



## The precision demands of viewing distance modulate postural coordination and control

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### ABSTRACT

There are contrasting views on the role of vision in modifying postural organization (information-driven and postural facilitation) and limited direct tests of the underlying postural mechanisms. Here, we examined whether the distinction between the two views is appropriate given that both are interrelated parts of task constraints modulating postural coordination and control. The study investigated whether changes in the organization of the postural system are a function of the visual precision demands of a task and, in addition, whether such organization could be described as reflecting an intermittent controller. Sixteen participants were instructed to maintain quiet postural stance while fixating a point at different viewing distances (25, 50, 135, 220, 305 cm) or standing with eyes closed. The 25-cm condition showed the lowest standard deviation of the center of pressure (COP) and the highest correlation dimension (CD) in the anterior posterior direction. Analyses revealed that, contrary to the intermittent controller hypothesis, adaptations in the continuous COP and center of mass (COM) coupling characterized the observed changes in CD. The findings show that the natural act of looking to the same feature in the environment as a function of visual viewing distance can lead to quantitative and qualitative changes in the dynamics of posture. This is consistent with the view that postural facilitation and information availability are integrated in the perceptual-motor dynamics.

### 1. Introduction

There is an ongoing debate on the cause and effect relationship between the outcomes of the postural system and task manipulations usually implemented under the quiet standing paradigm (e.g., availability of visual information, light-touch of a finger on a surface, etc.). On one hand, it is traditionally assumed that changes in postural behavior are a consequence of differences in information input – where more information reduces postural sway (e.g., Day, Steiger, Thompson, & Marsden, 1992; Lee & Lishman, 1975; Peterka, 2002): heretofore labelled the “information assumption”. On the other hand, there is the view that changes in postural measures reflect an active facilitation of the postural system to attend to new demands imposed by task manipulations (e.g., Mitra, 2004; Mitra & Fraizer, 2004; Riccio, 1993; Riley, Stoffregen, Grocki, & Turvey, 1999). That is, the postural system would actively increase/decrease sway in order to facilitate achievement of a task goal (e.g., maintain visual fixation, oscillate in synchrony with a stimulus). This perspective, here, is called “postural facilitation assumption”.

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An illustrative example of the contrasting views is whether the reduced postural sway of individuals with eyes open, as opposed to eyes closed, reflects the addition of visual information reducing the amplitude of postural sway or more fundamentally a qualitative reorganization of the postural dynamics to facilitate eye fixation. Notice that the latter is not simply stating that different tasks result in different postural behaviors. Rather, that the postural system modifies its dynamics to achieve a task goal: the system acts differently given a set of task requirements.

### 1.1. Postural coordination and control

The debate comes from the fact that the two interpretations (information driven and postural facilitation) cannot be differentiated in some situations. From the dynamical system approach, the organization of behavior can be captured by its invariant (topological) properties (its coordination function – Newell, 1985). Within a single coordination function, one can scale its parameters (maintaining its invariant properties) to attend to specific demands of the situation. Such scaling reflects “control” embedded in a coordination function.

One can contrast the information and postural facilitation assumptions based on this approach. Lee, Pacheco, and Newell (2018) proposed that if an experimental manipulation modifies the system’s coordination dynamics, the postural system is facilitating the achievement of a task. Manipulations that would reflect modifications in information input, on the other hand, would not modify the system coordination, just the scaling properties of “control”. The study showed that for visual manipulations, the COP maintained the same attractor dynamics while the addition of a light touch in the task induced a new postural organization. In this sense, the light-touch condition demonstrated a postural-facilitation to achieve the task goal; visual manipulations (i.e., open-eyes/closed-eyes) modified the information input and the degree of postural sway.

However, it is questionable whether the information-driven and postural facilitation interpretations of perceptual-motor control can be distinguished in this manner. The relation between information pickup and action is determined by the task, implying an intricate relation between perception and action (Warren, Kay, & Yilmaz, 1996). That is, the postural organization cannot be considered in terms of postural facilitation only but as an emergent result of the task constraints – that include information availability and goal demands (Newell, 1986). Under this systems approach to behavior, one cannot separate information and postural facilitation influences on postural coordination and control.

### 1.2. Precision demands modifying postural coordination and control

To examine information-driven and postural-facilitation assumptions, we tested an alternative explanation that considers information and postural facilitation as intricately related in posture. The coordination and control of action is dependent on the system’s intrinsic tendencies in acting (Kelso, 1995). Information availability and goal requirements are related parts of the task constraints. One can act in given ways if the required information is available and if this supports goal achievement. Thus, postural facilitation occurs as information is available for this to occur.

In this study, we manipulated the precision demands of a perceptual-motor task. Studies have shown that when a task requires precision in movement control of a concurrent action (e.g., placing an object in a small opening), it induces significant modifications on posture (Balasubramaniam, Riley, & Turvey, 2000; Chen & Stoffregen, 2012; Haddad, Ryu, Seaman, & Ponto, 2010). Additionally, information availability (spatial gain, temporal intermittency) has been shown to modulate how precise individuals are, even when the task requirements are similar (e.g., Lafe, Pacheco, & Newell, 2016; Vaillancourt, Haibach, & Newell, 2006).

Here, we systematically manipulated the precision demands in vision based on the retina image slip hypothesis (Paulus, Straube, Krafczyk, & Brandt, 1989). Fig. 1 provides a sketch of the hypothesis that states that the essential visual cue for postural control is retinal target displacement. For a given movement of the head, the amplitude of the optical flow is a function of the distance between each element of the visible surroundings and the point of observation. Closer objects will lead to greater optical change (angle  $\beta$  in Fig. 1) when compared to far objects (angle  $\alpha$  in Fig. 1) for the same amount of head motion. Thus, for the same amount of postural sway, target displacement increases as eye-target viewing distance is reduced. This target displacement angle changes with distance can be conceptualized as a change in visual angle gain.

In the experiment reported here we asked individuals in independent conditions to look to a target at different distances with the instruction to minimize postural sway as much as possible. If the information assumption holds, individuals are to maintain their posture in terms of the perceived motion in relation to a given target (i.e., visual angle gain). Then, postural sway would decrease as eye/target distance decreases (Kapoula & Lê, 2006; Lee & Lishman, 1975; Paulus et al., 1989). Body sway causes visual deviation from the fixed-point providing information needed for postural adjustment. The qualitative properties of the attractor dynamics, nevertheless, would remain the same provided the postural system is only perceiving more detailed information to scale the postural organization. If postural facilitation assumption holds, given that the instruction is to minimize postural sway while maintaining eye fixation on the target, the system should show no changes from all conditions: the system would facilitate task achievement similarly independent of the information available. Then, in this case both postural sway and attractor dynamics would be similar for all conditions. If this hypothesis holds, the system would facilitate goal achievement as information becomes available. Thus, postural sway would decrease as visual gain is increased and, as it reaches a critical level, attractor dynamics will change demonstrating active reorganization of the postural system to attend the task requirements. The dispersion measures of body sway (e.g., standard deviation) will follow changes in visual gain and reveal changes in attractor dynamics (e.g., correlation dimension [CD]). This is because postural coordination would change to achieve the task goal (postural facilitation) as a function of the available information.

