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Mobile brain/body Imaging in dance: A dynamic transdisciplinary field for applied research

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Abstract

Neuroscience of dance is an emerging field with important applications related to health and well-being, as dance has shown potential to foster adaptive neuroplasticity and is increasingly popular as a therapeutic activity or adjunct therapy for people living with conditions such as Parkinson's and Alzheimer's diseases. However, the multimodal nature of dance presents challenges to researchers aiming to identify mechanisms involved when dance is used to combat neurodegeneration or support healthy ageing. Requiring simultaneous engagement of motor and cognitive domains, dancing includes coordination of systems involved in timing, memory and spatial learning. Studies on dance to this point rely primarily on assessments of brain dynamics and structure through pre/post-tests or studies on expertise, as traditional brain imaging modalities restrict participant movement to avoid movement-related artefacts. In this paper, we describe the process of designing and implementing a study that uses mobile brain/body imaging (MoBI) to investigate real-time changes in brain dynamics and behaviour during the process of learning and performing a novel dance choreography. We show the potential for new insights to emerge from the coordinated collection of movement and brain-based data, and the implications of these in an emerging field whose medium is motion.

KEYWORDS

dance therapy, mobile EEG, motor learning, neuroplasticity

1 | INTRODUCTION

Complex, situated human behaviours challenge scientific methods and measures; they resist reduction, and efforts to isolate variables can destroy ecological validity along with the authenticity of the phenomenon in question. Techniques such as mobile brain/body imaging (MoBI; Gramann, Ferris, Gwin, & Makeig, 2014; Gramann et al., 2011; Makeig, Gramann, Jung, Sejnowski, & Poizner, 2009) are opening new frontiers in the study of complex naturalistic behaviour, a prime example of which is in the field of dance. Ranging in expression from spontaneous head-bopping along with a beat

Abbreviations: AMICA, adaptive mixture independent component analysis; ANOVA, analysis of variance; BeMoBIL, Berlin Mobile Brain/Body Imaging lab; BOLD signal, blood–oxygen-level-dependent signal; EEG, electroencephalography; fMRI, functional magnetic resonance imaging; HTC, High Tech Computer Corporation; IC, independent component; ICA, independent component analysis; MoBI, mobile brain/body imaging; MoCap, motion capture; SMA, supplementary motor area.

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to forms as diverse and demanding as ballet, butoh, folk, Krump and tango, dance marries creativity with technique and has been observed in every known human culture (Pusnick, 2010).[1] Dance has performative, cultural and individual dimensions, and traditional associations with health and healing, a role currently being revived in emerging therapeutic applications of dance for ageing, development and the treatment of conditions such as Parkinson's, Alzheimer's and Cerebral palsy.

Neuroscience of dance investigates how engagement in and with dance affects brain structure and function, as dance provides unique access to processes involved in action and perception, visuo-motor transformations, learning and expertise. Dance involves the production of complex motor sequences synchronised with external cues such as music, other people and the environment or studio, and probing these processes can provide rich data related to broader questions in neuroscience such as how memory, timing, and spatial orientation are realised by the brain. As a rehabilitative activity, dance demonstrates potential to slow neurodegeneration (DeSouza & Bearss, 2018) and foster neuroplasticity (Burzynska et al., 2017; Rehfeld et al., 2018). Over the past four decades, scientific interest in dance has steadily increased, with the number of published articles involving “dance” increasing exponentially over last two decades from 34 articles in 1979 to 648 last year, while those addressing “dance and health” have increased over the same period from 3 articles to 140 in 2019 (PubMed, accessed 2020–02–20).

