

# Chapter 7

## **External attentional focus enhances movement automatization: A comprehensive test of the Constrained Action Hypothesis**

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Elmar Kal  
John van der Kamp  
Han Houdijk

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## Abstract

**Background:** An external focus of attention has been shown to result in superior motor performance compared to an internal focus of attention. This study investigated whether this is due to enhanced levels of movement automatization, as predicted by the constrained action hypothesis (McNevin, Shea, & Wulf, 2000).

**Methods:** Thirty healthy participants performed a cyclic one-leg extension-flexion task with both the dominant and non-dominant leg. Focus of attention was manipulated via instructions. The degree of automatization of movement was assessed by measuring dual task costs, as well as movement execution parameters (i.e., EMG activity, movement fluency, and movement regularity).

**Results:** Results revealed that an external focus of attention led to significantly better motor performance (i.e., shorter movement duration) than an internal focus. Although dual task costs of the motor task did not differ as a function of attentional focus, cognitive dual task costs were significantly higher when attention was directed internally. An external focus of attention resulted in more fluent and more regular movement execution than an internal focus, whereas no differences were found concerning muscular activity.

**Conclusions:** These results indicate that an external focus of attention results in more automatized movements than an internal focus and, therefore, provide support for the constrained action hypothesis.

## 1. Introduction

An increasing body of evidence shows that motor performance can be directly influenced by the performer's focus of attention. More specifically, focusing on the effects of movement (i.e., an external focus of attention) has been found to result in superior motor performance compared to focusing on the movement pattern itself (i.e., an internal focus of attention; for comprehensive overviews see<sup>252,253</sup>). McNevin, Shea, and Wulf<sup>254</sup> (see also Wulf<sup>253</sup>) posited the 'constrained action hypothesis' to explain the differential effects of attentional focus on performance. The hypothesis holds that an external focus facilitates motor performance because it promotes automatic control of movement. By contrast, adopting an internal focus of attention induces more deliberate and conscious control of movement, thereby constraining or disrupting 'normal' automatic control processes. The constrained action hypothesis has proven useful in explaining the effects of focus of attention on performance and learning in a wide variety of tasks, such as basketball shooting,<sup>255</sup> balancing,<sup>256</sup> tennis strokes,<sup>257</sup> and jumping.<sup>258</sup> However, most of these studies merely described the effects of attentional focus using relatively simple outcome measures (e.g. accuracy or number of successful attempts). Outcome measures, however, do not easily allow inferences about *how* the two distinct attentional foci effectuate differences in performance. To address this issue, it is necessary to investigate the assumptions of the constrained action hypothesis by assessing to what extent automatization of movement differs as a function of attentional focus. To this end, we aim to measure the effects of attentional focus on automatization of movement in two ways: by assessing dual task interference and through the analysis of movement execution parameters associated with automaticity.

A common method to assess automaticity of movement is investigating the effects of secondary task loading on primary motor task performance.<sup>19</sup> The conjecture is that consciously controlled movements place a substantially higher demand on working memory than automatized movements. Therefore, the execution of a secondary task is expected to interfere with performance on a consciously controlled motor task (i.e., movements performed with an internal focus of attention) but should not – or to a lesser extent – affect performance on an automatized task (i.e., movements performed with an external focus of attention). To date, only a few studies have investigated the effects of attentional focus on dual task performance. In a study by Wulf, McNevin, and Shea<sup>87</sup> adopting an external focus of attention was not only associated with better balancing performance, but also with swifter reactions to auditory stimuli during balancing compared to an internal focus. Similar findings were reported by Poolton, Maxwell, Masters, and Raab.<sup>56</sup> The authors found golf putting performance to be robust to secondary task loading (e.g. a tone counting task) when attention was focused externally, but not when attention was focused internally. Notwithstanding these promising results (cf.<sup>259</sup>), a limitation of these studies is that they did not control for differences in task prioritization in dual task conditions. That is, dual task performance was not corrected for

differences in baseline (single task) performance. By contrast, this study assessed dual task costs (DTCs<sup>14</sup>) of both the primary motor and secondary cognitive task.

An alternative approach to assess movement automatization is the analysis of movement execution related parameters that indicate to what extent movements are under automatic or conscious control. One such parameter is electromyographic (EMG) activity. The rationale is that if task execution is consciously controlled this results in more EMG activity than when the task is performed automatically, since the latter constitutes a more efficient mode of motor control.<sup>258</sup> Indeed, a few studies reported that an internal focus led to significantly higher EMG activity than an external one (e.g.<sup>99,255,258</sup>). Two additional parameters that have been frequently discussed in motor control literature with respect to movement automatization – but have not yet been applied in the context of the constrained action hypothesis – are *fluency of movement* (e.g.<sup>260</sup>) and *movement regularity* (e.g.<sup>261</sup>). With regards to fluency of movement, the rationale is that in the course of acquiring a motor skill, the fluency with which a movement is performed increases (e.g.<sup>260,262,263</sup>). This can be illustrated by contrasting the fluent and smooth drive of elite golf players with the more rugged and rigid movements of novice players, reflecting a high degree of conscious control.<sup>264</sup> Fluency of movement is commonly operationalized with the dimensionless jerk, which is derived from the minimal jerk model<sup>265,266</sup> and defined as the rate of change of acceleration of the moving limb. Lower dimensionless jerk values are indicative of higher movement fluency. Movement regularity is operationalized using sample entropy (SEn<sup>267</sup>), a measure which is derived from the theory of stochastic dynamics. For static tasks such as balancing, a *higher* SEn (i.e., lower regularity) is indicative of more automatized movements (e.g.<sup>10,261,268</sup>). However, for cyclical, dynamic tasks such as walking a *lower* SEn (i.e., a higher regularity) is proposed to be indicative of more automatized movements (e.g.<sup>269–271</sup>).