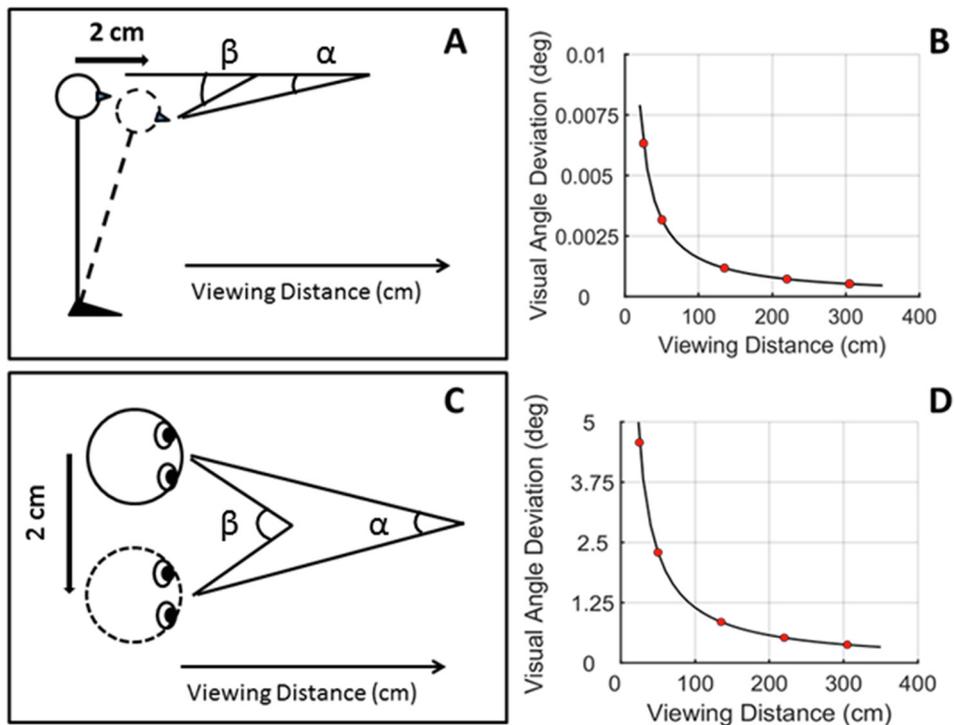


Fig. 1. Schematic of the resultant visual angle gain for postural sway in AP and ML for different eye-target distances. Figures A and C illustrate the differences in visual angle gain for long and short eye-target distances in AP and ML, respectively. Figures B and D show the visual angle gain as a function of eye-target distances assuming a 2-cm postural sway in AP and ML, respectively.

### 1.3. Postural system as an intermittent controller

It is also necessary to determine what the underlying process is that results in the observed changes in the CD of the postural dynamics. Although the head sway in a looking task is a variable of main relevance (Stoffregen, Smart, Bardy, & Pagulayan, 1999; Mitra, 2004; Stoffregen, Bardy, Bonnet, Hove, & Oullier, 2007), the multi-segmental nature of the postural system allows several means to achieve this goal – requiring investigation at this level.

We based our analyses on the intermittent control hypothesis; postural corrections are triggered when an organizational variable for posture crosses a critical value (Asai et al., 2009; Loram & Lakie, 2002; Resulaj, Kiani, Wolpert, & Shadmehr, 2009). This variable could be COM relative position to COP or the Head position. In intermittent control models (e.g., Asai et al., 2009; Bottaro, Casadio, Morasso, & Sanguineti, 2005), it is possible to have regions of passive constraint (e.g., stiffness, viscosity coefficients) and active ankle torques (e.g., feedback-driven) that are, respectively, continuous and intermittent. Small perturbations are damped out by a continuous feedback gain while large corrections occur when the system crosses a boundary value.

If precision demands drive both passive (gain) and active (threshold) parameters, we can interpret that a small difference on precision demands increases the passive gain and decreases the threshold (slightly). This would cause the system to have an overall lower SD (provided increased gain) but would not show qualitative differences. With large precision demands, on the other hand, the threshold would decrease markedly. This would lead the system to perform active corrections more frequently – modifying the observed dynamics (altering CD). That is, when the visual system detects the body sway over a threshold that is detrimental to visual stabilization, a postural adjustment will be induced. This sudden burst of activity in postural coordination could be revealed in the frequency-time profile of the COP, COM and head motion couplings. That is, COP/COM coupling with head would be observed when the postural system altered its sway to compensate head motion to maintain the looking. Given that the short eye-target distance amplifies the visual deviation, the system would perform active corrections more frequently.

In summary, we manipulated the precision viewing demands of the task by scaling the eye-target distance to test if visual viewing distance altered postural organization demonstrating a tight relation of information availability and postural facilitation. It was hypothesized that if this is the case, distinct CD values representing qualitative changes in postural organization would be observed between the far and near eye-target distances. Finally, we examined whether this could be explained by the occurrence of more frequent (intermittent) corrections in posture observed through increased bursts of posture–head movement coordination to support the perceptual-motor postural task.



**Fig. 2.** Schematic of the eye-target distance manipulation. The participant was asked to maintain the eye fixation at a point that was projected by a laser pen.

## 2. Methods

### 2.1. Participants

Sixteen individuals participated in the present study ( $24.8 \pm 3.9$  years, 9 females). None of the participants reported skeletal or neuromuscular disorders and physical injury for the past 8 weeks. All of them had normal or corrected to normal vision. Informed written consent was obtained before the experiment. The Institutional Review Board of the University of Georgia approved all experimental procedures.

### 2.2. Apparatus

The kinetic data of postural motion were recorded in the anterior-posterior (AP) and medial-lateral (ML) directions using two force platforms (AMTI, Watertown, MA). The center of pressure (COP) time series was calculated based on the ground reaction force and moments in the 3 orthogonal directions. The Vicon Plug-in Gait full body marker set (39 markers) and model were used to generate the kinematic and kinetic data. The kinematic and kinetic data were synchronized and sampled at 100 Hz. The individuals stood in front of a white background, and a tripod with a square white target ( $5 \text{ cm} \times 5 \text{ cm}$ ) was put in front of the individual (the distance was manipulated in each condition). This setting prevented participants to relate to another object in the environment as a reference for postural adjustment. Attached to a tripod, a laser pen was used to project a static light point on the center of the target from the rear side of the participant (Fig. 2).

### 2.3. Task and procedures

Participants stood barefoot on two adjacent force platforms using the side-by-side foot position (25 cm apart) with each foot on a separate force plate and both arms hanging naturally at their side. During the testing, they were instructed to maintain standing position and minimize postural sway while looking at a point projected in front of them at their eye level. We manipulated the visual viewing distance at 25, 50, 135, 220 and 305 cm. A closed-eyes condition was also included. This experimental design provided a way to replicate Lee et al. (2018) eyes closed and 305 cm conditions and covered a range of observed changes in postural sway given eye-target distances (cf. Paulus et al., 1989).

The goal of the task was to minimize postural sway and maintain eye fixation on the target point. The 6 viewing distance conditions were repeated 3 times. The total 18 trials (6 conditions  $\times$  3 trials) were randomized for each participant. Each trial lasted for 2 min. The trial length was based on Lee et al. (2018) results which showed that 2 min standing time (12,000 data points) is required to estimate a system with CD around four (see Williams, 1997 for details on the length requirements). The participant was allowed to take a break if requested and at least 5 min rest was provided between every 6 trials to avoid fatigue. The entire experiment lasted around 1.5 h.

### 2.4. Data processing and analysis

In this study, we analyzed the respective COP time series in both anteroposterior ( $\text{COP}_{\text{AP}}$ ) and mediolateral ( $\text{COP}_{\text{ML}}$ ) directions.

The position of the center of mass (COM) was estimated by applying the equations of [Zatsiorsky and Seluyanov \(1985\)](#). COP, COM and head position were used to identify the coupling between posture sway and visual angle. We discarded the first 2 s of data from each trial resulting in a total trial length composed of 11,900 data points. A fourth order zero-lag Butterworth filter at a 10 Hz low-pass cut-off was used to smooth out high-frequency fluctuation from the signals. The data were analyzed and processed with MATLAB software.

#### 2.4.1. COP dispersion

Standard deviation (SD) was calculated to estimate the amount of motion variability in COP, COM, and Head in both AP and ML directions.

#### 2.4.2. Run test

To perform the correlation dimension analysis  $COP_{AP}$  and  $COP_{ML}$  cannot be random. For a test of randomness, the Run Test was applied (see [Bendat & Piersol, 2011](#)). All trials passed the Run Test and were utilized in the analysis.

#### 2.4.3. Correlation dimension

Correlation dimension (CD) provides an estimate of the geometric structure of the attractor dynamics ([Grassberger & Procaccia, 1983](#), see [Appendix A](#)). We calculated CD on  $COP_{AP}$  and  $COP_{ML}$  time series. The average displacement method ([Rosenstein, Collins, & De Luca, 1994](#)) was used to calculate the time delay in the embedded dimension provided that this method considered the spatial and temporal relation of a single time series as well as reduced computation time. The range of embedding dimension was set up to 20 given that previous literature has shown that the dimension saturated before 12 (e.g., [Gurses & Celik, 2013](#)). The criterion to estimate the embedding dimension ( $m$ ) where CD estimates are saturated followed the equation:  $m \geq 2 * CD$  ([Takens, 1981](#)).