While some studies have shown anatomical differences that seem attributable to dance (Burzynska, Finc, Taylor, Knecht, & Kramer, 2017; Burzynska, Jiao, et al., 2017; Hänggi, Koeneke, Bezzola, & Jäncke, 2010; Karpati, Giacosa, Foster, Penhune, & Hyde, 2017) and others have demonstrated that dance learning is associated with functional differences suggestive of learning dependent plasticity (Bar & DeSouza, 2016), this research has been conducted while people were not in the process of actually moving. Considering the centrality of motion in dance, there is huge potential for new insights to emerge from investigation of mechanisms involved as people move in real time and space. What we know so far in the field of dance neuroscience has been inferred from comparative studies involving expert versus novice groups (Burzynska, Finc, et al., 2017; Burzynska, Jiao, et al., 2017) or contrasting types of expertise as in dancers and musicians (Karpati et al., 2017; Giacosa et al., 2019; Poikonen, Toiviainen, & Tervaniemi, 2018); there have also been anatomical studies that look at structural differences associated with training, mental rehearsal or imagery, and reactions to video stimuli. Most of these study designs relied on traditional neuroimaging methods, which restrict movement in order to limit motion artefacts, rather than emerging from the best means of studying the phenomena if technical constraints were not a factor. Previous investigation of changes in EEG (electroencephalography) related to dance therapy with specific conditions such as schizophrenia (Margariti et al., 2012; Ventouras et al., 2015), traumatic brain injury (Kullberg-Turtiainen, Vuorela, Huttula, Turtiainen, & Koskinen, 2019) and seniors (Zildou et al., 2018) has analysed resting-state pre/post-conditions using a variety of analysis methods and shown measurable changes in frequency bands that may be associated with alterations in network engagement or organisation. Cruz-Garza, Hernandez, Nepaul, Bradley, and Contreras-Vidal (2014) used MoBI to investigate the neural basis of expressive human movements, such as those found in dance, and found it feasible to identify and distinguish these by decoding EEG signals post hoc, demonstrating an identifiable change in neural signals associated with different manners of moving.

The field of scientific research on dance has shown clear potential to elucidate how brain structure and function may be shaped by expertise and the biological effects of dancing. However, the question of how specific elements of dance may be involved in these processes has been difficult to isolate. Mobile brain imaging technologies have opened up this field of inquiry, and in the next section, we describe the process of designing and implementing an experimental protocol using MoBI to investigate the brain dynamics underlying dance as an archetype of a common but highly complex human activity. Dance is composed of rich dynamic blending of motor and cognitive processes as well as neural dynamics, interacting to allow synchronisation with externally provided rhythms and taking place in a specific spatial and social context. The following protocol demonstrates how MoBI studies can provide significant insights into the processes involved in learning, performing, imagining and watching dance.

2 | THE DANCE PROJECT

Our goal was to investigate the potential for using MoBI to investigate real-time changes in brain dynamics and behaviour during the process of learning and performing a novel dance choreography. The project built on studies from members of our group that showed dance-based learning over 8 months produced blood–oxygen-level-dependent (BOLD) signal changes in supplementary motor areas (SMA) as measured with functional magnetic resonance imaging (fMRI; Bar & DeSouza, 2016) and resting-state alpha power increases in frontal cortex post-dance in people with Parkinson's disease compared to controls

[1] And in some animals, particularly birds, elephants and cetaceans; a recent study featuring Snowball the dancing cockatoo is notable for its observance of spontaneity and diversity of movement in a bird (Keehn et al., 2019).

(DeSouza & Bearss, 2018; Levkov, Di Noto, Montefusco-Siegmund, Bar, & DeSouza, 2014). The process of investigation in this new project was distinctly transdisciplinary, drawing on our individual areas of expertise in dance and movement studies, systems and cognitive neuroscience, and mobile imaging techniques.

Dance is a complex phenomenon; isolating variables can be extremely demanding if not impossible—almost every instance of dancing includes music or rhythm, social and cultural elements, specific uses of space and time that must be imitated, intuited or invented, and relational dynamics between dancers, dancer and teacher, or dancer and audience. We made a concerted effort to constrain or identify the influence of these elements and focus our study on the process of learning a dance over time, a question that seemed ideal for MoBI. To achieve this, we created five brief (~30-s) choreographies comprised of elements common to many dance forms, but not belonging to any one in particular, and used novel synth-generated music to reduce affective responses associated with music. The entire experiment's data collection lasted approximately one hour, and behaviour and data recording were continuous throughout.

Sessions were recorded at the Berlin Mobile Brain/Body Imaging lab (BeMoBIL), with a dedicated 150 m^2 lab space allowing for acquisition of motion capture data synchronised with wireless mobile EEG (actiCap; 128 electrodes, Brain Products, Gilching, Germany). Movements were captured using the HTC Lighthouse tracking system (High Tech Computer Corporation, Taoyuan City, Taiwan) with five trackers each on the dancer and five on the teacher (left/right wrist, left/right ankle and centre of back). EEG data, motion capturing data and event marker data were synchronised streamed and recorded using the open-source software Lab Streaming Layer.[2]