The aim of this study is to test the constrained action hypothesis in a comprehensive manner. To this end, we investigated whether an external focus of attention leads to superior motor performance compared to an internal focus of attention, and, if so, whether this is due to a higher degree of automatization of movement as predicted by the constrained action hypothesis. Healthy participants performed a cyclic one-leg extension-flexion task with both an internal and an external focus of attention. Motor performance was measured through movement duration. Automaticity of movement was assessed in two ways. First, we assessed dual task cost<sup>14</sup> as a function of attentional focus. For this purpose, participants performed the motor task concurrently with a letter fluency task.<sup>272</sup> Second, automaticity of movement was measured by assessing the EMG activity of knee flexors/extensors, the dimensionless jerk of the lower leg and the SEn of the lower leg's anterior-posterior accelerations.

We hypothesized that motor performance would be superior for the external compared to the internal focus conditions. Furthermore, it was expected that this difference in motor performance would be due to a higher degree of movement automatization for trials performed with an external compared to an internal focus of attention. Therefore, dual task costs for both motor and cognitive task performance were expected to be low when attention is focused externally relative to when attention is focused internally. With regards to the three movement execution parameters, it was expected that EMG and dimensionless jerk would be lower when an external focus was adopted. Taking into account the dynamic nature of the cyclic leg movement task,<sup>270</sup> the same pattern was expected for SEN. To independently verify the effects of automaticity on EMG, jerk, and SEN, the motor task was performed with both the dominant and non-dominant leg. We assumed that the dominant leg would induce more automatic motor control whereas that the non-dominant leg would induce more consciously controlled movements with the measures of automatization differing accordingly.

## 2. Methods

### 2.1. Participants

A total of 31 volunteers (11 male, 20 female) participated in the experiment. Mean age was  $25.06 \pm 6.8$  years. All participants were healthy and had no problems with speech. All participants signed an informed consent. The protocol of the experiment was approved by the ethical committee of the Faculty of Human Movement Sciences of VU University Amsterdam.

### 2.2. Equipment and data collection

Participants sat in a chair, in front of which (at approx. 25 cm) a line was taped to the floor in external focus conditions (Figure 7.1). Positioning of the line was adjusted such that participants could place the foot on the line when they flexed the knee approximately 90 degrees. For the letter fluency task a notebook was used to record all words named by the participants. Leg dominance was assessed with the Waterloo Footedness Questionnaire-Revised (WFQ-R<sup>273</sup>). Activity of the m. rectus femoris (RF), m. vastus lateralis (VL), and m. semitendinosus (SET) was recorded with paired bipolar surface EMG electrodes (Ag/AgCL, 2 cm centre-to-centre, 1 cm<sup>2</sup> recording area, Ambu Blue Sensor, type N-00-S). Placement of electrodes and preparation of the target location was in accordance with the SENIAM recommendations.<sup>274</sup> Data were sampled at 1000 Hz. Optotrak 3020 (Northern Digital Inc., Waterloo Ontario) was used to record the movements of the lower leg. LED markers were attached to the malleolus lateralis and halfway an imaginary line from the epicondylus lateralis to the malleolus lateralis of both legs. The Optotrak xyz-coordinate system was defined such that the x-axis pointed forwards (i.e., in the anterior-posterior plane), the y-axis pointed sideward (i.e., in the medio-lateral plane), and the z-axis pointed upwards (i.e., in the transversal plane). Sampling frequency was 100 Hz.

## 2.3. Experimental design

### 2.3.1. Experimental tasks

The motor task was a single leg movement task (Figure 7.1), for which participants were required to alternately flex and extend the leg at a comfortable pace for 60 seconds in a sitting position. No performance-optimizing criterion (e.g. move as fast possible) was given, even though this is habitually done in this area of research (e.g.<sup>252,256</sup>). The main reason for doing so is that motor tasks performed in daily life typically require comfortable rather than best performance. Nevertheless, comfortable pace can also be regarded as a performance characteristic. For instance, increases in comfortable walking speed are considered to reflect superior motor performance (e.g. the 10 meter timed walk<sup>224,275</sup>).