#### 2.4.4. Wavelet analysis

To investigate the nature of the changes on CD, we performed a number of analyses. First, provided that only  $COP_{AP}$  showed CD changes (see results section), we applied the continuous wavelet analysis on the  $COP_{AP}$  time series. Wavelet analysis is a tool to characterize the frequency power in a time series by decomposition into time and frequency domains ([Torrence & Compo, 1998](#)). This method reveals the power spectrum (based on mother/prototype function) in a given time window (see [Appendix B](#)). We applied the Morlet wavelet as the mother/prototype function.

Second, we investigated how COP, COM and head motion were coupled in both frequency and time using coherence analysis. The coherence analysis was based on the continuous wavelet transform (CWT) where the localized correlation coefficient was calculated between the joint powers of two CWT time series (see [Appendix B](#)). The method was applied to each of the three pairs COM-COP, COM-Head, and COP-Head of motions. Prior studies have indicated either that the COM-COP coupling is a variable reflecting global organization of standing system (e.g., [Ko, Challis, & Newell, 2014](#)) in that the COM and COP have a controlled and controller relationship ([Winter, Prince, Frank, Powell, & Zabjek, 1996](#)). Additionally, studies have utilized head position as the variable representing visual stabilization ([Mitra & Fraizer, 2004](#); [Stoffregen et al., 1999](#)).

In order to determine whether power and coherence could be considered statistically significant, we built a probability distribution based on 100 (for CWT) and 100 paired (for coherence) datasets generated as a random walk process – an autoregressive process with one lag. The averaged random walk resultant power spectrum was used as the null hypothesis to test whether the power of a given frequency in a given time from CWT on the COP time series was significant. Also, the resultant coherence distribution was used as the null hypothesis to test whether given paired variables was significantly coupled. Chi-square test was used to perform the statistic test.

To compare across conditions, the percentage of significant power (for COP) or coherence (for the couplings) time (time of significant power/coherence divided by total standing time) for each frequency was calculated. For coherence analysis, the values in the region of the cone of influence (COI)<sup>1</sup> were discarded due to the artificial edge effect. We selected the frequency bandwidth between 0.1 and 4 Hz with log at base 2 interval for further analysis due to artifacts (from COI) below 0.1 Hz and few significant coherence values over 4 Hz.

## 2.5. Statistical analysis

### 2.5.1. Hypothesis tests

The task effects on SD and CD were determined using a one-way repeated measure ANOVA (6 conditions). To test the effect of visual gain on postural sway, we performed a simple linear regression of SD (of COP, COM, and Head in both directions) as the dependent variable and visual angle gain as the independent variable (thus, not including the NV condition). The significance level was set at  $\alpha = 0.05$ . The sample size was based on the result of our previous study ([Lee et al., 2018](#)). These results were presented in [Section 3.1](#).

<sup>1</sup> Cone of influence (COI): To deal with the finite-length time series, the incomplete cycle at the beginning and end of the time series goes through a padding process (a method of extension of the time series). The procedure (independent of the type of padding utilized) causes artifacts at the end and beginning of the wavelet power spectrum (see [Torrence & Compo, 1998](#)).

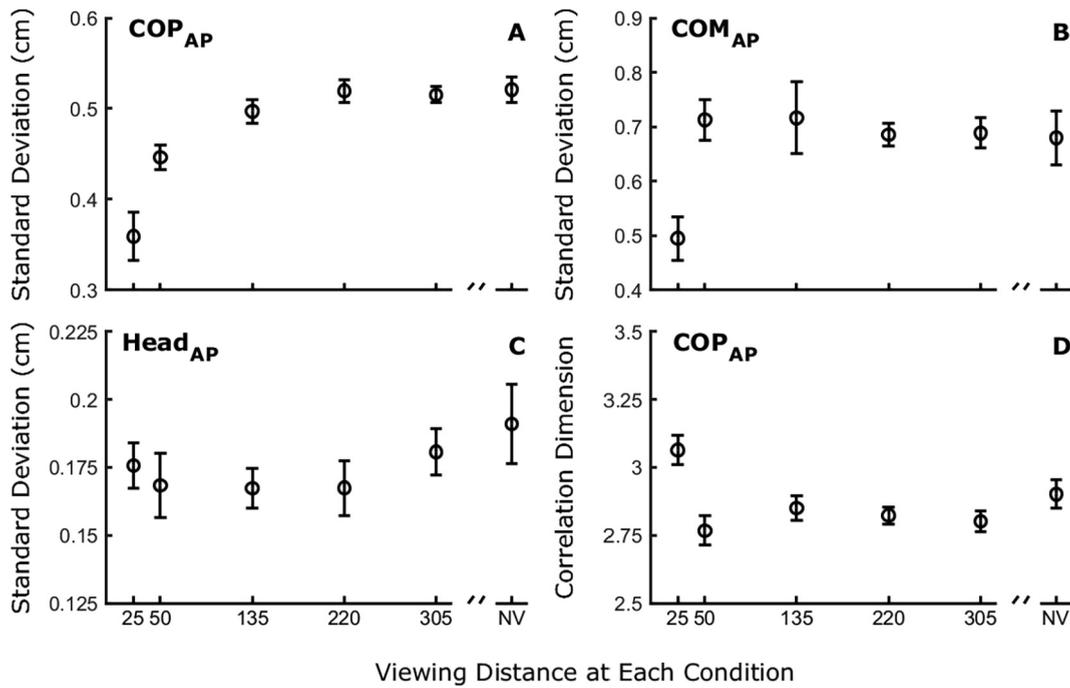


Fig. 3. Mean and 95% confidence interval of standard deviation of COP, COM and Head in AP (A, B and C, respectively) and correlation dimension of COP (Figure D) as a function of target distance and no vision (NV).

2.5.2. Follow-up analysis

For the percentage of significant coupling time, a two-way repeated ANOVA was conducted (6 conditions × 64 frequency bin). To control the familywise error rate for the two-way repeated ANOVA, the sequential Bonferroni procedure was applied to adjust the significant  $\alpha$  level and sequentially evaluate the null hypothesis according to the ascending order of the actual  $p$ -values (Hartley, 1955; Cramer et al., 2016). For the effects that reached the significance level, the standard Bonferroni test was used for the post hoc comparisons. These results were presented in Section 3.2.

3. Results

3.1. Hypothesis tests

3.1.1. Standard deviation (SD)

Fig. 3A, 3B and 3C respectively depict the SD of COP, COM, and Head in AP direction. For COP, both directions showed a significant difference between conditions (AP:  $F[5,75] = 13.58, p < .001, \eta_p^2 = 0.48$ ; ML:  $F[5,75] = 3.65, p = .005, \eta_p^2 = 0.20$ ). The post hoc analyses indicated that in AP direction the SD in the 25-cm condition was smaller than the other conditions, and the SD in 50 cm was smaller than the 305 cm ( $p = .048$ ) and NV ( $p = .021$ ) conditions. The source of the differences on the ML direction could not be found using the post hoc analyses.

For SD of COM, AP reached significant levels ( $F[5,75] = 3.188, p = .012, \eta_p^2 = 0.18$ ). The post hoc analysis indicated that in the AP direction the SD in 25-cm condition was smaller than the other conditions ( $p = .028$ ). There were no condition differences in ML ( $p > 0.999, \eta_p^2 = 0.11$ ). For SD of Head, there was not a significant difference between conditions (AP:  $p = .635, \eta_p^2 = 0.04$ ; ML:

Table 1

The results of the linear regressions for SD of COP, COM and Head SD in AP and ML as a function of visual angle gain ( $SD = a + b * \theta$ ).

		a	b	R <sup>2</sup>
COP	AP	5.33**	-274.40**	0.99
	ML	2.30**	-0.08*	0.75
COM	AP	7.36**	-323.34	0.72
	ML	2.49**	-0.12*	0.81
Head	AP	1.71*	3.67	0.02
	ML	0.19*	0.01	0.21

Note: \*\* significant at  $\alpha = 0.010$ . \* significant at  $\alpha = 0.05$ .  $\theta$  is the visual deviation angle at each viewing distance. All dependent variables were multiplied by 10 so to maintain the estimates up to 2 decimal places.

