# Towards real-time visualisation of a juggler's brain

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Surpassing the initial 'wow' effect of a complex juggling trick and producing long lasting engaging performance are the main goal of any juggling artistic performance. Conveying the skill and the effort required for the performance is often difficult to pass to the audience. In this paper, we use a wearable EEG headset to investigate how juggling skills can be inferred from a juggler's brain activity during movement execution. We observed characteristic neuronal activation and synchronisation while juggling in both an expert and intermediate juggler. We also found that processing of visuo-motor skills and memory retention can be distinguished during motor imagery and simulated juggling conditions. For the first time, we were able to monitor a juggler's brain in action. We show that using EEG while juggling could both improve our understanding of neuronal mechanisms governing visuo-motor control and, importantly, serve as aid to enrich artistic performance and increase audience engagement.

Keywords: juggling; motor imagery; visuo-motor coordination; memory retention; gamma/theta coupling

Subject classification codes: include these here if the journal requires them

## Introduction

Professional juggling requires coordination and synchronization of repetitive hand and body gestures to produce periodic throwing and catching of a number of objects (e.g., balls). For most skilful experts the number of objects can be 9 or more. Juggling involves complex technical and aesthetic visuo-motor skills that are acquired through rigorous practice and exercise over the course of months and years. As such it can be considered a highly relevant tool to investigate neuroplasticity associated with motor-learning and spatio-temporal dynamics of task-dependent perceptual-motor coordination.

Although juggling with more than 5 balls and introducing juggling tricks typically produces admiration and appreciation among observers of a juggler performing, the complexity of the performance and the skills required often remain unrecognized by a naïve audience.  To capture this hidden aspects of juggling, jugglers introduce auxiliary means of conveying the art of performance in recent years. These means are typically presented as artistic concepts based on synergic interaction between body movements and objects in the 3-D space. While these interpretations of a juggler's performance can illustrate complexity aspects of juggling, the skill required for the routines still remains hidden. To tap into this hidden legacy of a juggler, one must dig into his brain.

In this work, we explore the advantages of using wearable EEG headset to visualize the electrical brain activity of a juggler. Attentive screening of literature research on this topic failed to find studies where EEG activity was recorded during execution of juggling performances. The most trivial reason preventing studies in this direction can be attributable to the delicate nature of EEG systems and the requirement that the artists have to be able to freely move while juggling. Cumbersome EEG systems, that require the usage of conductive gel, wires that connect electrodes to the EEG acquisition system, highly sensitive to motion-induced noise are among the main obstacles. Furthermore, experiments confined to a limited working space are unsuitable for containing juggling posture and movements. Wearable, wireless EEG systems with dry electrodes offer viable alternative to traditionally used gel-based wired EEG systems (Mihajlović et al., 2015).

Here, we show a proof of concept of how such wearable EEG system can be used both for inquiring into the neuronal mechanisms underlying visuomotor processing during juggling and for application in training and enhancement of juggling performances. Two subjects participated in our study, one intermediate and one expert juggler.Two experimental conditions were designed. The first one was intended to characterise brain activity and connectivity during three-ball cascade juggling compared to other conditions such as rest, imagery juggling, and juggling movements without balls in both intermediate and expert juggle. We expected to find differences between the two jugglers due to network adaptation and functional specialisation induced by several years of juggling practice. The second experimental condition was intended to investigate if the difficulty of a juggling trick was reflected in the EEG of the expert juggler while performing juggling cascade with three, five and seven balls. This latter experiment was related to performance execution and was formulated together with the expert, professional, juggler to solve an apparently common problem during performance on stage: "both during competitions and standard shows, the audience is not always able to understand how difficult is for a juggler to perform certain trick, especially those that appear relative simple in balls pattern, but require high attention and visuo-motor control" - quoted from a brainstorm meeting with the expert juggler. The possibility to visualise brain activity of a juggler in a way that reflects the complexity of the executed trick could help to increase the engagement and tuning of the audience during a show.