**Figure 7.1. Motor Task.** The left panel shows the external focus of attention condition, in which a line is placed on the floor, while the right panel illustrates the internal focus of attention condition.

The cognitive task was a letter fluency task, for which participants were required to name as many unique Dutch words as possible starting with a certain letter within a limited amount of time (i.e., in this experiment 1 minute). Nine letters with similar level of difficulty were chosen based on Schmand et al.<sup>272</sup>: D-A-T-K-O-M-P-G-R.

### 2.3.2. Procedure

Participants first completed the WFQ-R to assess leg dominance. Subsequently, two familiarisation trials of motor performance – one for each leg were conducted. Participants did not receive instructions regarding attentional focus for these familiarisation trials. This was followed by a baseline assessment of the letter fluency task. After the familiarisation trials, participants performed two blocks of four trials: one single (ST) and one dual task (DT) trial for each leg. Participants performed the first block with one focus of attention, whereas the second block was performed with the other focus of attention. Focus was manipulated via

standardized instructions given prior to the start of the trial, which were repeated shortly every 20 seconds to ensure compliance. To induce an internal focus of attention, participants were instructed to focus on flexing and extending their leg, whereas an external focus of attention constituted an instruction to focus on alternately placing the foot in front of and behind the line. Trials within a block were separated by 2 minutes of rest and blocks were separated by 10 minutes of rest, in which the participant was required to solve a Swedish puzzle. This distraction task was incorporated to minimize the likelihood that the focus of attention in the first measurement block did transfer to the second block. After completion of the second block, performance on the letter fluency task was assessed again to investigate the existence of a learning effect. Both the order of the two blocks (i.e., external versus internal focus of attention) and the order of conditions within blocks (ST versus DT and dominant versus non-dominant leg) were counterbalanced across participants. For each letter fluency trial, participants were given a different letter, the order of allocation of which was randomized.

## **2.4. Data analysis**

Optotrak and EMG data were analysed with customized Matlab programs (Mathworks, Natick MA, USA). For all trials, only data between the first and last three full movement cycles were used for analysis.

### *2.4.1. Motor performance & dual task costs*

Motor performance was defined as movement duration. Median movement cycle duration was calculated for each trial (in seconds), with shorter duration indicating better performance. Heel strikes were identified in the Optotrak data to assess MCD. Cognitive performance was defined as the number of words named per trial. To identify the dual task interference on both tasks, dual task costs (DTCs<sup>14</sup>) were calculated for both motor and cognitive tasks using equation 5.2:

Thus, deterioration in performance in DT conditions is reflected by a higher DTC.

### **2.4.2 Movement execution related variables**

#### 2.4.2.1. EMG

EMG was amplified, and filtered online using a 10-400 Hz Butterworth bandpass filter. The raw EMG data were full-wave rectified and smoothed with a bidirectional, band-pass, fourth-order Butterworth filter (cut-off frequency 25-200 Hz). After rectification of the signal, the average EMG activity of the RE, VL, and ST was calculated resulting in the mean EMG amplitude (in mV) for each muscle per trial.

#### 2.4.2.2. Dimensionless jerk

Optotrak data were filtered bidirectional, using a fourth-order Butterworth filter. The cut-off frequency was set at 6 Hz after inspection of the power-spectral density plot of several randomly selected trials. Data of the marker attached halfway at the lower leg were used. Dimensionless jerk<sup>264</sup> was assessed as follows: first, the resultant acceleration was calculated from the position data. For each movement cycle, this resultant acceleration was normalized by dividing it by its mean. Next, the derivative of this normalized acceleration was calculated. However, since differences in movement duration will influence this step, the mean rectified jerk per movement cycle was calculated and multiplied with movement duration. The median of the resultant dimensionless jerk for all movement cycles was then calculated to determine the dimensionless jerk for the whole trial.

#### 2.4.2.3. SEn

SEn is quantified as “the negative natural logarithm of the conditional probability (CP = A/B) that a dataset of length N, having repeated itself within a tolerance  $r$  for  $m$  points, will also repeat itself for  $m + 1$  points, without allowing self-matches”.<sup>261 (p. 206)</sup> In this equation, B represents the total number of matches of length  $m$ , and A represents the total number of matches of length  $m+1$ . SEn is then assessed with  $-\log(A/B)$ . Consequently, more regular time series are indicated by lower SEn. SEn was calculated for the anterior-posterior acceleration of the same marker used for jerk analysis after parameter selection (i.e.,  $m$  and  $r$ ) was optimized in line with recommendations of Lake et al.<sup>276</sup> This resulted in  $m = 3$  and  $r = .03$  as parameter settings.

