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Multi-segmental movement patterns reflect juggling complexity and skill level

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ABSTRACT

The juggling action of six experts and six intermediates jugglers was recorded with a motion capture system and decomposed into its fundamental components through Principal Component Analysis. The aim was to quantify trends in movement dimensionality, multi-segmental patterns and rhythmicity as a function of proficiency level and task complexity. Dimensionality was quantified in terms of Residual Variance, while the Relative Amplitude was introduced to account for individual differences in movement components. We observed that: experience-related modifications in multi-segmental actions exist, such as the progressive reduction of error-correction movements, especially in complex task condition. The systematic identification of motor patterns sensitive to the acquisition of specific experience could accelerate the learning process.

1. Introduction

Juggling requires rhythmical and synchronized movements of hands and upper limbs to establish a precise spatial-temporal pattern of ball movements (Huys, Daffertshofer, & Beek, 2003). While throwing a single ball in the air and catching it back represents a simple sensory-motor task, adding extra juggle balls raises the complexity exponentially (Beek & Lewbel, 1995; Ericsson & Charness, 1994). In fact, the acquisition of juggling skills involves the assembly of a new spatiotemporal organization of the effectors, with learning times dependent on the task: it can take hours or days to learn handling three balls, and weeks or months for four balls. With five balls, the spatial and temporal constraints become much more severe (Yamamoto, Tsutsui, & Yamamoto, 2015), and the learning process could take up to months or even years (Beek & Lewbel, 1995).

Given its intrinsic complexity, studying the coordination in juggling allows testing the sensory-motor organizations and the control strategies involved in a multifaceted task (Beek & Lewbel, 1995; Huys & Beek, 2002; Post, Daffertshofer, & Beek, 2000; Yam & Song, 1995). Information about the structure of motor learning can be obtained by analyzing movement variability and dimensionality. Variability is inherently present in the organization of human movement, it is associated with the complexity of the neuro-musculo-skeletal system and with the redundancy of the possible motor solutions (Keetch, Schmidt, Lee, & Young, 2005). The quantification of movement dimensionality is considered important to depict the athlete's skill level; in particular, from a dynamical

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systems perspective, dimensionality indicates the range and number of coordination patterns that can be used to perform a motor task (Preatoni et al., 2013).

The juggling action naturally includes a certain amount of variability, for instance when the catching hand compensates for an inaccurate toss, thus preserving the stability of the juggling pattern. Some studies investigated movement variability considering the coefficient of variation or the standard deviation of pre-selected spatial or temporal parameters, like juggling frequency and spatial repeatability (Haibach, Daniels, & Newell, 2004; Huys, Daffertshofer, & Beek, 2004; Leroy, Thouvarecq, & Gautier, 2008; Rodrigues et al., 2016). These studies suggest that the acquisition of experience is accompanied by a reduction in movement variability and dimensionality (Huys et al., 2004). Nevertheless, to the best of our knowledge, we still lack information on how full-body, global movement dimensionality and variability depend on the experience and task-complexity level. This kind of information would allow to clarify whether different techniques involving the upper limbs reflect specific postural arrangements, and in turn might lead to the development of more effective training programs.

The organization of complex motor actions requires multiple subsystems to be organized in a specific and coherent manner (Huys et al., 2003). In particular, the assembly of the task relevant spatiotemporal relations between hands and balls is the key to learning the skill of juggling (Haibach et al., 2004). It is not clear, however, whether also spatial relations and synergies between other body segments can account for experience-driven changes in coordination. Based on previous studies (Zago, Codari, Iaia, & Sforza, 2016), we hypothesize that multi-joint patterns enabling complex juggling techniques could be experience-dependent. To address this issue, a kinematic data processing technique based on principal component analysis (PCA) has recently been used to detect "coordinative structures", "motor modules" or "synergies" by which the motor system organizes an action (Daffertshofer, Lamoth, Meijer, & Beek, 2004; Federolf, Reid, Gilgien, Haugen, & Smith, 2014; Young & Reinkensmeyer, 2014; Zago et al., 2016). This approach allows to identify the motor schemes (Czyz, 2010) or patterns that are more prone to change according to the skill or performance level (Donà, Preatoni, Cobelli, Rodano, & Harrison, 2009; Gløersen, Myklebust, Hallén, & Federolf, 2017; Memmert, 2006). An in-depth knowledge of which motor patterns are present and how they are modulated during the stages of learning would allow to systematically improve the process of expert performance acquisition (Schmidt & Lee, 2005).

Therefore, the aim of the current study was to quantify the modifications in movement dimensionality, in multi-segmental juggling patterns, and in rhythmicity as a function of proficiency level and task complexity. In particular, we hypothesized that the main juggling patterns can be objectively identified and separated from error-correction and redundant movements, and that expert performance is characterized by a lower dimensionality and a higher rhythmicity within the movement components.

2. Methods

2.1. Participants

Twelve male street jugglers (Table 1) gave their written consent to participate in the current study, which was approved by the local ethics committee and met the ethical standards in sports and exercise research. All participants were right-handed (Annet, 2001), possessed a valid medical certificate stating that they were physically healthy and had normal or corrected to normal vision. Participants able to juggle 6 or more balls were assigned to the expert group (N = 6), while those able to juggle up to 5 balls formed the intermediate group (N = 6) (Beek & Lewbel, 1995; Mapelli et al., 2012). In a previously published investigation on this dataset, no significant differences between the practice characteristics and anthropometrics of the two groups of jugglers were found (Mapelli et al., 2012).

2.2. Data collection

Our investigation was restricted to a task complexity that could be sustained by all participants, thus to 3-, 4- and 5-balls juggling conditions. For each complexity level, participants performed three trials, with a 30-s recovery period between repetitions (Mapelli et al., 2012). Participants were required to complete at least 15 throws per hand without dropping the balls on the ground. If a ball was lost earlier, the trial was repeated. To guarantee the best personal comfort, each participant used his own juggling balls, since ball weight between 130 and 550 g does not modify the characteristics of juggling (Hashizume & Matsuo, 2004; Leroy et al., 2008; Mapelli et al., 2012).

The 3D coordinates of 23 reflective markers (body landmarks: right and left lateral malleolus, femur lateral epicondyle, greater trochanter, anterior superior iliac spine, acromion, olecranon, radius styloid process, dorsal side of the hand, fingertips of thumb and

Table 1
Participants' anthropometrics and practice-related data.

Characteristic	Unit	Intermediates		Experts	
		Median	IQR	Median	IQR
Age	Years	22.0	1	21.5	5.0
Body mass	kg	62.5	6	61.0	7
Experience	Years	2.0	0	2.5	1
Practice	min/day	60	10	65	30