The paper is organised as follows. In an introductory *State-of-the-art section* we reported the most relevant works related to juggling from a neuroscience perspective (*Juggling-Induced neuroplasticity*), from a perceptual-motor perspective (*Spatio-temporal dynamics of juggling visuo-motor task*) and from a more performance oriented perspective (*Tech-based Artistic concepts for juggling performances*), to offer the reader a wider view on how juggling is an attractive practice for both scientists and art performers. In a *Methods and materials section* we presented the experimental setup and protocols, the techniques adopted for processing the EEG signals and the statistical analysis performed on our data. This section is followed by a *Results section* illustrating the main outcomes of the research and a *Discussion section* in which we contextualize our results with reference to our research questions and related works. Finally, in the *Conclusion section* we outline follow up studies and propose other interesting directions for the use of wearable EEG during juggling.

## 1. State-of-the-art

### *1.1 Juggling-Induced neuroplasticity*

The effect of juggling training on cortical organisation and brain functioning has been tackled using neuro-imaging techniques, other than EEG, before and after training. Scholz et al. (2009) used diffusion tensor imaging (DTI) to measure variation of fractional anisotropy, correlates of white-matter microstructure variation, and voxel-based morphometry (VBM) to measure gray-matter changes in response to learning of complex visuo-motor skill in juggling. They reported significant training-related increases in fractional anisotropy in white-matter underlying the right posterior intraparietal sulcus and significant increases of gray-matter density in the medial occipital and parietal lobe in cortical regions overlying the white matter area of significant fractional anisotropy increase. They also showed that, in general, structural changes did not correlate significantly with training progress or the performance level (Driemeyer et al., 2008; Draganski et al., 2004), suggesting that the majority of structural changes might be related to the amount of time spent training and learning a new task than to the training outcome.

Similar conclusions were drawn earlier by Driemeyer et al.(2008), where VBM was applied to investigate activity-dependent gray-matter changes using the same experimental paradigm as in Scholz et al. (2009), i.e., three-ball cascade juggling. Driemeyer et al. (2008) showed that learning to juggle can induce gray-matter changes in the occipito-temporal cortex as early as after 7 days of training. These changes were referred as transient because further alterations of brain structure were not observed in conjunction with improvement of the juggling skills over time due to training.

When comparing expert and non-expert jugglers, Gerber et al. (2014) found significant increase of gray-matter density in regions involved in visual motion perception and eye-hand coordination in expert jugglers, additionally. For this group gray-matter density in right visual areas (hMT+/V5) were found to correlate with juggling performance.

### *1.2 Spatio-temporal dynamics of juggling visuo-motor task*

Other studies have looked at juggling from a perceptual-motor coordination prospective using high speed cameras and optoelectronic three-dimensional motion trackers to analyse posture (Leroy et al., 2008), pattern stability and amount of error correction (Dessing et al., 2007), coupling between point-of-gaze and ball movement (Huys et al, 2002), attentional control and gaze fixation (Dessing et al., 2012), spatio-temporal dynamics of specific juggling pattern (van Santvoord et al., 1996) and variation of these dynamics during learning (Haibach et al., 2004; Huys et al., 2003; Huys et al., 2004a; 2004b; Beek et al. 1992; Ichikawa et al., 2014).

Different characteristics have been identified to quantify the quality of juggling performance and the level of expertise of a juggler (Mapelli et al, 2012): higher number of catch, lower execution frequency for increased difficulty (ability to master higher throws with increasing number of balls), gaze-thought behaviour, consisting in fixation of gaze at a central location within the pattern (Dessing et al., 2012) and use of peripheral vision and kinaesthesia against foveal vision (Huys et al., 2011), reduced hand variability and greater movement amplitude of the dominant hand compare to the non-dominant one (Mapelli et al, 2012), reduced variability of space-time trajectories of the balls, more stable posture. In particular, Leroy et al. (2008) reported reduced lateral oscillations of the sacrum and of maximal flexion/extension of the right elbow in experts compared to intermediate jugglers during three-ball cascade juggling.

### *1.3 Tech-based Artistic concepts for juggling performances*

More artistic works related to juggling have been oriented to combine juggling movement with acoustic and visual effects both for training and performance enhancement.

Willier et al. (2002) developed a concept for recycling mastered gestures of juggling to allow jugglers to produce music with no additional effort, they proposed a technique based on processing of surface electromyography signals from flexor and extensor muscles of the wrist, and able to detect catch and throw events, for placation in real-time control of music.