The session was organised to resemble, to the greatest extent possible, an actual dance class or dance intervention (Bearss, McDonald, Bar, & DeSouza, 2017). Trials included warm-up, watching the choreography to be learned and an alternate choreography that would not be learned, to allow for eventual comparison pre/post of EEG for known versus novel movement sequences (VIDEO, 2 times each), watching live performances of the choreography to be learned (WATCH, 6 times), moving with the teacher (LEARN 3 to 20 times, as per each participant's requirements to reach our criterion of 80% accuracy in repeating the movement sequence, assessed by a trained rater), imagining performing from a first-person perspective (IMAGINE, 6 times) and finally performing the choreography in space (PERFORM, 6 times). We also collected pre/post-resting EEG data from the participant while standing, with eyes open and eyes closed (rsEEG) and included a pre/post-activity of walking a predetermined path through the space twice, plus an additional trial of imagining walking this path pre and post-dance learning phases (spacewalk; see Figure 1 for an overview of all phases of the study design). The spacewalk had a dual function of providing additional warm-up and cool-down time along with the opportunity to collect data relating to spatial coding as the subject explored the room before and after learning the dance sequence.

We hypothesised that brain-based changes observed in previous imaging studies of dance could result specifically from challenges involved in learning and reproducing motor sequences; dance, as opposed to most forms of exercise, is spatially oriented and temporally cued. For this reason, we developed choreographies designed to address this question, while remaining within the technical constraints of conducting scientific research in a laboratory environment. The choreographies used in this protocol were both 30 s in length and included elements of extension, one-support balance, weight shift, rotation and coordinated movements of arms and legs (Figure 2). We limited movements with high acceleration or jerk that could lead to movement of the electrodes or cable sway but included other potentially challenging aspects of dance that were still accessible to a novice participant, such as fast rotation. We used novel synth-generated music that was rated for valence pre/post the experiment and was unfamiliar to all subjects and thus lacking in emotional associations.

3 | STUDY DESIGN

Implementing MoBI with dance offers unique means of investigating different aspects of movement and brain dynamics, along with their combined range and interactions. The power of the protocol developed here is in the vast possibilities for analysis and comparison of different kinds of data, including movement, EEG, combined motion and EEG data, participant experiences, video materials, and correlations or interactions between these. In Figure 1, we gave an overview of elements in our experimental design; the entire protocol was completed in approximately one hour per subject and allowed for continuous collection of EEG, motion capture, video, participant feedback through open-ended questionnaires and brief interviews, and experimenter observation. The following section will provide an overview of how the data will be processed and provides examples for concrete analyses that will be conducted to test specific hypotheses associated with the Dance Project.

4 | DATA RECORDINGS AND ANALYSES

For the EEG-recordings, a 128-channel mobile EEG System (actiCap; Brain Products, Gilching, Germany) with

[2]Kothe, C. (2014). Lab streaming layer (LSL). https://github. com/sccn/labstreaminglayer. Accessed on October 10, 2019.