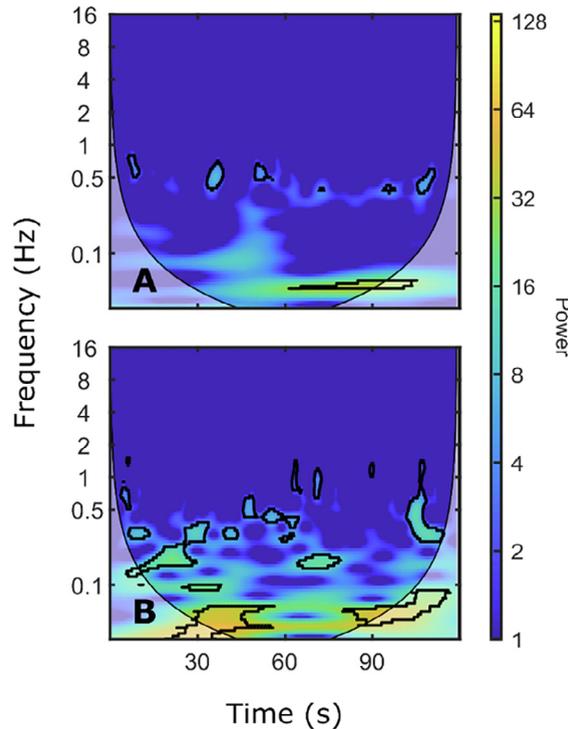


Fig. 4. The two frequency  $\times$  time profiles of CWT from an exemplary subject. Fig. 4A and B provide the 25 cm and NV conditions, respectively.

$p = .276$ ,  $\eta_p^2 = 0.079$ ) in both directions.

Table 1 shows the result of the first order linear regression between SD (COP, COM, and Head) and visual gain. COP<sub>AP</sub>, COP<sub>ML</sub>, and COM<sub>ML</sub> demonstrated significant proportional changes in terms of visual angle gain ( $R^2$  of 0.99, 0.75 and 0.81, respectively) with COM<sub>AP</sub> showing a borderline effect ( $p = .062$ ,  $R^2 = 0.72$ ). SD of Head in both AP and ML did not show a linear relation with the visual angle gain.

### 3.1.2. Correlation dimension (CD)

The main focus of this study was whether the visual manipulations would also induce qualitative modifications in postural organization. Fig. 3D shows the correlation dimension of COP<sub>AP</sub> motion. In AP direction, there was a significant main effect of condition ( $F[5,75] = 4.31$ ,  $p = .002$ ,  $\eta_p^2 = 0.22$ ). The post hoc comparisons revealed that CD in the 25-cm condition was larger than all other conditions ( $p$ 's  $< 0.048$ ). No significant difference was found in the ML direction ( $p = .240$ ,  $\eta_p^2 = 0.08$ ).

## 3.2. Follow-up analysis

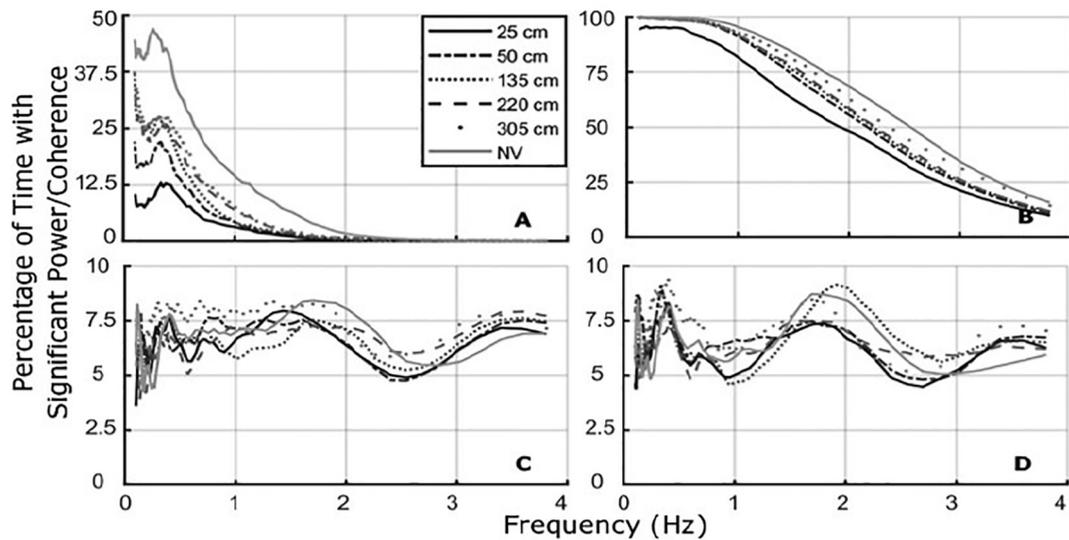
### 3.2.1. COP-AP percentage of significant power time

Fig. 4 depicts two frequency  $\times$  time profiles of an exemplary subject in the 25 cm and NV conditions. Fig. 5A shows the percentage of significant power time in COP<sub>AP</sub> per condition. The two-way ANOVA revealed a significant main effect of condition ( $F[5,75] = 26.10$ ,  $p < .001$ ,  $\eta_p^2 = 0.64$ ), frequency ( $F[63,945] = 30.31$ ,  $p < .001$ ,  $\eta_p^2 = 0.67$ ) and a significant interaction between condition and frequency ( $F[315,4725] = 9.42$ ,  $p < .001$ ,  $\eta_p^2 = 0.39$ ). The post hoc analyses showed that the percentage of time in 25 cm at 0.11–0.95 Hz was lower than the other conditions ( $p$ 's  $< 0.047$ ). In 0.11–1.4 Hz, at low frequency NV was significantly higher than the other conditions ( $p$ 's  $< 0.047$ ). Up to 0.95 to 1.4 Hz, only 25 cm and NV showed a significant difference ( $p$ 's  $< 0.047$ ). No condition difference was found at frequencies larger than 1.4 Hz.

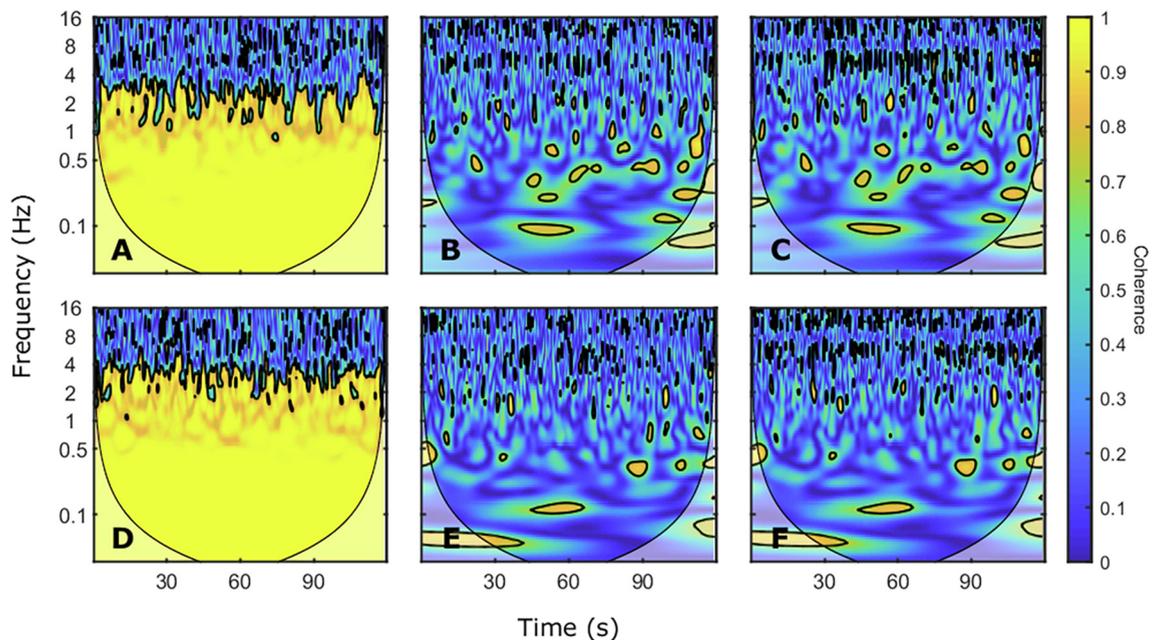
### 3.2.2. COP, COM and head percentage of significant coherence time