Bovermann et al. (2007) developed “the juggling sound”, a sonification system for real-time auditory monitoring of juggling patterns. Inputs for the system are streamed and events-type features related to orientation, distance and speed of juggling clubs with respect to body segments and swinging patterns, correlated with movement precision and symmetry. These features are extracted from video recorded with optical motion capture system and mapped into sound control functions (pitch, gain, frequency) or different typologies of sounds.

Reynolds et al. (2001) used sonar tracking system and accelerometers embedded into gloves to track performer's positions, hand accelerations and arm angle, respectively. They developed a multi-user, polyphonic sensor stage environment where position information of the performers on stage is used to create stereophonic sound, and accelerometer features are used to trigger notes or produce sustained notes and staccato notes.

Schipperheyn et al., (2013) have designed "Sonic Juggling Balls", a flexible platform for professional jugglers to create performances involving sound. The platform consisted of set of balls with embedded accelerometer-based catch sensors and on-board sound synthesis, able to encode site swaps technique (a mathematical approach for noting juggling patterns). The balls could discriminate juggling events, such as, throw, ball in air, catch, ball in hand, and movements while the ball is in hand, and could be programmed to map different type of sounds and sound effects.

## 2. Materials and Methods

### *2.1 Participants*

Two subjects participated to our study, an intermediate (male, 40 years old) and an expert juggler (male, 23 years old). The intermediate juggler was recruited among colleagues, juggling amateurs, while the expert juggler had more than 15 years of experience in juggling. He has won numerous prices in jugging competitions, was 8 times gold medal winner on the Dutch Juggling Championships, was 5 times Dutch record holder, with the most number of throws and catches, within the 6/8/9/10/11 balls games. We consider the difference between intermediate and expert juggler in line with previous definitions (Huys et al., 2002): experts defined as those who could juggle five or more balls; intermediate jugglers defined as those who could comfortably maintain a three-ball juggle for more than a minute.

### *2.2 EEG head set*

The experiments were performed using the wireless imec EEG headset, shown in Figure 1. It has the capability of continuously measuring EEG and electrode-tissue impedance signal at up to

1024Hz (Patki et al., 2012). In this study sampling rate of 256Hz was used and the impedance was monitored only in case of observing noise signals. Commercially available dry Ag/AgCl electrodes with pins were used to penetrate the hair and they are mounted on a spring-loaded support to ensure good contact with the skin and more comfort to a user (see Figure 1). Active electrode chips that buffer the electrical signal are placed directly on top of the spring-loaded contact to prevent noise from entering the EEG system as much as possible. The headset measures the potential difference between measurement electrodes at locations C3, C4, Cz, and Pz, of the International 10-20 System for EEG measurements, and the reference electrode positioned at the right earlobe. Patient bias electrode is located behind the left earlobe.

Figure 1. Experimental set up: A) imec wireless EEG with 4 dry electrodes; B) snapshot of expert juggler wearing the EEG while juggling a five-balls saccade pattern

### *2.3 Procedure*

Two experimental protocols were performed.

The first protocol involved both intermediate and expert jugglers and consists in five conditions:

- **Rest**: rest and think to something outer than juggling,
- **Imagery**: imagine to juggle,
- **Juggle**: play three-ball cascade pattern,
- **ImageryHands**: move upper limbs in a juggle-like fashion and imagine to juggle without balls,
- **NoBalls**: move upper limbs in a juggle-like fashion and think to something outer than juggling.

Each condition lasted 20 seconds and was repeated 15 times (trials) for the intermediate juggler and 10 times (trials) for the expert juggler. The number of trials were minor in the expert juggler due to time availability. In each trial the sequence of conditions was randomised. For all the conditions the subjects had eyes open and they were asked to keep their head as still as possible and to limit overall upper body motion to reduce the impact of motion on the EEG signal. During the Juggle condition, whenever a ball fell down, before the established execution time, the trial was discarded and the condition was repeated. Pauses of few minutes between trials were done whenever required by the subject.

The second protocol involved the expert juggler only and consists in three conditions with incremental difficulty:

- **3Balls**: play three-balls cascade pattern,
- **5Balls**: play five-balls cascade pattern,
- **7Balls**: play seven-balls cascade pattern.