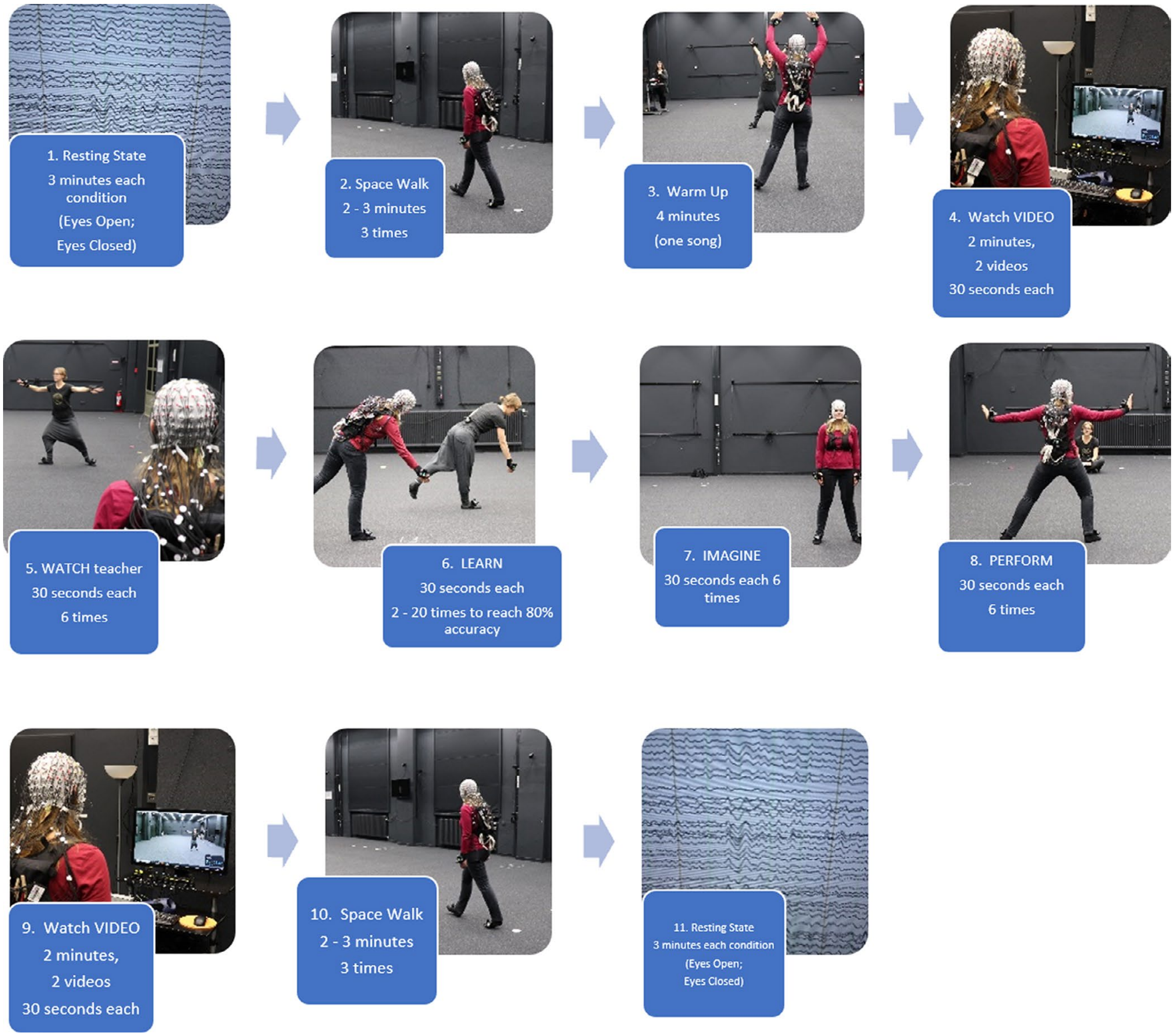

FIGURE 1 Elements of study design and time required for each segment

a customised channel arrangement was used, including two frontal electrodes relocated under the eyes for the recording of ocular activity. In this project, we decided against the use of additional neck electrodes to record dorsal neck muscle activity, as extensive data analyses provided evidence that the use of such neck electrodes increases noise and reduces the number of brain sources that can be identified (Klug & Gramann, submitted to this special issue). Data preprocessing was conducted using Matlab 2019b (MATLAB, The MathWorks Inc., Natick, MA, USA) and standard routines from the EEGLAB plugin (Delorme & Makeig, 2004) as well as customised scripts based on the BeMoBIL pipeline (Klug, 2019). Further details can be found in publications with similar processing approaches (e.g. Gramann et al., 2018) that are based on channel cleaning and interpolation, filtering and downsampling as well as subsequent independent component analysis using adaptive mixture independent component analysis (AMICA; Palmer, Makeig, Kreutz-Delgado, & Rao, 2008). The advantages of independent component analysis (ICA) and subsequent equivalent dipole modelling of independent components (ICs) are the dissociation of brain and non-brain activity such as eye movement and muscle activity that contribute to the volume conducted signals recorded at the sensor level (particularly for studies that include active movement, as in the Dance Project), an increased signal to noise ratio for data analyses when moving from the sensor to the source space, as well as additional neuroanatomical information gained from the approximation of the cortical origins of the recorded data. Independent components across participants will be clustered using repetitive k-means clustering

FIGURE 2 LEARN trial with the teacher; subject is wearing an actiCap with 128 active electrodes (Brain Products); both subject and teacher are wearing 5 Vive Motion capture pucks (HTC Vive): 2 each on wrists and ankles, and 1 on the centre of the back. Pictures courtesy: Benjamin Paulisch

(Gramann, Hohlefeld, Gehrke, & Klug, 2018) to allow for group level analyses of cortical activity associated with different aspects of dance.