### **2.5. Statistics**

All statistical analyses were executed using SPSS version 18.0 (PASW Statistics, 2011). Motor performance outcome scores were first analysed with a repeated measures ANOVA with Focus (external vs. internal) and Side (dominant vs. non-dominant) as within factors. Dual task performance was analysed with a 2(Focus) x 2(Side) x 2 (Task: motor vs. cognitive task) repeated measures ANOVA on motor and cognitive DTCs. To investigate automatization of movement, EMG results were analysed with a paired samples t-test for each muscle separately, whereas dimensionless jerk and SEn data were analysed with a 2(Focus) x 2(Side) repeated measures ANOVA. Significant effects were followed up using Bonferroni-adjusted t-tests. For ANOVA's, effect sizes were calculated with partial eta squared ( $\eta_p^2$ ), with values of .01, .06, and .14 indicating small, medium, and large effect sizes respectively.<sup>277</sup> For t-tests, effect sizes were assessed with Cohen's  $d$ , with .2, .5, and .8 representing small, medium, and large effect sizes respectively.<sup>278</sup> Significance level was set at  $p = .05$ .

### 3. Results

Thirty participants completed the experiment successfully. One male participant was excluded because of non-compliance with the instructions. Results of the WFQ-R revealed that 26 of the remaining 30 participants were right-footed.

#### 3.1 Motor performance

Analysis of variance revealed a large main effect of Focus ( $F(1,29) = 13.7, p < 0.01, \eta_p^2 = 0.32$ ): Movement duration was significantly shorter when an external focus was adopted ( $M = 1.25$  s,  $SEM = 0.05$  s) than when attention was focused internally ( $M = 1.31$  s,  $SEM = 0.05$  s). No main effect of Side ( $F(1,29) = 0.7, p = 0.4$ ) and no interaction of Focus and Side ( $F(1,29) < 0.1, p > 0.8$ ) was found.

#### 3.2. Automatization of movement

To investigate to what extent the beneficial effects of an external focus on motor performance were related to increased automatization of movement, the effects of performing a concurrent secondary task will be reported first, followed by results for the parameters related to movement execution.

##### 3.2.1. Dual task cost

The DTCs (in percentages) for the motor and the cognitive tasks are illustrated in Figure 7.2. This shows that ST motor performance was maintained at the expense of cognitive task performance when an internal focus of attention was adopted, whereas no dual task interference was apparent when an external focus was adopted. This effect seemed more pronounced for the non-dominant leg.

Accordingly, the analysis of variance revealed a large significant main effect of Focus ( $F(1,29) = 7.4, p < 0.05, \eta_p^2 = 0.20$ ), indicating that DTCs were indeed higher in the internal compared to the external focus conditions. The main effects of Task ( $F(1,29) = 3.7, p = 0.06, \eta_p^2 = 0.11$ ), Side ( $F(1,29) = 3.1, p = 0.09, \eta_p^2 = 0.10$ ) and the interaction effects of Focus x Side ( $F(1,29) = 4.2, p = 0.08, \eta_p^2 = 0.10$ ) and of Focus x Side x Task ( $F(1,29) = 3.2, p = 0.08, \eta_p^2 = 0.10$ ) failed to reach significance, but had medium sized effects. The interaction effect of Focus and Task ( $F(1,29) = 15.8, p < 0.01, \eta_p^2 = 0.34$ ) did reach significance however, and was of large effect size. Post hoc tests indicated that cognitive DTCs were higher for the internal compared to the external focus conditions ( $t(29) = 3.4, p < 0.01, d = 0.70$ ), whereas motor DTCs were lower for the internal compared to external focus conditions ( $t(29) = 2.6, p < 0.05, d = 0.48$ ).

Finally, Bonferroni corrected one sample t-tests were used to examine if DTCs were larger than zero. Neither motor ( $t(29) \leq 1.8, p > 0.6$ ) nor cognitive DTCs ( $t(29) < 0.4, p = 1$ ) significantly exceeded zero when an external focus of attention was adopted. An internal

focus of attention did not result in motor DTCs that significantly differed from zero either ( $t(29) < 0.4$ ,  $p = 1$ ). However, focusing internally did result in cognitive DTCs larger than zero for trials performed with the non-dominant leg ( $t(29) = 6.1$ ,  $p > 0.01$ ,  $d = 1.57$ , 95%  $CI = [10.2\%, 26.2\%]$ ), but not with the dominant leg ( $t(29) = 2.6$ ,  $p = 0.11$ ,  $d = 0.68$ , 95%  $CI = [-0.08\%, 19.2\%]$ ).

In sum, although motor DTCs were somewhat higher when an external compared to an internal focus of attention was adopted, motor task performance remained similar in dual compared to single task conditions, irrespective of attentional focus. However, an internal focus of attention resulted in a deterioration of cognitive task performance, especially in trials performed with the non-dominant leg.

### ***3.2.2. Movement execution related parameters***

EMG (in mV), dimensionless jerk, and SEn in the single motor task condition are displayed in Figures 7.3, 7.4, and 7.5. With regards to dimensionless jerk and SEn, it was first investigated whether differences existed between trials performed with the dominant or non-dominant leg to verify the effect of automaticity on these variables. This analysis was not possible for the EMG data, since no measurements of maximal voluntary contraction were conducted and non-normalized EMG values of different muscles cannot be compared. For each variable, it was assessed whether differences existed between external and internal focus conditions.