Each conditions was repeated three times (trials) in a randomised order at each trial. Because of the difficulty of sustaining the seven balls game for longer time a duration threshold of 15 seconds was considered for each trial. If a ball fell down within this threshold the trial was discarded and repeated, if the juggler was able to sustain the game for a longer period the recording was continued and stopped at the first ball drop. The cascade game was chosen because of the consistency of the balls pattern (horizontal figure-eight above the hands, produced by throwing one prop in a arc-like fashion before catching another on its way down) across task difficulties induced by the increasing the number of props.

## *2.4 Processing*

### *2.4.1 Filtering and Artifacts removal*

EEG signals collected in both the experiments were processed in similar fashion. To ensure the integrity of the data we initially inspected all the signals visually and manually removed segments containing spike-like artefacts representative of non-physiological signal disturbances, physiological (EOG and ECG) artifacts, and motion artifacts. We then band-pass filtered the signal in a 3-70Hz frequency band, and applied the 50Hz notch filter. We used a third order Butterworth filter and select the cut off at 3Hz for the band pass filter to remove EOG artefacts and movement artefacts, considering that juggling movement can reach up to 2-3 Hz for intermediate and advanced jugglers (Mapelli et al., 2012).

Our empirical evaluation showed that in all cases in this study (except for juggling with 7 balls), motion artifacts were impacting EEG content below 4Hz. Given also the unknown impact motion artifact reduction methods can have on the EEG content (Mihajlović et al., 2014), we decided not to use any motion artifact reduction method but instead not focus on delta band in the analysis.

Artifact removal processing resulted into a total of about 31 minutes of recording for EEG channel ((15 for intermediate +10 for expert) trials* 15 seconds (clean signal)*5 conditions) for the first experiment and a total of about 1.5 minutes for EEG channel (3 trials*10 seconds (clean signal)*3 conditions) for the second experiment, for this latter, signals in Pz were excluded from further analysis (power, coherence and statistical analysis) because of high electrode-tissue impedance signal, caused by skin-electrode contact loss.

*2.4.2 Spectral analysis*

Cleaned and filtered signals were segmented into epochs of 4 seconds in length with 75% of overlap and Welch spectral analysis (Welch, 1967) was applied to each epoch (1024 samples = number of DFT points ). After visual inspection of peaks in broad band power spectra profiles averaged across trials (Figure 2), five frequency bands were considered for the power analysis: theta (3.5-8Hz), alpha (8-13Hz), beta (13-29Hz), low gamma (29-35Hz), high gamma (35-45Hz). Average of log power spectra across each frequency band for each electrode was computed and used for further statistical analysis.

Figure 2. Sample of a 4 second epoch of the EEG signal after cleaning and filtering pre-processing. Oscillation in time are illustrated for each electrode and each conditions of the first experimental protocol.

Figure 3. Broad band power spectra of the expert (1) and intermediate (2) jugglers during the first experimental protocol

*2.4.2 Coherence analysis*

Spectral coherence between pairs of EEG channels was considered to measure synchrony of oscillations between electrodes in each frequency bands, as defined for the spectral analysis. The mscohere function for MATLAB was used. It computes the magnitude squared coherence estimate of the two EEG signals using Welch's averaged modified periodogram method and measure linear synchronisation between two series, taking on a value of 1 for perfect linear relationship, meaning perfect agreement in phase difference, and a value of 0 if the series are uncorrelated, meaning completely random phase differences.

### *2.5 Statistical analysis*

Repeated measure ANOVAs were used for the statistical analysis for the first experiment. For both the power and coherence modulations within-subject three-factors repeated measure ANOVA was performed with the factors being: electrode site (C3/C4/Cz/Pz) for power spectra and electrodes pairs (C3-C4/C3-Cz/C3-Pz/C4-Cz/C4-Pz/Cz/Pz) for coherence measure, task condition (Rest/Imagery/Juggle/ImageryHands/NoBalls) and frequency (theta/alpha/beta/low gamma/high gamma) with subjects as random factor (1 = expert juggler, 2 = intermediate juggler). This ANOVA was further interrogated with separate two-factor ANOVAs (with factor frequency and task condition) for each subject. Turkey's test was performed for post-hoc analysis and differences between Juggle and other conditions, Rest and Imagery condition, ImageryHands and NoBalls condition were tested.