Motion capture data were recorded as *x*, *y* and *z* as well as quaternion orientations of the ten rigid bodies from each Vive tracker and preprocessed using adapted functions from the MoBILAB toolbox (Ojeda, Bigdely-Shamlo, & Makeig, 2014). Processing steps included low pass filtering, transformation from quaternion data to Euler angles and computation of the first two derivates of position data for subsequent analyses of velocity and acceleration of each rigid body.

For answering our main research questions on real-time changes in brain dynamics and behaviour during the process of learning and performing dance, we intend to analyse sensor level as well as source level data. Here, we give a brief overview of some of our primary hypotheses and examples of planned analysis.

4.1 | Dance impacts resting-state alpha activity

Previous studies from our group showed modulation of baseline resting-state alpha power in frontal cortex after participation in a one-hour dance class (Barnstaple & DeSouza, 2018; Levkov et al., 2014). The MoBI protocol developed for this study allows for robust comparison of baseline alpha and any frequency domains pre/post observing and learning a specific dance, with minimal interference as subjects remain in the same experimental environment for the duration of the study. To this end, EEG spectral power in the alpha (8–12 Hz) frequency band will be compared for pre- and post-resting-state sessions for the sensor level using frontal electrodes as well as the source level identifying clusters of ICs located in or near the lateral and central prefrontal cortical regions. Aiming at a replication of previous results indicating changes in the frequency domain (Levkov et al., 2014), tonic power spectrum density estimates will be calculated for each three minute pre/post-dance resting-state condition over a frontal electrode cluster (e.g. using Welch's method on windows of 256 points length, zero padded to 512 points) and statistically assessed by a repeated measure analysis of variance (ANOVA) with factors resting-state condition (eyes open, eyes closed) and timing (pre- and post-dance).

4.2 | Dance and spatial orienting

Along with resting-state data (rsEEG) including eyes open and eyes closed conditions, we collected pre/post sessions of walking a predetermined path through the space, along with *imagining* performing this same task once the path was learned (spacewalk). This activity provided subjects with a simple warm-up and cool-down exercise, along with furnishing a rich data set pertaining to spatial coding before and after participants interact with the environment in the spatially constrained and oriented activity of learning specific movements comprising the dance. Assuming that participants learn the boundaries of the space they move through while learning the choreography, we will specifically contrast event-related spectral perturbations in the theta, alpha and beta frequency bands of clusters of ICs with their centroid located in or near the retrosplenial complex as well as the parietal cortex. These areas are implicated in computing heading representations and transformation of egocentric sensory information sampled from the senses into an allocentric representation of space stored in the medial temporal cortex (Gramann et al., 2010; Lin, Chiu, & Gramann, 2015; Vann, Aggleton, & Maguire, 2009).

4.3 | Dance impacts action representation

Pre/post-VIDEO segments provide further EEG data for analysis related to viewing unfamiliar versus familiar motor sequences, and the possibility of detecting error signals in the case of the learned dance. The advantage of analysing EEG data during watching of video segments lies in the direct comparison of videos presenting an unfamiliar motor sequence *before* participants learn the choreography, with identical videos *after* dance learning; at this point, one of the videos now shows a choreography that has been directly experienced while the second video shows a still unknown motor sequence. We will focus the analyses again on the frequency domain at the sensor as well as source level, concentrating on electrodes and clusters with their centroids located in or near motor cortices to investigate mu desynchronisation using repeated measures ANOVA with factors of timing (pre-dance, post-dance) and familiarity (learned versus. novel choreography).

4.4 | Perception of live versus recorded dance

The protocol also includes watching video versus live performances of a dance, in the same setting and with the same dancer, potentially addressing gaps in the literature as to any difference between these kinds of viewing. Given the growing research on the effects of watching dance (Cross, Kraemer, Hamilton, Kelley, & Grafton, 2009; Di Nota, Chartrand, Levkov, Montefusco-Siegmund, & DeSouza, 2017), and the dependency on video material in standard neuroimaging protocols using fMRI or EEG, these data have potential to be highly informative. Increasing ecological validity of stimulus material leads to higher variance in eye movements and information selected for attentive processing (Dorr, Martinetz, Gegenfurtner, & Barth, 2010). Here, we will focus on analysing specific periods of the choreography that contain easy versus difficult movements to investigate whether video material and live-performed movements elicit comparable activations in motor and parietal brain regions of observers. Frequency domain parameters can be further investigated using regression models with subsequent performance of participants during the learning stage (number of necessary repetitions) as the dependent variable of frequency modulations during viewing of the choreography.

