions respectively. The test statistic *U* was equal to 134.5, with $p = 0.009$.

Comparisons within GR2. A Wilcoxon signed-rank test showed a significant difference between the **W/O feedback** and **EOF** conditions, $T = 91$, $z = -3.81$ and $p < 0.001$.

Comparisons within GR3. A Wilcoxon signed-rank test showed a significant difference between the **W/O feedback** and **AR** conditions, $T = 78$, $z = 3.3$ and $p < 0.01$.

Comparisons within GR1. A Friedman's test rendered a significant difference between the five conditions for **Gr1**, $\chi^2_F(4) = 57.9$, $p < 0.001$. Post hoc analysis using Wilcoxon rank-sized test with a Bonferroni adjustment showed significant pairwise comparisons between the **AR** and **W/O feedback**, $p < 0.01$. **W/O feedback** is significantly different from the other conditions, $p < 0.001$. **AR** is is significantly different from the other conditions, $p < 0.01$.

Fig. 2 summarizes the main results. Our results show that the **AR** and **W/O feedback** are significantly different, which means that the coupling is not completely rejected. The significant difference between the **AR** and the **EC**, **EO** and **EOF** conditions suggest a drastic decrease of the coupling when participants are actively rejecting it.

4. Discussion

The main finding is the robustness of our proposed biofeedback to cognitive processes. Nevertheless, light-touch is still penetrable by cognitive processes. To dramatically reduce the existing coupling between the finger and CoP motions, participants should be aware of the external motion, how it impacts sway, and actively reject its influence. Results from groups **GR2** and **GR3** suggest the absence of a significant learning effect during the experimental session. We will discuss the results obtained from **GR1**.

Light-touch compares well to vision. Unlike vestibular and kinesthetic inputs, cognitive processes could reduce the coupling of evoked postural responses to their artificial manipulation. The similarity between vision and light-touch is due to their capacity to signal self and environment movements [3,5,8]. These two sensory information are subject to ambiguous information, especially in a moving environment. To this regard, the re-weighting mechanism (either sensory or cognitive), could be seen as a defense mechanism allowing to maintain an upright posture in a moving environment.

The environmental motion could either present high dynamics (high amplitude and high velocity) or low dynamics (low amplitude and low velocity). In the former, vision and light-touch can easily separate the external and self-motion. In the latter, the ambiguity increases, and the

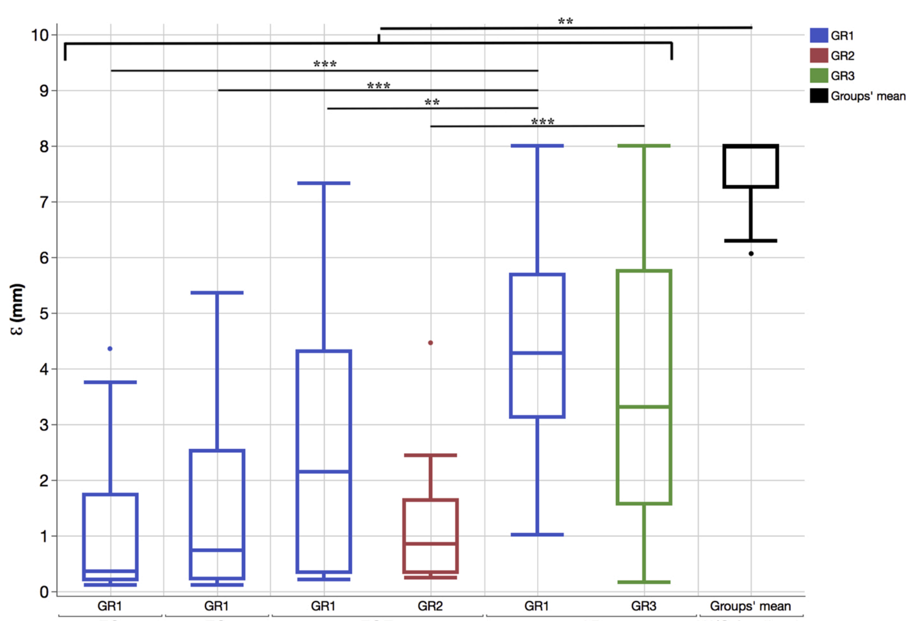

Fig. 2. A Tukey outlier boxplot of the tracking error. Note that for sake of clarity, the W/O feedback of all the groups are merged. The full statistical analyses are provided in Section 3.