For the second experiment grand average across trial repetitions for frequency band and conditions where reported without performing further statistical analysis, due to the low number of trials per condition.

All statistical analysis was performed in R. The statistical analysis performed for this work should be considered as indicative not assertive given that only two subjects participated to the study.

## 3. Results

### ***3.1 Results of Experiment 1***

#### *3.1.1 Power spectra modulation*

Figure 4 shows the modulation in power across task condition and frequency. The three-way within-subject repeated measure ANOVA showed significant main effects of frequency($F(4,4) = 33.58, p = 0.002$), condition($F(4,4) = 6.572, p = 0.047$) and channel($F(3,3) = 12.76$, $p = 0.032$) an interaction between frequency and condition ($F(16,16) = 4.84$, $p = 0.0015$). We proceed by investigating Turkey's test two-factor ANOVAs, with factor task condition (Rest/Imagery/Juggle/ImageryHands/NoBalls) and frequency (theta/alpha/beta/low gamma/high gamma), for each subject, and consider results of the comparison between Juggle condition and other conditions, Rest and Imagery conditions, ImageryHands and NoBalls. Qualitative assessment on effects at each electrode sites is also reported (Figure 5 depicts observation at the electrodes level for the intermediate subject).

In the *Juggle vs other conditions* comparison, we found that, for the expert juggler, power in Juggle condition is significantly higher ($p<0.005$) than in other condition in all frequency bands; for the intermediate juggler, power in Juggle condition is significantly higher ($p<e\text{-}06$) than in other conditions in high gamma and theta (across all electrodes); it is significantly higher ($p<e\text{-}08$) than in Rest and Imagery conditions in low gamma (in C3,C4,Cz); it significantly differs ($p<0.005$) in alpha (being higher in C3, C4, Cz) from all other conditions apart from NoBalls condition; no significant differences are observed for beta band.

In the *Rest vs Imagery conditions* comparison, we found overall significantly (p<e-04) higher power in alpha band for Rest condition compared to Imagery condition for the expert juggler; no significant differences between these two condition were found for the intermediate juggler.

In the *ImageryHands vs NoBalls conditions* comparison, we found overall significantly ($p<0.05$) higher alpha power in the NoBalls condition compared to the ImageryHands conditions for the intermediate juggler; no significant differences for the expert juggler.

Figure 4. Log of power spectral density for expert (1) and intermediate (2) jugglers, averaged across electrodes and trials, for different task conditions and frequency bands in the first experimental protocol.

Figure 5. Log of power spectral density for intermediate juggler, averaged across trials, for different electrode locations, task conditions and frequency bands in the first experimental protocol.

*3.1.2 Coherence modulation*

Figure 6 shows the modulation in coherence across task condition and frequency. The three-way repeated measure ANOVA showed significant main effects of condition ($F(4,4) = 19.27, p = 0.007$) and paired channel ($F(5,5) = 36.31$, $p = 0.0006$) an interaction frequency: condition ($F(16,16) = 2.685$, $p = 0.028$). We proceed by investigating Turkey's test two-factor ANOVAs, with factor task condition (Rest/Imagery/Juggle/ImageryHands/NoBalls) and frequency (theta/alpha/beta/low gamma/high gamma), for each subject, and consider results of the comparison between Juggle condition and other conditions, Rest and Imagery conditions, ImageryHands and NoBalls. Qualitative assessment on effects at each electrode sites is also reported (Figure 7 depicts observation at the electrodes level for the expert subject).

In the *Juggle vs other conditions* comparison, for the expert juggler, the theta coherence during Juggle is significantly different ($p<e-05$) from theta coherence in ImageryHands condition (being higher in Juggle in CzPz, C4Cz,C4Pz; lower in Juggle in CzC3); the alpha coherence in Juggle significantly differs ($p<0.05$) from other conditions (is lower in CzC3 compared to NoBalls, is higher in C4Cz, C4C3, C4Pz compared to other); the beta coherence in Juggle significantly differs from the beta coherence in Imagery condition ($p<0.05$) and in Rest condition ($p<0.001$) (being higher for all electrode pairs apart from Cz,Pz); same for high gamma coherence ($p<0.001$) (here coherence while juggling is higher for all pairs). For the intermediate juggler, gamma bands coherence during Juggle is overall significantly ($p<e-05$) higher than in other conditions; for beta and theta coherence Juggle significantly differs ($p<e-09$) from Rest condition (being higher in beta and lower in theta).