4.5 | *Dance imagery* versus *dance performance*

Our design also provides data on processes involved in imagining performing the dance, which can be directly compared with watching, learning and performing it in space; we can probe for changes in the frequency domain during learning and performance by comparing across trials as the subject becomes more proficient and comfortable in reproducing the movements of the dance. The study design also includes data where there are no physical movements, and behaviour remains the same while the task changes, as in the trials of imaging the dance, imagining the spacewalk and resting state.

4.6 | Movement and brain synchronisation

The inclusion of five Vive trackers each on the subject and teacher provides ample opportunities for various kinds of motion analysis from the behavioural data. We can mathematically model speed, acceleration, and path for each tracker or sets of trackers; we can look at the level of synchronisation between the subject and teacher over LEARN trials; we can correlate movement dynamics from LEARN to PERFORM; we can compare the movement trajectories of different subjects with different learning curves and between subjects and teacher; and we can model evolution or decay in reproducing the motor sequence across trials. These data are further enriched by the inclusion of video recordings, along with teacher/experimenter observation and phenomenological data as subjects are asked to rate the extent to which they felt as though they are “fully dancing” on each PERFORM trial and reflect on any changes. Motion data, correlated in this way with experiential aspects of dancing, can enhance understanding of essential elements that may have been overlooked in existing clinical and scientific research, by providing “hard data” on aspects of dance experience that can be difficult to quantify but may be of high importance. Additionally, investigating frequency domain changes, specifically in frontal cingulate and motor cortex, and correlating these with the level of movement synchrony between teacher and participants over learning trials (and across participants) may provide insights into action-perception coupling, and how variations in performance impact brain dynamics and vice versa.

4.7 | Moving beyond entrainment

Previous research on dance for therapeutic purposes has focussed on elements such as entrainment (Grahn & Brett, 2007; Thaut, 2015), suggesting that beat-locking or moving to regular rhythmic stimulation is the primary driver of physiological changes. While entrainment certainly appears to contribute to observed effects, focussing solely on rhythmic stimulation is not an ecologically valid representation of dance, which can involve “groove” (off-beat or syncopated rhythms), live music and a significant degree of personal expression.

Entrainment is an easy target for researchers, as it is relatively simple to assess, even in a stationary set-up. An analysis of more complex aspects of dance, correlated with participants' percepts while they are dancing, may provide new evidence for the importance/inclusion of aspects such as dynamic movement, imagery, sequence learning and individual motor expression in therapeutic dance programmes. Neuroimaging data can be added to the analysis of motion capture to increase our understanding of systems and strategies mobilised through dance, in the fullest realisation of the potential inherent in MoBI: combined motion capture (MoCap) and EEG Analysis (Gehrke, Guerdan, & Gramann, 2019; Gehrke, Iversen, Makeig, & Gramann, 2018).

4.8 | General analyses perspectives

Studies have shown long-term plasticity associated with dance learning in elderly populations (Muller et al., 2017; Zildou et al., 2018). MoBI offers the possibility for us to investigate short-term plasticity within a brief window of time, by correlating behavioural/motion data associated with learning and changes in cortical network organisation through network analysis (for an example of this in a longitudinal EEG study, see Zildou et al., 2018). We can also look at more granular distinctions in the frequency domain and assess their dependence on movement, motor preparation or learning processes such as trial and error. There is potential to investigate how changes in frequency bands may depend on velocity profiles of specific trackers, or the level of challenge involved in producing the movement. And finally, in relation to existing literature on entrainment, we can assess the degree of synchronisation between frequency domains, the music and actual movements in space and time.

This study demonstrates the huge potential for insights to emerge by bringing new technologies such as MoBI into an ecologically valid setting. Dance is one of the oldest aspects of human culture, depicted in ancient cave drawings[3] and early manuscripts; MoBI offers the possibility of investigating brain dynamics involved in this highly complex activity, how these change over time, and how aspects of expertise and learning can affect and be affected by the acquisition of new movement repertoire including artistic elements and dynamic range. Extending current scientific literature on dance, our study includes pre/post data enriched by the additional insight available from data collected *while* people are dancing—learning, making mistakes and improving performance—in each trial. All participants ($n = 19$) reached our target criteria of 80% or higher accuracy in reproducing the movement sequence within 20 LEARN trials; however, previous dance training was associated with significantly fewer trials required to reach criteria. In just one of the many possible avenues of exploration within this rich data set, we can investigate whether experience is associated with different learning strategies that correlate with alternate brain activation patterns, an important distinction as therapeutic applications of dance most often involve non-expert populations who may benefit from the degree of novelty or difficulty involved in dance-based learning. We can probe this by comparing trials of watching live and recorded performances of the choreography with data collected during each subject's process of performing the dance, correlating this analysis with previous dance experience.