#### 3.2.2.1. EMG

Although EMG activity was generally higher in the external compared to the internal focus conditions (see Figure 7.3), Bonferroni-corrected paired samples t-tests revealed that these differences were not significant ( $t's(29) < 2.4$ ,  $p's > 0.10$ ); muscular activity was not different between focus conditions.

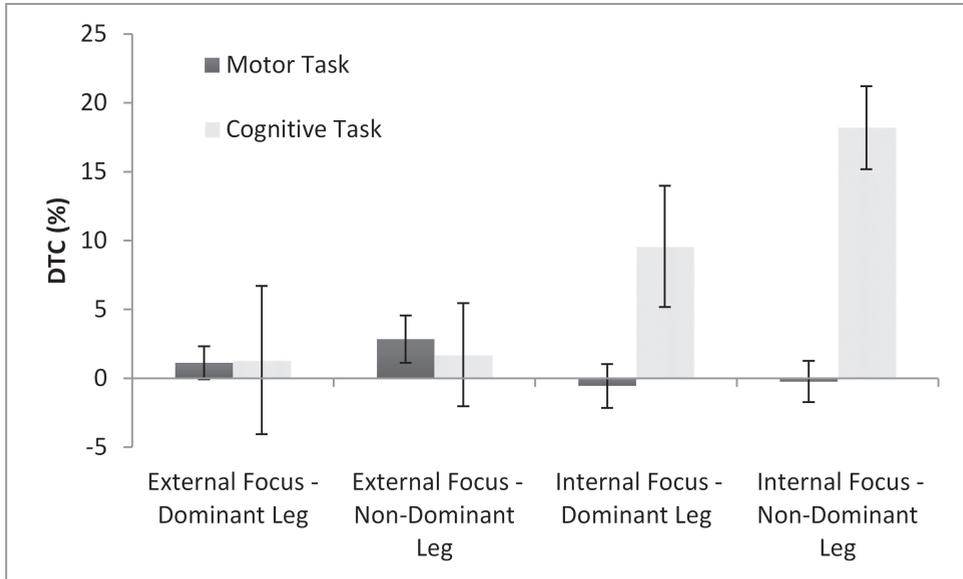
#### 3.2.2.2. Dimensionless jerk

Analysis of variance revealed a trend towards a significant main effect of Side of medium effect size ( $F(1,29) = 4.1$ ,  $p = 0.053$ ,  $\eta_p^2 = 0.12$ ). This indicated that the dominant leg produced more fluent movements compared to the non-dominant leg. The large main effect of Focus ( $F(1,29) = 6.1$ ,  $p < 0.05$ ,  $\eta_p^2 = 0.18$ ) indicated that movement execution was more fluent when attention was focused externally as opposed to internally (see Figure 7.4).

#### 3.2.2.3. Sample entropy

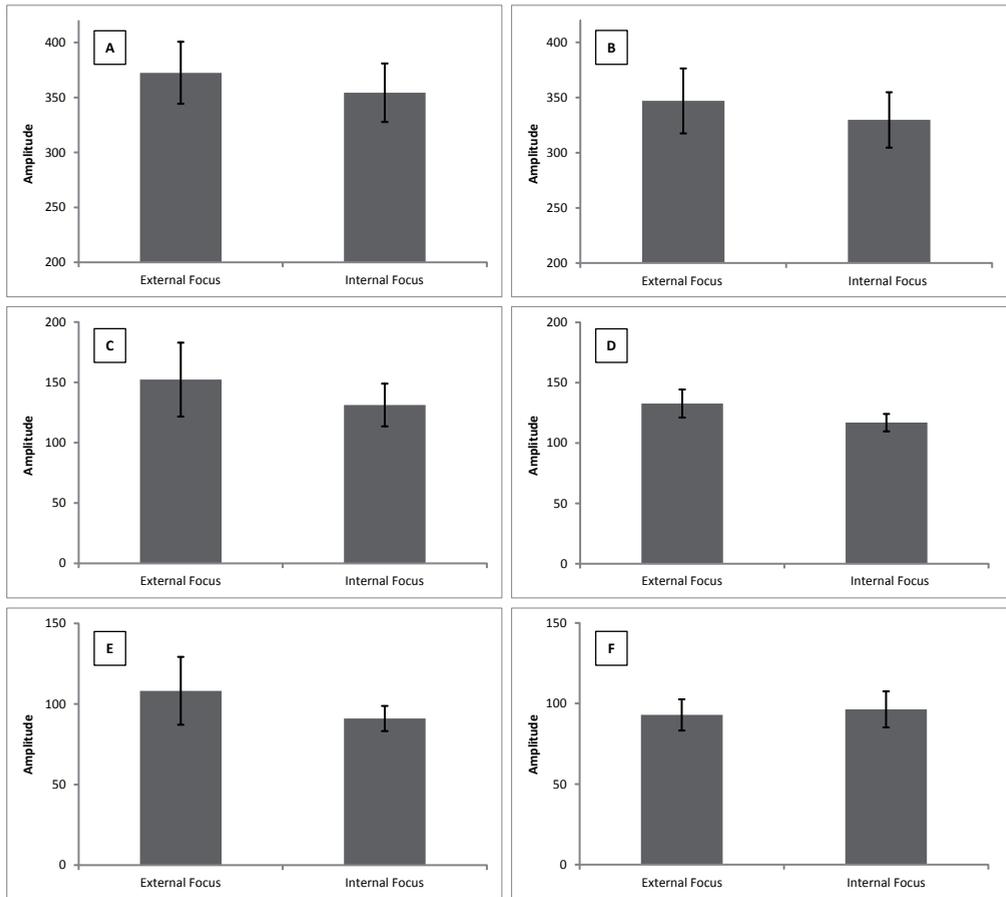
Analysis of variance revealed a large main effect of Side ( $F(1,29) = 7.1$ ,  $p < 0.05$ ,  $\eta_p^2 = 0.20$ ), which indicated that movement execution was of higher regularity when movements were performed with the dominant compared to the non-dominant leg. The large main effect of Focus ( $F(1,29) = 9.5$ ,  $p < 0.01$ ,  $\eta_p^2 = 0.25$ ) was due to the fact that an external focus resulted in higher movement regularity compared to an internal focus of attention (see Figure 7.5).

