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Executive function orchestrates regulation of task-relevant gait fluctuations

Leslie M. Decker

University of Nebraska at Omaha

Fabien Cignetti

University of Nebraska at Omaha

Nicholas Stergiou

University of Nebraska at Omaha, nstergiou@unomaha.edu

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2 **Title:**

3 **Executive function orchestrates regulation of task-relevant gait fluctuations**

4

5 **Authors:**

6 Leslie M. Decker^{1,2,*}, Fabien Cignetti^{1,3}, Nicholas Stergiou^{1,4}

7

8 **Affiliations:**

9 ¹ Nebraska Biomechanics Core Facility, University of Nebraska at Omaha, Omaha, NE, USA.

10 ² Movement to Health Laboratory (EA 2991), Montpellier-1 University, Montpellier, France.

11 ³ Laboratoire de Neurosciences Cognitives (UMR 7291), CNRS & Aix-Marseille Université,
12 Marseille, France.

13 ⁴ Environmental, Agricultural and Occupational Health Sciences, College of Public Health
14 Department, University of Nebraska Medical Center, Omaha, NE, USA.

15 * Corresponding author at: Movement to Health Laboratory (EA 2991), Montpellier-1
16 University, Euromov, 700 Avenue du Pic Saint Loup, 34090 Montpellier, France. Tel.: +33
17 411 759 072; fax: +33 411 759 050. E-mail address: leslie.decker@univ-montp1.fr

18

19 **Abstract:**

20 Humans apply a minimum intervention principle to regulate treadmill walking, rapidly
21 correcting fluctuations in the task-relevant variable (step speed: SS) while ignoring
22 fluctuations in the task-irrelevant variables (step time: ST; step length: SL). We examined
23 whether the regulation of fluctuations in SS and not in ST and SL ~~relies~~ depends on high-
24 level, executive function, processes. Young adults walked on a treadmill without a cognitive
25 requirement and while performing the cognitive task of dichotic listening. SS fluctuations
26 became less anti-persistent when performing dichotic listening, meaning that taxing
27 executive function impaired the ability to rapidly correct speed deviations on subsequent
28 steps. Conversely, performing dichotic listening had no effect on SL and ST persistent
29 fluctuations. Findings suggest that high-level brain processes are ~~only~~ involved only in
30 regulating gait task-relevant variables.

31

32 **Key-Words:**

33 Walking; Variability; Minimum Intervention Principle; Executive Function; Detrended
34 Fluctuation Analysis

35 1. Introduction

36 In a wide range of tasks, humans apply a minimum intervention principle to regulate
37 movement, correcting fluctuations only if they interfere with task performance [1,2]. This
38 control holds because correcting task-irrelevant fluctuations in addition to task-relevant
39 fluctuations has detrimental effects on the central nervous system (CNS), increasing noise
40 and computational effort.

41 In gait, such a principle has been demonstrated by examining the statistical
42 persistence/anti-persistence of the stride-to-stride fluctuations during treadmill walking [3,4].
43 Specifically, fluctuations in stride time and stride length were found to be persistent, meaning
44 that their values continued increasing or decreasing over several subsequent strides before
45 reversing. ~~Conversely~~ ~~versely~~, fluctuations in stride speed were anti-persistent, rapidly
46 reversing direction on subsequent strides. Given that the treadmill walking task requires
47 maintaining (on average) the same walking speed (to ~~not walk~~ avoid walking off the treadmill)
48 and that many combinations of stride length and stride time equally achieve that speed, only
49 task-relevant fluctuations ~~only were~~ therefore were immediately corrected.

50 However, the question remains as to whether persistent and anti-persistent
51 fluctuations stem from similar or different control processes of the CNS. Interestingly, only
52 anti-persistence in step speed is needed to achieve the treadmill walking goal (to maintain
53 constant walking speed [3,4]). Accordingly, high-level executive function processes, which
54 are involved in handling goal-directed actions [5], may ~~only~~ play a role ~~only~~ in shaping anti-
55 persistent behavior. If ~~true~~ ~~so~~, taxing these processes ~~by~~ ~~with~~ a concurrent cognitive task
56 during treadmill walking would alter anti-persistence in step speed while persistence in step
57 time and step length would remain unchanged.

58 2. Methods

59 Twenty healthy adults (12♀/8♂, 24.45±0.87 years, 1.73±0.02 m, 70.41±2.63 kg)
60 participated in two experimental sessions after providing written informed consent. The
61 experiment included The order of the two sessions was counterbalanced between subjects.
62 In one session, subjects performed the cognitive task of dichotic listening while ~~being~~ seated
63 to establish baseline performance [6,7]. They had to listen and report consonant-vowel
64 syllables (phonologically salient, but semantically meaningless) presented dichotically under
65 three attention conditions: non-forced (NF) consisted in reporting the syllable heard best, and
66 forced-right (FR) and forced-left (FL) the syllable heard in the right and left ear, respectively.
67 The conditions increased ~~in~~ the need ~~of~~ ~~for~~ executive control, from NF to FL. In the other
68 session, subjects walked on a treadmill at preferred speed (1.06±0.03 m/s) with markers
69 attached at anatomical landmarks [8], first without a cognitive requirement (walking: W) and
70 afterwards while performing dichotic listening in NF (W+NF), FR (W+FR) and FL (W+FL) (Fig.