5 | APPLICATIONS

Dancing is intensively multimodal and complex, involving physical and cognitive coordination, uniting motor control with memory, attention and artistry. This may explain why dance provides a potent environment for health and healing; it mobilises all our faculties while challenging us on many levels. As the age of our global population increases, conditions such as Parkinson's and Alzheimer's affect a growing number of individuals, along with their families and loved ones. Neurodegenerative ailments manifest in a broad and wide-ranging array of symptoms affecting movement, mood, cognition and the capacity to carry out tasks associated with daily living. At this point, there is no cure for either of these conditions; however, there is a growing body of research suggesting that dance-based programmes and therapies can be effective in slowing disease progression (Ciantar, Bearss, Bar, Levkov, & DeSouza, 2019; DeSouza & Bearss, 2018). Collecting EEG can provide putative biomarkers needed for early neurodegenerative detection once a ground truth of the neural mechanisms can be discovered and then implemented with diagnostics and modelling (Leger, Herbert, & DeSouza, 2020).

The multimodal nature of dance is both a challenge and an opportunity—while it presents obstacles and a high level of complexity for researchers, as it is hard to exclude or isolate variables, there is a rich opportunity to develop novel study designs using new technologies. Using MoBI in dance research is a perfect example of how emerging capacity in neuroimaging can be leveraged to explore some of the most vital and humanistic aspects of our experience. The impact of this research is far-reaching and important; as dance is increasingly brought into the therapeutic realm, a clearer understanding of why and how elements involved in dance contribute to resilience or recovery will allow for the development of evidence-based programmes with the highest

[3]Figures in the Magura Cave drawings and Bhimbekta rock shelters from the Mesolithic period are interpreted as dancing; for an overview of the cultural history of dance, see Royce 1977.

possible efficacy. Dance has long played a central role in societies that recognise holistic dimensions of health; the integrity of a phenomena such as dance, with its power to move us and support quality of life, invites the engagement of our best faculties and tools. This study only scratches the surface of what is possible in using MoBI with dance; we hope other researchers will join us in the pursuit of knowledge that dissolves the boundaries of arts and sciences, revealing new dimensions of the human condition.

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CONFLICT OF INTEREST

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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AUTHOR CONTRIBUTIONS

The authors (RB, JP, JFXD and KG) contributed to different aspects of this project and collaborated on others: RB, JFXD and KG conceived and designed the original study and participated in data acquisition; JP contributed to data acquisition and analysis; and RB prepared the draft of this paper. All authors contributed to critical revisions of the draft and agree to be accountable for all aspects of the work.

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REFERENCES

Bar, R. J., & DeSouza, J. F. X. (2016). Tracking plasticity: Effects of long-term rehearsal in expert dancers encoding music to movement. *PLoS One*, *11*, e0147731. https://doi.org/10.1371/journal.pone.0147731

Barnstaple, R., & DeSouza, J. F. X. (2018) Dance and Neurorehabilitation - Mixed-methods research models. *Journal of Functional Neurology, Rehabilitation, and Ergonomics*. Nova Science Publishers *7*, 1. Editor-in-chief: Gerry Leisman.12–17.

Bearss, K., McDonald, K., Bar, R., & DeSouza, J. F. X. (2017). A 12 week Dance Intervention for Parkinson's disease: Motor functions and quality of life. *Advances in Integrative Medicine*, *4*, 10–13. https://doi.org/10.1016/j.aimed.2017.02.002

Burzynska, A. Z., Finc, K., Taylor, B. K., Knecht, A. M., & Kramer, A. F. (2017). The dancing brain: Structural and functional signatures of expert dance training. *Frontiers in Human Neuroscience*, *11*, 566. https://doi.org/10.3389/fnhum.2017.00566