In sum, an external focus of attention resulted in more fluent and more regular movement execution than an internal focus of attention. Muscular activity did not differ between these focus conditions. The dominant leg produced more fluent and more regular movements than the non-dominant leg.



**Figure 7.2. Average DTC scores as a function of task, focus, and side  $\pm$  SEM. Scores are in percentages, with positive and negative values indicating increment and decrement, in dual task costs respectively.**

NB: EFA = External focus of attention; IFA = Internal focus of attention; DOM = Dominant leg; NDOM = Non-dominant leg.



**Figure 7.3. Average EMG amplitude  $\pm$  SEM for the single task conditions.** EMG amplitudes are displayed for the m. rectus femoris, m. vastus lateralis, and m. semitendinosus of the dominant (A, C, and E respectively) and non-dominant leg (B, D, and F, respectively).

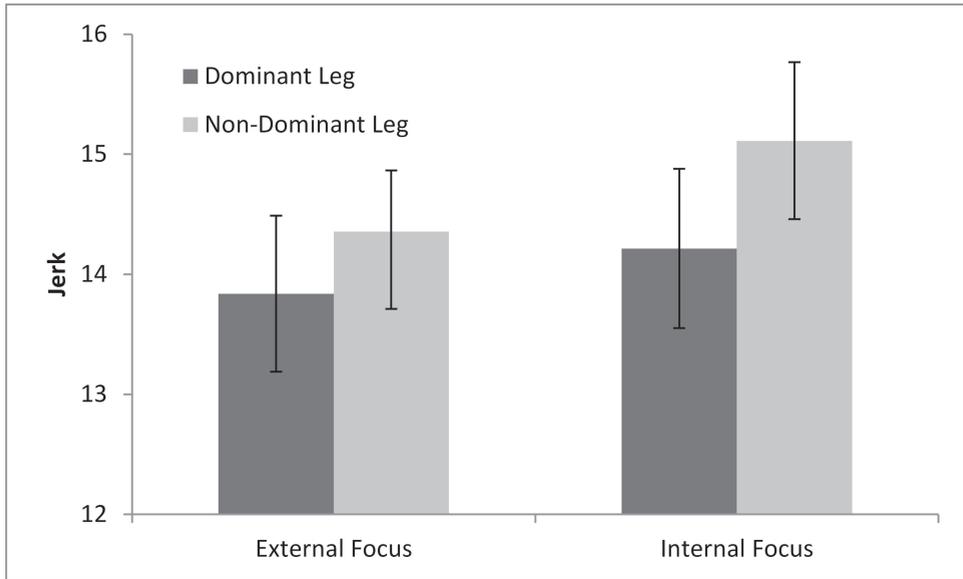


Figure 7.4. Average dimensionless jerk  $\pm$  SEM for the single task conditions.