In the *Rest vs Imagery conditions* comparison, no significant differences in coherence across frequencies were found for both expert and intermediate juggler.

In the *ImageryHands vs NoBalls conditions* comparison, significant differences ($p<0.0001$) were found only for expert juggler in alpha coherence and in theta coherence (with higher coherence in NoBalls compared to ImageryHands).

Figure 6. Coherence measure for expert (1) and intermediate (2) jugglers, averaged across electrodes and trials, for different task conditions and frequency bands in the first experimental protocol.

Figure 7. Coherence measure for expert juggler, averaged across trials, for different electrode locations, task conditions and frequency bands in the first experimental protocol.

### *3.2 Results of Experiment 2*

Grand averages of power spectra across trial repetitions (Figure 8) show that increasing difficulty due to increased number of balls for the cascade pattern is reflected in an increase of power across all frequency bands and channels.

Grand averages of coherence across trial repetitions (Figure 9 and Figure 10) show that for 7 balls compared to 3 and 5 balls cascade coherence between central electrodes increases in theta and alpha bands and decreases in beta and gamma bands. Interestingly, for the 5 balls cascade coherence increases across all frequency bands, apart from beta band, and for all channels pairs compared to the 3 balls game, while in the range of beta band coherence between Cz-C4 and Cz-C3 is attenuated compared to the 3 balls game.

Figure 8. Boxplot of log power spectral density averaged across electrode and trials for each frequency band and conditions in the second experimental protocol

Figure 9. Boxplot of coherence measure averaged across electrode and trials for each frequency band and conditions in the second experimental protocol

Figure 10. Coherence measure for expert juggler, averaged across trials, for different electrode locations, task conditions and frequency bands in the second experimental protocol.

## 4. Discussion

### *4.1 Experiment 1: the expert juggler brain*

#### *4.1.1 Juggle vs other conditions*

Our results show that the experienced juggler exhibits specific brain activation while juggling compared to other conditions, as outcome of network adaptation and functional specialisation induced by several years of juggling practice. In particular, the power of oscillations across the scalp was higher, while juggling, for all the considered frequency bands, even when juggling movement was mimicked and isolated in the NoBalls and ImageryHands conditions. Higher theta coherence between electrodes in the right hemisphere compared to mimic movements in the ImageryHands condition could be attributable to the involvement of theta band in reaching movements (Perfetti et al., 2011) and degree of motor learning and retention (Caplan et al., 2003; Tombini et al., 2009; Gentili et al., 2011). Higher interhemispheric gamma and beta coherence in

Juggle condition compared to Imagery and Rest conditions could represent synchronous oscillations associated to intrinsic (body-related) and extrinsic (object centered) coordinate transformations during right-to-left and left-to-right movement (Lange et al., 2006) both in presence (Juggling) and absence of goal-directed motor planning (ImageryHands and NoBalls). Overall higher alpha coherence compared to other conditions can be associated with hemispheric synchonization in the control and coordination of bimanual movement, in particular, here we notice a dominance in synchronous activity in the right hemisphere, possibly reflecting the established efficient bimanual motor routine or internal models (Gerloff et al. 2002) and a stronger visuo-motor adaptation (Ghilardi et al., 2000) due to extensive practice.

In the intermediate juggler, on the other hand, Juggle condition was specifically characterised by higher power in theta and high gamma frequency bands and higher inter hemispheric gamma (low and high) coherence. Interestingly, when comparing Juggle and Rest conditions, as seen in the expert juggler, also in the intermediate juggler, higher beta coherence was found in juggling compared to Rest, while, differently from the expert juggler, lower theta, instead of higher gamma coherence, was found. It is possible that for both experienced and intermediate juggle synchronous activations of beta oscillations are associated with intrinsic coordination coding, while interplay of synchronous gamma and theta oscillation and modulation of gamma and theta spectral amplitude are attributable to extrinsic visuo-motor coordination and movement planning, allowing to switch from already acquired internal models to formation of new motor memories, more for the intermediate than for the expert juggler (Perfetti et al., 2011).