71 1). In both sessions, NF was presented first and FR and FL were counterbalanced between
72 subjects. Each condition lasted ~~for~~ three minutes, involving 36 different syllable pairs. E-
73 prime® was used for syllable presentation and report collection. The marker movements
74 were recorded (60 Hz) with an 8-camera Motion Analysis Eagle Digital system and low-pass
75 filtered at 10 Hz with a zero-lag Butterworth filter.

76 ----- Please insert Figure 1 here -----

77 Dichotic listening was scored through the laterality index (LI), which is the ratio of the
78 difference between correct reports for the right ear and those for the left ear to the total
79 number of correct reports, expressed ~~in~~ as a percentage. Step time (ST) and step length (SL)
80 were defined as the time interval and horizontal distance between consecutive toe-off events,
81 with the toe-off defined from the maximum backward displacement of the marker located
82 between the second and third metatarsal phalangeal joints during each step. Step speed
83 (SS) was defined as $SS=SL/ST$. The time series were shortened to 272 data points (the
84 number of steps of the slowest subject). Persistence/anti-persistence in ST, SL and SS was
85 examined using Detrended Fluctuation Analysis (DFA) [9,10]. DFA ~~computes~~ computed
86 mean square roots of detrended residuals, $F(n)$, of the integrated time series over a range of
87 interval lengths, n . The scaling exponent ~~α is~~ was then estimated from the slope of the linear
88 relationship between $\log[F(n)]$ and $\log(n)$. A restricted range of interval lengths was used,
89 from $n=17$ steps to $n=45$ steps, where the slope was the most stable as determined by the
90 DFBETA statistics [10] (Fig. 2). $\alpha < 0.5$ indicates anti-persistence, with fluctuations in one
91 direction immediately followed by corrections in the opposite direction. $\alpha > 0.5$ indicates
92 persistence, with fluctuations in one direction followed by fluctuations in the same direction.
93 LI and α were subjected to two-way (*session* × *condition*) and one-way (*condition*) within-
94 subjects analyses of variance (ANOVAs), respectively.

95 ----- Please insert Figure 2 here -----

96 3. Results

97 Cognition. There was a *condition* effect for LI ($F_{2,38}=32.91, p < 10^{-9}, \eta^2=0.44$), which
98 increased from NF ($11.27 \pm 3.29\%$) to FR ($43.65 \pm 3.13\%$; $p=0.003$) and decreased from FR to
99 FL ($-9.08 \pm 4.93\%$; $p < 0.001$) (Fig. 3A). As previously found, subjects reported more correct
100 answers ~~at~~ for the right ear in NF and FR, and inversely reported more correct answers ~~at~~ for
101 the left ear in FL [7]. The ANOVA did not reveal a *session* effect for LI, meaning that
102 cognitive performance was maintained during walking.

103 Gait. DFA revealed anti-persistence in SS ($\alpha < 0.5$) and persistence in ST and SL
104 ($\alpha > 0.5$). The ANOVA yielded a *condition* effect for $\alpha(SS)$ ($F_{2,44}=4.71, p=0.01, \eta^2=0.12$).
105 Fluctuations were less anti-persistent in W+FL ($\alpha=0.45 \pm 0.04$) than in W ($\alpha=0.31 \pm 0.03$,

106 $p=0.006$) and $W+NF$ ($\alpha=0.34\pm 0.03$, $p=0.041$). There were no significant results for $\alpha(ST)$ and
107 $\alpha(SL)$ (Fig. 3B).

108 ----- Please insert Figure 3 here -----

109 **4. Discussion**

110 This study examined the origins of persistent/anti-persistent fluctuations in gait. As
111 expected, taxing the executive function processes with dichotic listening led to less anti-
112 persistent SS, which reflected an impaired ability to rapidly correct speed deviations on
113 subsequent steps. Therefore, executive function was involved in regulating anti-persistence
114 in the variable relevant for achieving the treadmill walking goal (to maintain constant speed
115 [3,4]). Interestingly, a previous model of gait dynamics reproduced anti-persistent fluctuations
116 in ST (the task-relevant variable) during metronomically-paced walking [11,12]. The authors
117 suggested that anti-persistence resulted from the “human consciousness” of being
118 constrained to walk at a controlled pace by following external timing cues. Accordingly, our
119 finding supports the proposal that anti-persistence in gait results from high-level brain
120 processes.