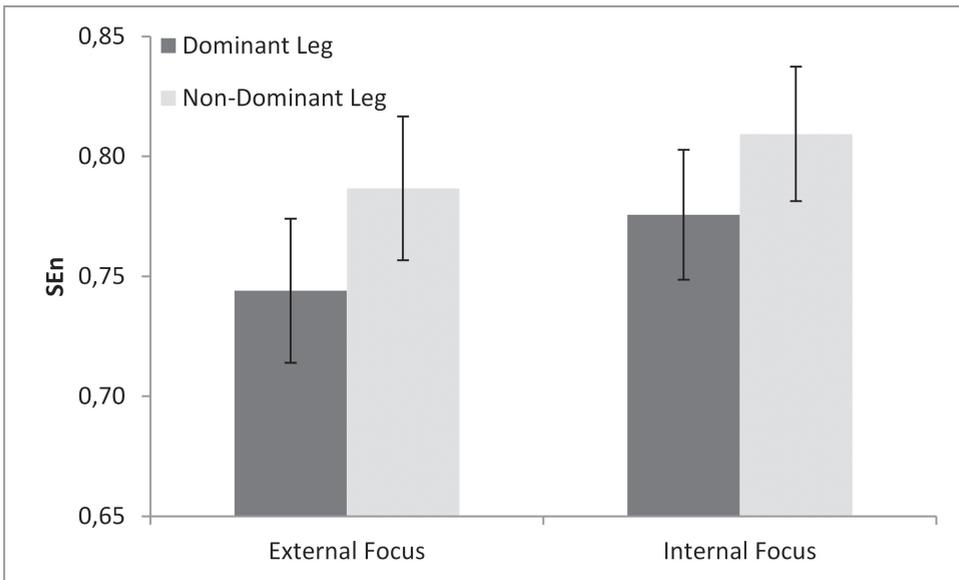


Figure 7.5. Average SEN  $\pm$  SEM for the single task conditions.

### 3.3. Effects of secondary task loading on movement execution related parameters

Although, it was not a specific aim of this study, its design also allowed us to explore the effect of secondary task loading EMG, dimensionless jerk, and SEN as a function of focus. To this end, we conducted six 2(Focus) x 2(Task: ST vs. DT) ANOVAs to analyse the EMG results of each muscle, and two 2(Focus) x 2(Side) x 2(Task) ANOVAs for the analysis of dimensionless jerk and SEN data. Only main and interaction effects of Task (i.e., comparing single and dual task outcomes) are reported, so as to not duplicate the effects discussed above.

Analyses of EMG data revealed a significant main effect of Task for the RF of both the dominant ( $F(1,29) = 16.5, p < 0.001, \eta_p^2 = 0.36$ ) and non-dominant side ( $F(1,29) = 12.9, p < 0.01, \eta_p^2 = 0.31$ ) as well as for the dominant SET ( $F(1,29) = 7.5, p < 0.05, \eta_p^2 = 0.21$ ). These effects indicated that muscular activity was significantly lower in DT compared to ST conditions with regards to the dominant RF ( $M = 363.4$  mV, SEM = 26.5 mV vs.  $M = 323.6$  mV, SEM = 23.4 mV, for ST and DT trials respectively), non-dominant RF ( $M = 338.3$  mV, SEM = 26.8 mV vs.  $M = 318.0$  mV, SEM = 26.8 mV, for ST and DT trials respectively), and dominant SET ( $M = 99.6$  mV, SEM = 11.9 mV vs.  $M = 92.7$  mV, SEM = 11.9 mV, for ST and DT trials respectively), but not for the non-dominant SET or VL of either leg. No interactions of Focus and Task were found for either muscle ( $F(1,29) < 0.9, p > 0.3$ ).

In contrast to the EMG results, analysis of the dimensionless jerk results did not reveal significant (interaction) effects of Task ( $F_s(1,29) < 3.9, p's > 0.07$ ). Thus, movement fluency was not significantly different in DT compared to ST conditions.

With regards to third variable, SEN, only a significant interaction between Side and Task was found with a large effect ( $F(1,29) = 5.22, p < 0.05, \eta_p^2 = 0.16$ ). Post-hoc testing revealed a non-significant increase in movement regularity in DT ( $M = 0.736$ , SEM = 0.027) compared to ST ( $M = 0.760$ , SEM = 0.028) conditions for the dominant ( $t(29) = 2.34, p = 0.051, d = 0.43, 95\% CI = [-0.000, 0.047]$ ) but not for the non-dominant leg ( $M = 0.796$ , SEM = 0.029, and  $M = 0.798$ , SEM = 0.027 for DT and ST conditions, respectively;  $t's(29) < 0.2, p's > 0.8$ ). Hence, SEN values indicated that secondary task loading might enhance automatization, but only for movements performed with the dominant leg.

## 4. Discussion

The present study investigated the constrained action hypothesis. To this end, it was assessed whether performance benefits associated with an external compared to an internal focus of attention were due to differences in automatization of movement. We used the typical approach to measuring automaticity – a dual task paradigm – as well as independently obtained measures of automaticity by measuring variables that reflect movement execution: EMG, dimensionless jerk (fluency of movement), and SEn (movement regularity).

Congruent with previous studies,<sup>252,253</sup> we found an external focus of attention to result in superior motor performance (i.e., shorter movement duration) compared to an internal focus of attention. Assessment of dual task interference indeed revealed that this was likely due to enhanced automaticity of movement. In agreement with earlier work on this topic,<sup>56,87</sup> interference seemed to occur only when an internal focus of attention was adopted whereas performance remained robust when attention was focused externally. Different from these studies, however, secondary task loading interfered with performance on the cognitive task only and not with performance on the motor task. This most probably reflected good compliance of participants to the instruction to prioritize performance on the leg movement task. However, maintaining motor task performance was at the expense of cognitive task performance when attention was focused internally, an effect that was most pronounced for the (presumably) least automatized non-dominant leg. This supports the constrained action hypothesis in that an external attentional focus seems to reduce the attentional capacity required for movement execution compared to an internal one. It also shows the importance of considering the DTCs of the second task as well, something which earlier studies did not address.<sup>56,87,259</sup>