The complexity and the variety of synchronous neuronal activities observed in the expert juggler are the necessary results of a learning process characterised by temporal hierarchy and multiform dynamics. As reported in (Huys et al., 2004a) and (Mapelli et al., 2012), the level of expertise of a juggler and his performance are shaped by the successive acquisition of different visuo-motor skills from control of postural sway to eye-head and hand movement coordination, at monotonically increasing frequency locked ratio to the balls trajectories. This allows the proficient juggler to switch adaptively between functional organizations involving distinct perceptual systems (Huys et al, 2004).

*4.1.2 Rest vs Imagery conditions*

Rest and Imagery conditions were included in the first experimental protocol to control for neuronal activity involved in the mental representation of the juggling movement. As previously reported, our results show that for both the expert and the intermediate juggler, neuronal activity distinguishing Imagery and Rest conditions from actual juggling movement resulted in higher beta coherence while doing the movement as expression of visuo-motor processing, also suggesting as in (Kilner et al., 2004) that differences between real and imagined movement are realised not by the activity in a given area but by the functional interactions between areas. Comparing the act of imagining the movement with the rest condition, we could not find difference in synchronous activity across frequency band for both the jugglers. On the other hand significantly higher power in alpha oscillation during Rest compare to the Imagery condition was found only in the experienced juggler. Alpha suppression during movement imagination is associated to the ability to generate motor imagery, and is commonly used in BCI applications (Pfurtscheller et al., 2001). It is possible that the intermediate juggler had more difficulty in generating motor imagery of juggling while the expert juggler had stronger and stable internal representation of motor movement induced by extensive practice (Barrett et al., 1982).

*4.1.3 ImageryHands vs NoBalls conditions*

ImageryHands and NoBalls conditions were introduced in the first experimental protocol to control for neuronal activity involved in movement control and right-left hand coordination, isolating the visual component of juggling as goal-directed task. As previously reported, our results show that, for the expert juggler, juggling is clearing distinguishable from other juggling-like movements by looking at the increase of power spectra across different frequency bands. For the intermediate any statistical difference between power of alpha oscillation during Juggling and NoBalls condition was found, and higher alpha suppression in the NoBalls condition in central electrodes compared to Juggle was observed.

When comparing the condition in which the movement is simulated but not imagined (NoBalls) and when the movement is simulated and also imagined (ImageryHands) overall higher alpha power was found for the NoBalls condition in the intermediate juggler, while higher alpha and theta coherence in NoBalls condition compared to ImageryHands was found in the expert juggler only. Also alpha coherence while juggling was also found significantly lower compared to NoBalls for the expert juggler.

We suggest that the intermediate juggler was more able to produce motor imagery while during the motor action which translated in higher suppression of alpha oscillations. On the other hand, reduced synchronisation of theta and alpha oscillation during motor imagery combined with motor movement and actual juggling in the expert juggler could be interpreted as the capability to quickly represent motor imagery as retrieved from strong memory retention of the juggling movement.

### *4.2 Experiment 2: visualising cascade juggling difficulty*

The second experiment was designed to determine if the increasing difficulty in performing cascade juggling with 3, 5 and 7 balls could be reflected in the EEG of the experienced juggler. We found that the power of neuronal oscillations across all the frequency bands generally increases with the task difficulty. Also synchronous activity was found to increase across all frequencies when passing from 3balls to 5balls cascade game. Synchronisation of activities was similar for the 7balls game was higher in alpha and theta band and lower in beta and gamma bands compared to the 3 and 5 balls game. This effect could have been also produced by unaccounted artifactual components due to increased body movements and instability of the juggler tossing 7balls.

### *4.3 Outlook of results: A performance scenario*

The results obtained in our analysis open up new opportunity for a juggler to increase the engagement of the audience during a performance. We envision a scenario in which the juggler wears the EEG headset during the performance and the EEG biomarkers identified in this paper, such as, power across frequency and gamma and theta coherence, are visualised in real-time. By directly looking at the variation of these biomarkers on a big screen, the audience would be able for example to see wether in a moment of pause the juggler is thinking about juggling or if he is generating motor imagery in preparation for the show, or have a better perception and understanding of the mental effort required by juggler during the performance of tricks of increasing difficulties. Other possibilities could include the mapping of the variation of these biomarkers into sounds or other visual outputs, as the works presented in the *Tech-based Artistic concepts for juggling performances* section have done using movement mapping.