Fig. 6 shows example coherence profiles in frequency and time for an exemplary individual in the 25 cm and NV conditions. As can be observed, the coordination pattern of COP-COM was different than that of COP-Head and COM-Head: the COP-COM coupling was significant during most of the trial below 1 Hz frequency and long periods up to 2 Hz ( $82 \pm 1\%$  overall). In contrast, COP-Head and COM-Head revealed intermittent coupling in varied frequencies and trial periods ( $7 \pm 0.2\%$  and  $6.5 \pm 0.2\%$  of significant coherence, respectively). These general patterns of COP-COM, COP-Head and COM-Head coherence occurred across all conditions.

Fig. 5B shows the percentage of coherence time in COP-COM in each frequency and condition. The ANOVA indicated significant main effects for condition ( $F[5,75] = 11.32$ ,  $p < .001$ ,  $\eta_p^2 = 0.43$ ), frequency ( $F[63,945] = 500.54$ ,  $p < .001$ ,  $\eta_p^2 = 0.97$ ), and a significant interaction between condition and frequency ( $F[315, 4725] = 5.74$ ,  $p < .001$ ,  $\eta_p^2 = 0.28$ ). The post hoc analyses



**Fig. 5.** The average percentage of significant power for COP<sub>AP</sub> (A) and coherence time for COP-COM, COP-Head and COM-Head pairs (B, C and D, respectively) as a function of the eye-target conditions.



**Fig. 6.** Coherence profile for representative trials of participant 1 on 25 cm (top row) and NV (bottom row) conditions for COP-COM (A and D), COP-Head (B and E) and COM-Head pairs (C and F). The regions circled by the black thick lines represent significant coherence in the given frequency and time between the time series pairs. The gray shaded area is the COI region. The 0.1–4 Hz bandwidth is considered in our analyses. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

revealed that the NV had a longer coherence time than the conditions with eye-target distance shorter than 135 m in 3.02–3.81 Hz band ( $p$ 's < 0.044). In 2.14–2.85 Hz band, the NV showed a longer coherence time than the other conditions except for 330 cm ( $p$ 's < 0.027). In 1.01–2.02 Hz band, the 25-cm condition had a shorter coherence time than the NV and conditions with eye-target distance longer than the 220 cm ( $p$ 's < 0.047). In the same band, the 50 cm condition showed a shorter coherence time than the NV condition ( $p$  = .047). In 0.8–0.95 Hz band, the 25 cm, and 50 cm conditions showed a shorter coherence time than the NV condition ( $p$ 's < 0.031). In sum, the NV condition showed longer coherence times above 2.14 Hz (differentiating especially from short eye-target distance conditions) and 25 cm and 50 cm showed shorter coherence times in the band from 0.8 to 2.02 Hz (differentiating especially from NV and larger eye-target distances). No differences were found below 0.8 Hz.

Fig. 5C and D show the results of the percentage of significant coherence time of COP-Head and COM-Head, respectively. For

COP-Head, the ANOVA revealed a significant main effect of frequency only ( $F[63,945] = 2.18, p < .001, \eta_p^2 = 0.13$ ). The post hoc analyses failed to find the locus of differences but from the visual inspection, it seems there was a drop of percentage of significant time around 2–3 Hz.

For COM-Head, the ANOVA revealed a significant main effect of frequency only ( $F[63,945] = 2.19, p < .001, \eta_p^2 = 0.14$ ). The post hoc analyses failed to find the locus of differences but from the visual inspection, it seems there were two peaks of percentage of significant time, approximately around 0.1–0.5 Hz and 1.5–2 Hz.

#### 4. Discussion

The purpose of this study was to investigate whether the precision demands of viewing distance in looking at a target altered the qualitative and quantitative dynamics of postural organization. We examined the hypothesis that if information availability and postural facilitation are, indeed, components of a complementary relation, there would be changes in the dynamics of COP (distinct CD values) between different eye-target viewing distances with SD following the visual gain manipulation. In addition, we examined whether the postural organization (and its changes) could be described by an intermittent control model through observing more frequent (and intermittent) posture adjustments in shorter eye-target viewing distance conditions.

##### 4.1. Quantitative changes in postural control

The main findings on dispersion (SD) of postural motion showed in both COP and COM that a smaller SD was observed at the short eye-target distance. The results of the linear regressions indicated that posture dispersion changed as a function of visual angle – i.e. SD of COP<sub>AP</sub>, COP<sub>ML</sub>, COM<sub>AP</sub>, and COM<sub>ML</sub>. These results are consistent with the previous literature showing that with larger visual gain at a short distance, a smaller posture sway was observed (25 and 50 cm) (e.g., Kapoula & Lê, 2006; Lee & Lishman, 1975; Paulus et al., 1989). This effect of visual gain has also been shown in other perceptual-motor paradigms (e.g., Vaillancourt et al., 2006).

For the SD of COP there were different trends over viewing condition in both AP (quadratic) and ML (linear). Previous studies have found a range of proportional increase in postural motion in relation to increased eye-target distance (Kapoula & Lê, 2006; Paulus et al., 1989), but not all have done so (e.g., Guerraz, Sakellari, Burchill, & Bronstein, 2000). One reason for the contrasting findings could be the use of different measures of postural sway (e.g., body sway path in percentage to the baseline condition, variance of speed, sway area) but the fact that we found linear trends for ML and not AP (using both SD) refrain us from this rationale. At present, we consider that the interaction of perception (vestibular, visual, etc.) and action (stiffness, joint motion, etc.) systems might provide some clarification on the issue, but to interpret more than this would be highly speculative.

Our study showed that the dispersion of head position did not change with viewing distance and the variation of head motion was at most half that of COP and COM motion. These results did not follow previous studies that have shown a viewing distance effect on head dispersion – namely, a decrease of head motion with short distances. These studies inferred that the vision requirements (stabilization of head to see the target) induced change postural control to decrease its sway (Mitra, 2004; Stoffregen et al., 1999). The inconsistency of the current and related studies could arise from the experimental design. These earlier studies utilized a larger target size with broader sway tolerance that probably allowed more head variation. Additionally, in their studies, two targets were presented. The presence of multiple targets in both far and near distances might have led participants to switch their viewing focus back and forth. Nevertheless, our task had higher precision demands and induced modification in the postural multilink organization. Importantly, we explicitly instructed participants to stabilize sway while the other studies did not. This was intentional in order to examine the interaction between postural facilitation and information availability.

Our findings are consistent with these previous studies in highlighting the effect of task constraints on posture. The requirement to focus viewing on a single point demands high precision of head position. This was accomplished through a motion of the head of around 0.175 cm (a quarter of the variation compared to Mitra, 2004; Stoffregen et al., 1999). As we will discuss in the next section, the constraints on COP/COM cooperation allowed this range of motion to occur. This points to an interpretation of the standing system acting as a hanging pendulum with the head position relatively fixed while torso and lower limb segments moving to support this outcome. Indeed, the variation of COM and COP were 3 times larger than head motion (see Fig. 3). Similar result was found in a postural task on which individuals were standing on moving base of support (Dutt-Mazumder & Newell, 2017); similar dynamics through different manipulations.