121 Conversely, decreasing the cognitive resources available had no effect on the
122 persistence of the task-irrelevant variables for treadmill walking (ST and SL). Accordingly, the
123 persistent fluctuations likely stem likely from low-level processes of the CNS and the inherent
124 biomechanics of the locomotor system. This interpretation is in agreement with modeling
125 studies that reproduced persistent fluctuations in ST using either an intra-spinal network of
126 neurons coupled, or not, to a mechanical oscillator [9,11-14] or a biomechanical model of
127 walking operating under minimal feedback (spinal reflex) [15].

128 In sum, high-level brain processes were only involved in regulating anti-persistent
129 speed fluctuations. This finding suggests that the minimum intervention principle minimizes
130 the cognitive cost of locomotion by tightly regulating solely-only step speed, the variable that
131 is directly relevant to achieving the task goal.

132

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135 Nebraska Research Initiative.

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174 **Legends**

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177 **Fig. 1.** Experimental setup with a subject walking on the treadmill while performing the
178 dichotic listening test. Consonant-vowel syllables /ba/, /da/, /ga/, /pa/, /ta/, and /ka/ were
179 presented as stimulus-pairs (e.g., /ga/-/ba/) using a headphone, one syllable to the right ear
180 (e.g., /ga/) and simultaneously the other syllable to the left ear (e.g., /ba/). The subjects were
181 asked to freely report the consonant-vowel syllable they heard best from the dichotic syllable
182 pair in the non-forced (NF) condition (e.g., /ga/, assuming a right ear advantage). On the
183 other hand, they were instructed to report only the syllable presented to the right ear in the
184 forced-right (FR) condition (e.g., /ga/) and to the left ear in the forced-left (FL) condition (e.g.,
185 /ba/). The subjects were secured into the LiteGait® harness system for safety purposes.
186 Reflective markers were attached to specific anatomical landmarks, including the anterior
187 and posterior superior iliac spine, lumbosacral joint, greater trochanter of the femur, lateral
188 mid-thigh, front lower thigh, lateral and medial epicondyles of the femur, front mid-shank,
189 lateral lower shank, lateral and medial malleoli, lateral border of the fifth metatarsal head,
190 medial border of the first metatarsal head, lateral and medial processes of the calcaneal
191 tuberosity, heel, and between the second and third metatarsal phalangeal joints.

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193

194 **Fig. 2.** (A) Step length (SL), step time (ST) and step speed (SS) time series (N=272 steps)
195 obtained from a representative subject walking at preferred speed. (B) Corresponding log-log
196 plots of average fluctuations $F(n)$ vs. interval lengths n , obtained using the Detrended
197 Fluctuation Analysis. The $\log_{10}[F(n)]$ vs. $\log_{10}(n)$ plots were fitted with linear functions and the
198 scaling exponents α were obtained from the slopes of these lines over the range of interval
199 lengths $n=17$ to $n=45$. This range provided the most stable estimates of α for SL, ST, and SS.
200 As illustrated, step-to-step fluctuations of both SL and ST time series were persistent ($\alpha>0.5$)
201 while those of SS time series were anti-persistent ($\alpha<0.5$). (C) The stable interval length
202 fitting range was determined from the distribution of the diagnostic measure DFBETA, which
203 reflects how much the exponent α changes when sequentially removing the intervals of
204 length n . The values presented here are means \pm standard deviations of the population. For
205 small interval lengths ($n<17$ data points), the DFBETA values exhibited bias away from zero
206 and were importantly dispersed, reflecting estimations of α over- or under-estimated and
207 poorly stable, respectively. Indeed, small intervals contain few data points for fitting the
208 trends, which likely render the α estimates inaccurate and variable. For large interval lengths
209 ($n>45$ data points), the DFBETA values did not exhibit bias but were importantly highly
210 dispersed. These interval lengths provide sufficient data for fitting to fit the trend but the

211 average fluctuations around the trends are more variable, making the α estimates less stable.
212 Therefore, the restricted range of lengths $17 \leq n \leq 45$ was considered for estimating α .

213

214 **Fig. 3.** (A) Laterality indexes (LI) obtained in the dichotic listening conditions (NF: non-forced,
215 FR: forced-right, FL: forced-left) during the sitting and walking sessions. Results from the
216 two-way within-subjects ANOVAs (*Condition* × *Session*) indicated a significant main effect of
217 *condition* for LI, with the p-value for the effect - p_c - reported on the graph. (B) Exponents α
218 obtained from step length (SL), step time (ST), and step speed (SS) time series as a function
219 of the experimental conditions (walking: W, walking when performing dichotic listening:
220 W+NF, W+FR, and W+FL). Results from the one-way within-subjects ANOVAs indicated a
221 significant main effect of *condition* for α (SS), with the p-value for the effect - p_c (SS) - reported
222 on the graph. LI and α values are means \pm standard errors of the population.