### *4.4 Limitations*

The study described in this paper investigated EEG monitoring in an entirely different settings than traditional controlled lab environments with a clearly specified user behavior protocol. In our case, the user is allowed to freely move and perform juggling activities, while his/her EEG is recorded with a wireless dry electrode EEG headset. While such convenient setup minimizes the impact on user behavior and performance, it also brings a number of limitations. They stem from fragility of the captured EEG signal. The recorded signal is prone to various interferences that are difficult to characterize and isolate from the EEG. We believe that body and eye movement artifacts have the most detrimental effect on the signal (Mihajlovic et al., 2015). Given that those artifacts impact low frequency components of EEG, we excluded the signal in the delta band from the analysis. However, this does not ensure that all artifact components are removed from the signal. For example, large increase in the theta and alpha bands with the increased complexity of juggling performance or increase in the theta band due to performing tasks involving hand movements can partially be attributed to the amount of movement required. Further studies in this domain should address proper characterization of artifacts and should incorporate artifact handling techniques in the signal analysis step, e.g., by using electrode-tissue contact impedance (Mihajlovic et al., 2014).

Including only two participants in the study, one expert and one intermediate, also limits the interpretation power of the results reported. Although with a larger number of repetitions we were able to extract clear patterns across activities in different EEG frequency bands (for both participants), it is yet to be determined to what degree the same effects can be observed in other jugglers. This goes along two different axes, jugglers with different skill level as well as different juggling techniques used. Furthermore, here we exploited only a short segment of 20s of juggling performance which captures just a snapshot of the EEG activity during performance. Continuous monitoring over longer period of time, before, during, and after the practice or performance, could provide many more insights into juggler's brain.

## 5. Conclusion

In this work we have shown that monitoring electrical activity of the brain using dry electrode, wearable and wireless EEG headset during juggling is possible. Using such setup with 3 central and one parietal electrode, the exploration of neuronal mechanisms underlying visuomotor processing during juggling of two jugglers, one expert and one intermediate, led to a number of discoveries. When performing juggling, experienced juggler shows a specific brain activity signature observed in all frequency bands, indicating juggling as a specific brain state. Also in a less experience juggler specific brain signature can be observed, involving higher theta and gamma activity and larger coherence in these bands, suggesting visuo-motor coordination and movement planning. The difference between two jugglers can be seen in different patterns of alpha and theta activity and coherence while performing imagined juggling movement compared to performing the movement only, illustrating different involvement of memory retrieval and motor coordination among the two. Higher beta coherence while performing the movement (i.e., visuo-motor processing) can also be observed in both participants, suggesting functional interactions between different brain areas.

Capturing all these insights with a convenient EEG headset opens the possibility to articulate hidden and intrinsic brain activity of a juggler, that can illustrate the complexity and skill required for performing particular juggling trick or activity. Such possibility can be utilized to both explore the dynamics of the brain during juggling skill acquisition and performance and enhance the engagement of the audience during the juggling performance. The former can be used to tune the skill learning process for a particular juggler (style) and hence speed-up the learning process. The latter would provide jugglers with a completely new modality of conveying their artistic and juggling skills to the audience.

Observations reported here are just a tip of an iceberg, given the limited number of jugglers used and the simplistic method used. More insights can be provided by involving a larger number of jugglers, having different skill levels using different juggling techniques. Monitoring the brain of juggler while he is preparing for the performance (e.g., for more than an hour) until he enters the state of 'flow' might provide new insight of the evolution of neuronal activation. Also monitoring brain activity and other cognitive aspects (e.g., attention, stress level, emotional status) before the preparation and after the performance can provide insight on the effects juggling act has on human mind. Similarly, capturing brain activity while juggler is performing another mental activity while juggling (e.g., speaking, mental arithmetic, problem solving), or is a subject to sensory stimulation (e.g., evoked responses) can give more cues in understanding the cognitive processes during juggling. These are just few areas for exploration that could provide further insights in what happens in a mind of a juggler.

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