##### 4.2. Qualitative changes in postural control

Measures of postural dispersion (e.g., SD) that do not take into account the dynamics of the system fail to fully describe the system's organization (e.g., Newell, van Emmerik, Lee, & Sprague, 1993; van Emmerik & van Wegen, 2002). When considering the postural dynamics, the results of CD, in contrast to SD, showed differences only for the condition with highest precision demands: the 25-cm viewing distance. Interpreting these results back to the ecological theory of perception-action, if an individual is required to decrease postural sway, posture will cooperate in its function to facilitate the completion of the task in terms of the available information (Mitra, Knight, & Munn, 2013; Stoffregen, Pagulayan, Bardy, & Hettinger, 2000; Stoffregen et al., 1999). Our results showed that the same postural dynamics accommodated such requirements up to the shortest eye-target distance. When the precision demands were extremely high, the postural system dynamics reorganized interacting with the information available.

It can be interpreted that the precision demands acted as a control parameter altering the stability of a given postural organization and revealing a qualitative change in the dynamics (c.f. Haken, Kelso, & Bunz, 1985). The findings indicate that the critical value of

the eye-target distance that separates two qualitative dynamics of quiet stance is somewhere between 25 and 50 cm. That is, when the target distance was above 25 cm (including the NV condition), the visual fixation distance only quantitatively scaled the dynamics (demonstrating changes in sway dispersion). When the precision demands increased (the 25-cm eye-target distance), however, postural organization demonstrated new qualitative and quantitative properties.

These findings extend those of Lee et al. (2018) that provided evidence of the requirements to include non-linear measures to fully comprehend the postural system changes in common quiet standing manipulations. The results here replicated their study showing that the NV condition had the greatest postural sway and no qualitative difference in the attractor dynamics when compared to the 305 cm condition. Nevertheless, when the precision demands were scaled to a greater extent, the same differences that their study observed in the light touch condition (differences in SD and CD) were also found here for vision. Thus, as we have proposed, it is difficult to separate the information and postural facilitation to task requirements as the availability of one alters how one can and will act in a given task.

Our findings point to the interpretation that one cannot hold that different information manipulations serve one or another role without considering the related additional demands that the experimental manipulations pose on the individual. That is, one cannot assume that visual manipulations alter informational or task demands as if these were independent of each other. The task interacts with perception/action possibilities of the individual giving rise to a system that acts using information in a given way for a given task: there is a confluence of constraints to action (Newell, 1986). Manipulations such as those employed here clearly show that precision demands require the postural/motor system to act in given ways for visual information to be picked up and acted upon. Thus, manipulations in experimental task paradigms will alter both information input and how the postural system acts to facilitate performance in action.

The observed changes in postural dynamics occurred only in the AP direction. Although this matches the findings from Lee et al. (2018), we have no firm position on why the changes in dynamics could primarily be observed in this direction. One could consider that this is caused by differences in terms of the number of joint degrees of freedom that *can* act in each direction (as knees, angle, hip have a great contribution for modulation in AP and less in ML). Also, one can consider the fact that the AP variation is approximately two or three times larger than in ML, which might provide a broader range for changes.

#### 4.3. Postural system as an intermittent controller and COP-COM as an essential variable

To deepen our understanding of the observed qualitative changes in postural dynamics, we examined the time/frequency properties of COP, COM and Head motions. We tested the extant hypothesis that the system functioned as an intermittent controller (see Asai et al., 2009) with the CD changes being accompanied by the observance of more frequent corrections in the spectral profile. This would be observed as an increase in power for relatively faster frequencies in COP with more coherence time between COP-COM and COP-Head indicating bursts of intermittent corrections. However, the pattern of results was opposite to our expectations. Considering the COP AP, we found that the time with significant power was mainly at the lower frequency and the closer distance condition showed less significant time than in NV and 305 cm. That is, instead of an increase in power of faster frequencies, the COP decreased sway amplitude at slow frequencies.

When considering the coupling between COP, COM, and Head, we found that COP-COM motions were highly coupled (82% of the standing time) in the 0.1–4 Hz frequency band. This high degree of synchronization remained unchanged irrespective of the eye-target distances at the low-frequency band (< 0.85 Hz). At higher rates (0.85–2.2 Hz), on the contrary, the conditions with highest precision demands (25 cm and 50 cm) showed less synchronized time between COP and COM when compared to 305 cm and NV conditions. Despite the fact that these changes occurred in the same conditions that observed changes in both CD and SD, these results are still contrary to the intermittent control position: the coupling *decreased* and, observing Fig. 5, it was never intermittent in that the COP-COM coupling seemed to be a continuously present feature.

The observed coupling between COP-Head and COM-Head is in line with the expectation of an intermittent controller. The couplings between Head and either COP and COM emerged from the possible strategies that individuals could implement to attend to the task demands (COM-Head could reflect adjustments at the hip while COP-Head would reveal adjustments at the ankle) (e.g., Bardy, Oullier, Bootsma, & Stoffregen, 2002; Bardy, Marin, Stoffregen, & Bootsma, 1999). Sudden bursts of significant coherence were found in the 0.1–4 Hz frequency band which is consistent with intermittent control (see Fig. 6). However, the significant percentage of coherence time showed no difference across conditions and, more importantly, no differences between open and closed eyes (all distances compared to NV condition). It is counter intuitive to interpret that corrections based on visual deviation occurred similarly in a condition where visual input was not provided. Thus, in addition to the fact that the hypothesis that CD changes are related to increased intermittent corrections is false, we could not find more general support for the idea of an intermittent controller in postural organization.

The COP-COM coupling has been hypothesized to be an essential organizing variable in postural control (e.g., Ko et al., 2014; Wang, Ko, Challis, & Newell, 2014). Indeed, we observed here that this coupling was present throughout the lower frequency range of the power spectrum and standing trial time. Considering that many studies have shown that the majority of the frequency power in postural sway resides below 1.0 Hz (e.g., Wang et al., 2014; Zatsiorsky & Duarte, 1999), our findings support the proposition that to maintain upright stance one sustains a tightly coupled relation between COM and COP in the lower frequency band.

The COM-COP coupling was modulated by the eye-target distance conditions (there was a COP frequency  $\times$  time profile) in the same directions as the CD. Furthermore, we found that if the system shows qualitative changes in postural organization, it occurs in terms of this essential COM-COP coupling. This interpretation corroborates with previous studies that have proposed that COM-COP coupling is the collective variable that supports maintaining balance rather than the local joint variables (Dutt-Mazumder & Newell,

2017; Ko et al., 2014). In these studies, the participants stood on an oscillating platform and acted as a hanging pendulum that fixed the head position while allowing the body segments to move in support of head posture. It was shown that as an effect of frequency of oscillation, the system COM-COP coupling would qualitatively change as the platform frequency of oscillation crossed a critical value (see also Wang et al., 2014). The findings here extend these studies in showing qualitative changes in COP-COM coupling in quiet standing as an effect of eye-target viewing distance.

## 5. Conclusion

In closing, we conclude that the visually induced precision demand of a viewing task acts as a control parameter that constrains the coordination and control in standing posture. Our results point to a more integrated view on informational and postural facilitation to task requirements on posture. That is, we have highlighted how perceiving to act and acting to perceive are tightly linked in ways that information availability and action possibilities are inseparable. Qualitative and quantitative modifications of postural organization are emergent from the confluence of information availability as task goals induce behavioral change. This mutuality of influence is consistent with the ecological view of the mapping of perception and movement in action (Gibson, 1979; Turvey, 1992).

## Appendix A. Correlation dimension

Correlation Dimension (CD) is used to quantify the space filling properties of an attractor and the question of how many dimensions are required to describe the attractor of a given system. CD finds the number of dimensions by investigating distance between time points of the time series in a reconstructed phase space (see next section). The idea, roughly, is that if by increasing the number of dimensions in determining the dynamics of a given system we cannot get more “information” about the attractor, then, we have found the necessary number of dimensions to describe it (for a full introductory consideration on CD, refer to Williams, 1997).

Briefly, the correlation dimension will measure, for a different number of dimensions, the relation between how many data points are closer than a given distance and the distance itself ( $r$ ) in the phase space. This is done for all data points. By varying the number of dimensions, we understand how this relation changes. At some point, the relation is the same independent if we increase the number of dimensions or not. Thus, by seeing the resultant relation, we can find what the actual required dimension to describe the system is.