separation becomes difficult. Barela et al. showed, in their work [18], a group of participants not aware of the used moving-room paradigm were able to reduce the coupling after being exposed to a faster and larger moving-room motion. The increase in dynamics allows an implicit understanding of the stimulus and its influence on posture, which in turn allows a greater attenuation of the coupling than in the case of an explicit indication from the experimenter. This compares favourably to light-touch, where postural responses also depend on the stimuli dynamics. In [19], the authors displayed ten consecutive high-velocity and high-amplitude linear sagittal stimuli. In the first trial, more than half of the participants perceived by themselves the platform motion and their involuntary postural responses, which then vanished in subsequent trials. According to the authors, participants understood their overreaction and chose to actively ignore the stimulus. The cited study is in line with our results. The weaker coupling comes from the learnt awareness of the external motion and its influence on postural balance. The coupling rejection was not due to an explicit instruction from the experimenter but is instead an effect of understanding that the first evoked postural response could have threatened balance stability. When the stimulus is periodic and presents a low velocity and low amplitude, it becomes less easy to be detected and the coupling less easy to reject. The low dynamics of the stimulus increases its ambiguity. The authors of [20] reported that participants felt that their sway was increasing, without successfully attributing it to the touched device motion. Only one participant attributed the sway increase to the external motion and thus exhibited weaker coupling. This finding compares favourably with the results of [7,18], where the authors informed participants about visual manipulation, and this information allowed them to decrease the coupling, even without being asked to do so. One can conclude that the only awareness of an external motion may change participants' postural control strategy and lead them to reject the coupling, but the change of strategy differs across individuals. In the study of Jeka et al. [10], all participants noticed by themselves that the motion of the moving touched-plate was ambiguous and failed to characterize it. Their postural sway remained strongly coupled to moving plate. One could hypothesize that the awareness of the external motion without understanding its impact on balance could be insufficient to reduce the coupling. Our proposed biofeedback highlights this hypothesis; we designed it to increase the ambiguity, decreasing the probability of guessing its effect on balance. This allows us to induce a relatively large CoP displacement without the participants' knowledge.

In their works [21,22], the authors studied the visual sensorimotor coupling under a moving-room paradigm with participants asked to "resist the room's movement". They reported two results. The first is that the active resistance condition reduces the coupling, in line with the results of this paper. Second, the reducing rate decreased when resisting the visual manipulation and performing at the same time a concurrent cognitive task, since the attentional resources should then be shared. Preliminary trials reported in [13], indicates that the proposed biofeedback performances were not significantly influenced by a concurrent cognitive task. This is a little bit contradictory with the results of [23,24], where a concurrent cognitive task altered the assistance provided by lightly touching a stable surface. One should notice, that none of these studies required intentional resources dedicated to the coupling between posture and the stimuli. A moving-light touch paradigm with the explicit instruction to reject the coupling, associated with an additional cognitive task, needs to be addressed carefully.

Finally, our biofeedback contrasts with previous studies on moving-light touch. Unlike the results reported in [15], where the addition of a stationary visual input reduced the sensorimotor coupling significantly, our study revealed no significant difference between the **EC** and **EO** conditions. The median slightly increased when participants looked at earth grounded visual information, but to a lesser extent than expected. The design and the tuning of the biofeedback explain the difference: it is based on the current CoP position and tuned to increase the ambiguity. Any attempt of reducing the coupling, e.g. due to a piece of reliable sensory information, will result in deviation of the CoP position. This deviation would constitute an error, and the biofeedback will gently compensate for by bringing the CoP to its target position.

In conclusion, the main implication of our findings is that light-touch behaves to a large extent, like vision when taking into account cognitive processes. Similarly to vision, participants can voluntary reduce the coupling between a moving-light touch and the evoked postural responses. A plausible interpretation is that, as a defense mechanism, the CNS is able to re-weight these two sensory inputs to preserve balance in moving environments. Future research needs to focus on the attentional resources sharing when participants are asked to resist the coupling while achieving a concurrent dual-task.

Authors' contribution

The authors contributed equally to conceptualization, methodology, data analyzes, writing and editing.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.neulet.2021.135743.

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