From a practical point of view, dual task interference is of special interest to patients with acquired brain injury (ABI), since many experience significant problems with the concurrent performance of multiple tasks (e.g.<sup>14,279</sup>). This may – partially – be related to an increased tendency to focus on movement execution.<sup>28</sup> Impairments in dual task performance limit successful daily functioning and have been associated with an increased risk of falls.<sup>279</sup> The current results of this study may imply that shifting the focus of attention of ABI patients away from movement execution and towards movement effects might be an efficacious intervention to address this problem. However, considering the differences in motor skill, (heterogeneity of) neurological damage, and cognitive impairments, more experimental work is needed to assess whether the effects of attentional focus on motor and motor-cognitive task performance in ABI patients are indeed similar as observed here in healthy adults.

Additional evidence for the constrained action hypothesis is provided by the analysis of the movement execution related parameters in the single motor task condition. Dimensionless jerk and SEn results showed that an external relative to an internal focus of attention resulted in more fluent movements of higher regularity, which is in accordance with studies that have found both movement fluency (e.g.<sup>260,262,263</sup>) and regularity (e.g.<sup>269-271</sup>) to increase as a function of motor skill and automatization. The fact that both dimensionless jerk and SEn accurately differentiated between the dominant and non-dominant leg provides further support for the validity of these variables. Of note, in contrast to several studies (e.g.<sup>99,255,258</sup>), EMG activity was similar regardless of attentional focus. However, since an external focus of attention resulted in significantly faster motor performance but similar levels of muscular activity, this may actually indicate that an external focus of attention induces more efficient movement control and hence reflect a higher degree of automatization. This explanation is in line with earlier work that suggested that an internal focus of attention may result in less efficient (inter)muscular coordination compared to an external focus of attention.<sup>99,258,280</sup> In sum, the EMG, dimensionless jerk, and SEn results support the constrained action hypothesis: an external focus leads to more automatized movements than an internal one. Nonetheless, the constrained action hypothesis does not specify *what* exactly is constrained by adopting an internal focus of attention,<sup>281,282</sup> the present findings are largely inconclusive on how an internal focus disrupts movement automaticity. This remains a critical issue for future work.

Brain imaging is another important avenue for research that may further enhance understanding the effects of attentional focus. Currently, not many studies have explicitly investigated the differences in neural substrates between movements performed with an internal or external focus, but preliminary work suggests that an internal focus results in reduced activity of the primary motor and somatosensory cortex compared to an external focus.<sup>283</sup> Furthermore, increased activation of the prefrontal cortex indicates that conscious control of movement relies on executive function to a greater extent than automated motor performance.<sup>284</sup> Increased involvement of analytical processing is consistent with results of studies that applied electroencephalography (EEG). Specifically, automatization of movement has been related to the degree to which verbal-analytical brain areas of the left-hemispheric temporal lobe show synchronized activation with motor planning regions in the right hemisphere (i.e., premotor cortex; e.g.<sup>285</sup>): higher levels of synchronization or coherence reflect increased conscious control of movement. Recently, Zhu and colleagues have shown that implicit or incidental motor learning results in less synchronization compared to when motor learning is conscious and under executive control (e.g.<sup>68,69</sup>). Future studies should assess whether lower levels of synchronization between verbal and motor areas are also characteristic for external versus internal focus of attention. This would not only provide insight into the constrained action hypothesis but would also yield information regarding the possible common neural substrate underlying the concepts of implicit motor learning and learning with an external focus of attention (see also <sup>56</sup>).

A final note concerns the results of the exploratory analyses into the effect of secondary task loading on movement execution. Our findings indicated that differences existed in movement automatization between ST and DT trials. That is, EMG activity and SEN of trials performed with the dominant leg were lower during ST than during DT performance, whereas for dimensionless jerk no differences were found. This suggests that movement execution tended to show an increased level of automatization under secondary task loading relative to single motor task performance. First, with respect to the constrained action hypothesis, it is pertinent to note that these differences in movement automatization between ST and DT were not mediated by attentional focus. Second, although there were clear costs (i.e., degraded performance of the cognitive task) when concurrently performing two tasks, secondary task loading does appear to have enhanced movement automatization. There is no straightforward explanation for these findings. Possibly, the secondary task prevented any conscious control of the leg flex and extension movement, thereby in fact increasing automatization (see e.g.<sup>286</sup>). Clearly, more work is needed to better understand the effects of secondary task loading on movement automatization.

## **5. Conclusion**

To conclude, this study showed that an external focus of attention resulted in superior motor performance compared to an internal focus. Assessment of dual task performance, EMG activity, movement fluency, and movement regularity indicates that this is due to an external focus of attention promoting more automatized movements than an internal focus, as is predicted by the constrained action hypothesis.

## **6. Acknowledgements**

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