First, we need to have the time series data in the phase space. For the correlation dimension, the phase space is built (a process called phase space embedding) by plotting the time series of the system in terms of delayed versions of itself. The number of dimensions considered is called the embedded dimension ( $m$ ) and for each one of them, a time-delay must be specified.

In the present paper, we explored the system considering 2–20 embedded dimensions. This choice was made given that the literature showed that a range up to 15 embedded dimensions was enough to characterize the correlation dimension.

The specification of the time-delay for each embedded dimension was carried out as provided by Rosenstein et al. (1994):

$$S_m(\tau) = \frac{1}{N - (m - 1)\tau} \sum_{i=1}^{N-(m-1)\tau} \sqrt{\sum_{j=2}^m (X_j^\tau(i) - X_1(i))^2} \quad (\text{A1})$$

where  $S_m(\tau)$  is the function of average Euclidean distance of all data from the identity line when a dimension is added in terms of the time delay, the  $X_j^\tau(i)$  is one component (dimension  $j$ ) of the vector describing  $X$  when the new dimension is added,  $X_1(i)$  is the original data point position (identity line),  $N$  is the length of the time series,  $m$  is the number of dimensions being considered,  $\tau$  is the time delay. In simple terms, here we got how much an added dimension (as a function of the time delay) modifies the path in the phase space. The time delay used here was the first that would modify the path by an amount less than 40% than time delay 1.

Now, we get the maximum and minimum value of the time series and divide by 20 (arbitrary choice). The resultant value becomes the size of  $r$ . For each reconstructed phase space trajectory, the sum of Euclidean distances from one point to all others within an  $r$  radius is calculated and noted. This is repeated for all points and summed up. After, by increasing  $r$  (i.e.,  $2*r$ ,  $3*r$ , ...,  $20*r$  – the result was always rounded to the closest integer) we have characterized the summed Euclidean distances (called correlation sum) as a function of  $r$ . Taking the logarithm of both correlation sums and  $r$  we find a curved relation that stabilizes (does not change) after a given value of  $r$ . By getting the initial slope (before stabilization) of the curve we found the correlation dimension for the given embedded dimension tested ( $CD_m$ ) (we present an example later).

This whole procedure is repeated for all possible embedded dimensions (here, up to 20). Plotting  $CD_m$  as a function of  $m$ , we, theoretically, should find a curve that asymptotically approaches a given value. If that is the case, the asymptote would be the correlation dimension of the given system. Usually, nevertheless, real data has noise attached to the measurement – from unknown sources. This creates an issue provided that the  $CD_m$  curve would never stop increasing (small increments) – almost as if the correlation dimension would increase if we consider more and more dimensions. Thus, we need a criterion to define what the correlation dimension is. Takens (1981) stated that CD should be the  $CD_m$  at which  $m \geq 2 * CD_k + 1$ .

To demonstrate that the CD measurement is reliable, we used a time series generated from the limit cycle attractor as an example. The limit cycle attractor is denoted as  $r^2 = x^2 + y^2 + \omega$  where  $x = r * \sin(\theta) + \omega$ ,  $y = r * \cos(\theta) + \omega$ , and  $\omega$  is white noise (Fig. A.1a and b). This time series  $x$  was used as the example to demonstrate the estimation of CD.

By definition, the limit cycle attractor should have a dimension of 1 (a line). Provided we added noise (1% of the amplitude of the sine wave), the estimate should be slightly above 1. Fig. A.2a provides the estimation of the correlation sum ( $C_r$ ) as a function of  $r$  (in log scale) considering  $m = 2$ . As it is shown, we estimate the  $CD_m$  from the slope of the region before the curve stop changing as a function  $r$ . Fig. A.2b shows the  $CD_m$  as a function of  $m$ . The first value that crossed the  $m \geq 2 * CD_k + 1$  criterion was 1.27. Thus, this

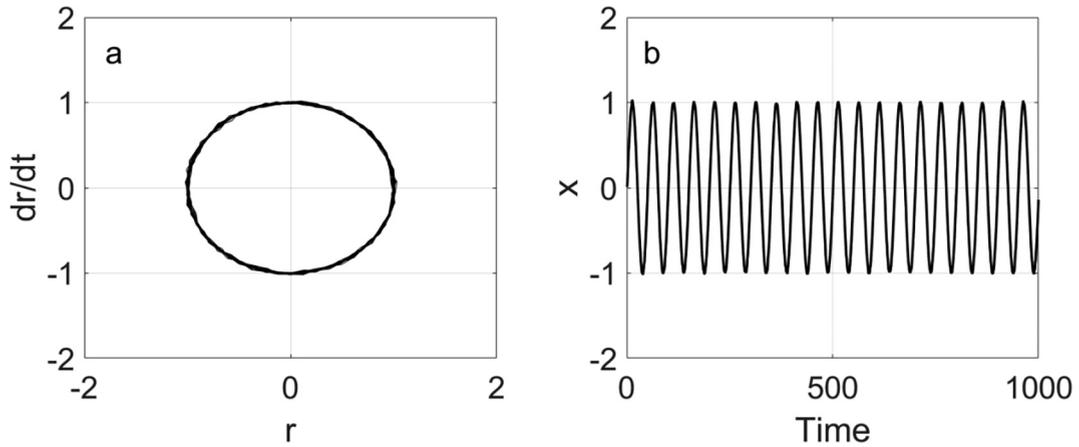


Fig. A1. Schematic of a limit cycle attractor (a) and the correspondent time series  $x$  (b).

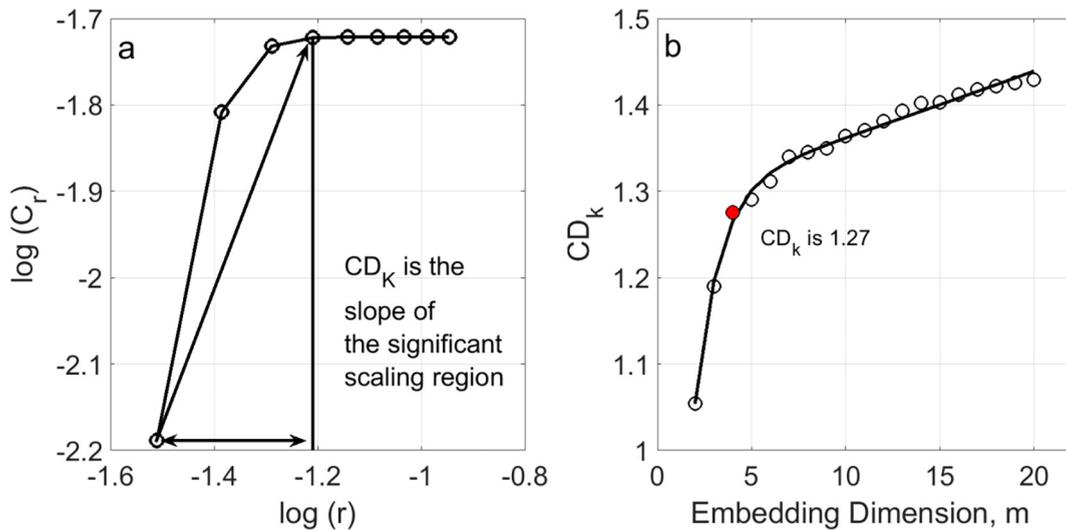


Fig. A2. (a) Illustration of the  $\log(C_r)$  versus  $\log(r)$  at  $m = 2$ . The estimated  $CD_k$  is the slope of the significant scaling region. (b) Computed  $CD_k$  estimates for varying dimensions,  $m$ .

was considered the CD of the presented time series and it demonstrates the feasibility of the method to identify the underlying attractor dynamics of the time series.

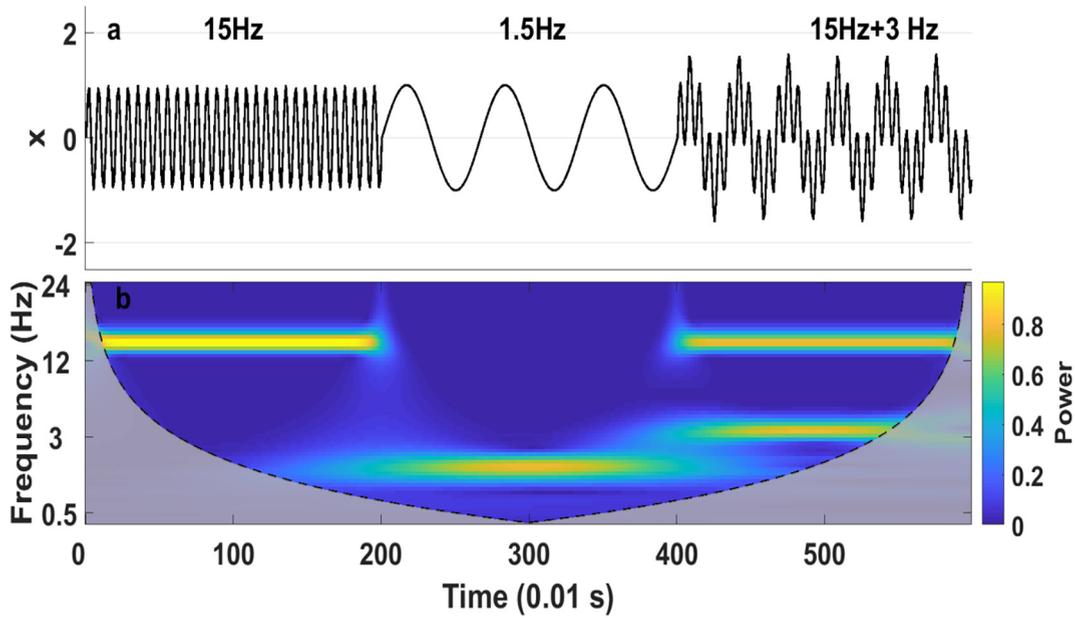
### Appendix B. Wavelet analysis

Wavelet analysis is a tool that decomposes a time series into a time-frequency space as a way to determine the variation of dominant frequencies over time (Torrence & Compo, 1998). The idea, roughly, is “adjusting” a prototype function scaled/dilated in terms of amplitude and time into different time windows of the time series. By doing that, we can understand the time scales of the time series in terms of how fast/slow and how large/small the prototype function should be to describe that signal at that time window.

The process is similar to a Fourier transformation if we consider the prototype function a sine wave. The main difference with the more common spectral analyses is that the wavelet analysis provides the spectral profile for each time point instead of a single spectral profile for the whole time-series,

We chose the Morlet wavelet as the prototype/mother function, which provides a good balance between time and frequency localization. This prototype function ( $\psi_{a,b}(t)$ ) was chosen provided it gives the best fit to the typical fluctuations of the signal and detection of the structure of a signal over various time-scales. This function can be scaled/dilated and shifted along time constructing an image showing both the power (amplitude) over the frequency spectrum and its variation in time.

$$\psi_{a,b}(t) = \frac{1}{\sqrt{a}} \psi\left(\frac{t-b}{a}\right) \tag{1}$$



**Fig. B1.** Schematic of CWT from a simulated time series. Figure a provides a time series that combine three sinusoid components (15 Hz, 1.5 Hz and 15 Hz + 3 Hz). Figure b shows the frequency vs. time profiles of CWT from the simulated time series. The high power (yellow region) matches the localized time and frequency characteristics of the sine wave. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

where  $a$  represents timescale and  $b$  is the localized time instant.

The continuous wavelet transform (CWT) was applied to obtain the wavelet coefficient (WC) of the time series with uniform time step at each instant time  $b$  and scales ( $a$ ). Each wavelet coefficient represents the relation between the signal to the prototype function – a measure of how much the signal is described by that scaling and time-scale of the prototype function in that specific time point of the time series. By using Eq. (2), the WC at each timescale  $a$  and time instant  $b$  can be calculated.

$$WC(a, b) = \int_{-\infty}^{\infty} x(t)\psi_{a,b}^*(t)dt \tag{2}$$

where  $x(t)$  represents the time series data, the function  $\psi_{a,b}(t)$  represents the mother function at timescale ( $a = 2^n/f_s$ ,  $f_s$  as the sampling frequency of the signal) and time instant ( $b$ ), and the symbol  $*$  represents the complex conjugate of a function (Torrence & Compo, 1998).

Fig. B1 provides a schematic of CWT from a simulated time series.

The wavelet coherence analysis is used to examine whether two time series present similar frequency profiles (in time). This is similar to the usual coherence analyses but, as for the CWT, it is different in that it will demonstrate the coherence over time.

Two time series  $x(t)$  and  $y(t)$  are used to perform a cross-wavelet transformation

$$WC^{xy}(a, b) = W^x(a, b) * W^y(a, b) \tag{3}$$

where,  $WC^{xy}(a,b)$  represents the amount of joint power between  $x(t)$  and  $y(t)$ .

Then, we need to standardize the coherence by the power exhibited in the single signal – a procedure similar to standardizing covariance by the variance. Thus, the wavelet transfer function  $H(a, b)$  can be defined as

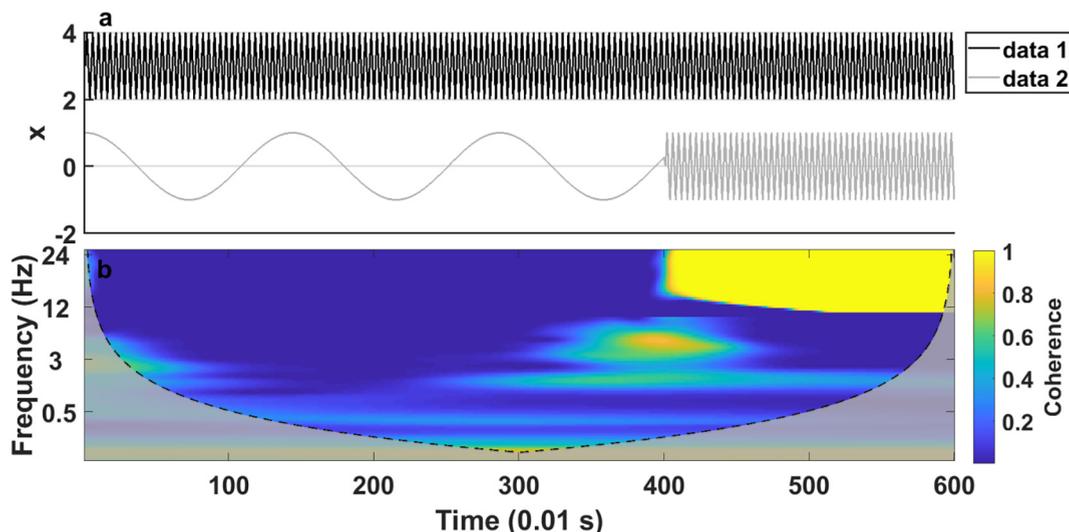
$$H(a, b) = \frac{S[S^{-1}WC^{xy}(a, b)]}{S[S^{-1}W^{xx}(a, b)]} \tag{4}$$

where  $S$  is a smoothing operator in the time-frequency (scale) domain – eliminating non-reliable values of the cross-wavelet transformation, and  $W^{xx}$  is the CWT of the  $x(t)$  signal. It could be done using a weighted running average in both the time and scale directions (Torrence & Compo, 1998).

The step to compute the cross-wavelet coherence  $R^2(a,b)$  is similar to the magnitude-squared coherence function base on the Fourier transform

$$R^2(a, b) = \frac{|S[S^{-1}WC^{xy}(a, b)]|^2}{|S[S^{-1}W^{xx}(a, b)]|^2 * |S[S^{-1}W^{yy}(a, b)]|^2} \tag{5}$$

where  $R^2(a,b)$  can be regarded as a localized coefficient of determination between  $x(t)$  and  $y(t)$  and ranges between 0 and 1. Fig. B2 provides a schematic of wavelet coherence from two simulated data sets.



**Fig. B2.** Schematic of wavelet coherence. Figure a provides two simulated time series showing that at time 401–600 the two data sets were highly coupled at 20 Hz. Figure b shows the frequency vs. time profiles of coherence. The high coherence (yellow region) around 20 Hz at time 401–600 agrees with both time series showing similar frequency profile at that time window. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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