Burzynska, A. Z., Jiao, Y., Knecht, A. M., Fanning, J., Awick, E. A., Chen, T., … Kramer, A. F. (2017). White matter integrity declined over 6-months, but dance intervention improved integrity of the fornix of older adults. *Frontiers in Aging Neuroscience*, *9*, 59. https://doi.org/10.3389/fnagi.2017.00059

Ciantar, S., Bearss, K., Bar, R., Levkov, G., & DeSouza, J. F. X. D. (2019) Investigating Affective and Motor Improvements with Dance in Parkinson's Disease. *bioRxiv*. doi: https://doi.org/10.1101/665711

Cross, E. S., Kraemer, D. J. M., Hamilton, A. F. D. C., Kelley, W. M., & Grafton, S. T. (2009). Sensitivity of the action observation network to physical and observational learning. *Cerebral Cortex*, *19*, 315–326. https://doi.org/10.1093/cercor/bhn083

Cruz-Garza, J. G., Hernandez, Z. R., Nepaul, S., Bradley, K. K., & Contreras-Vidal, J. L. (2014). Neural decoding of expressive human movement from scalp electroencephalography (EEG). *Frontiers in Human Neuroscience*, *8*, 188. https://doi.org/10.3389/fnhum.2014.00188

Delorme, Arnaud, & Makeig, Scott (2004). EEGLAB: an open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. *Journal of Neuroscience Methods*, *134*(2004), 9–21.

DeSouza, J., & Bearss, K. (2018) *Progression of Parkinson's disease symptoms halted using dance over 3-years as assessed with MDS-UPDRS*. Neuroscience Meeting Planner. San Diego: Society for Neuroscience Abstracts. Online.

Di Nota, P. M., Chartrand, J. M., Levkov, G. R., Montefusco-Siegmund, R., & DeSouza, J. F. X. (2017). Experience-dependent modulation of alpha and beta during action observation and motor imagery. *BMC Neuroscience*, *18*, 28. https://doi.org/10.1186/s12868-017-0349-0

Dorr, M., Martinetz, T., Gegenfurtner, K. R., & Barth, E. (2010). Variability of eye movements when viewing dynamic natural scenes. *Journal of Vision*, *10*, 28. https://doi.org/10.1167/10.10.28

Gehrke, L., Guerdan, L., & Gramann, K. (2019). Extracting Motion-related Subspaces from EEG in Mobile Brain/body Imaging Studies Using Source Power Comodulation. *9th International IEEE/EMBS Conference on Neural Engineering (NER)*, IEEE, 344–347.

Gehrke, L., Iversen, J., Makeig, S., & Gramann, K. (2018). The Invisible Maze Task (IMT): interactive exploration of sparse virtual environments to investigate action-driven formation of spatial representations. *German Conference on Spatial Cognition*, 293–310.

Giacosa Chiara, Karpati Falisha J., Foster Nicholas E. V., Hyde Krista L., Penhune Virginia B. (2019). The descending motor tracts are different in dancers and musicians. *Brain Structure and Function*, *224*, (9), 3229–3246. http://dx.doi.org/10.1007/s00429-019-01963-0

Grahn, J. A., & Brett, M. (2007). Rhythm and beat perception in motor areas of the brain. *Journal of Cognitive Neuroscience*, *19*, 893–906. https://doi.org/10.1162/jocn.2007.19.5.893

Gramann, K., Ferris, D. P., Gwin, J., & Makeig, S. (2014). Imaging natural cognition in action. *International Journal of Psychophysiology*, *91*, 22–29. https://doi.org/10.1016/j.ijpsycho.2013.09.003

Gramann, K., Gwin, J. T., Ferris, D. P., Oie, K., Jung, T. P., Lin, C. T., … Makeig, S. (2011). Cognition in action: Imaging brain/body dynamics in mobile humans. *Reviews in the Neurosciences*, *22*, 593–608. https://doi.org/10.1515/RNS.2011.047

Gramann, K., Hohlefeld, F., Gehrke, L., & Klug, M. (2018) Heading computation in the human retrosplenial complex during full-body rotation. *bioRxiv*. doi: https://doi.org/10.1101/417972

Gramann, K., Onton, J., Riccobon, D., Mueller, H. J., Bardins, S., & Makeig, S. (2010). Human brain dynamics accompanying use of egocentric and allocentric reference frames during navigation. *Journal of Cognitive Neuroscience*, *22*, 2836–2849. https://doi.org/10.1162/jocn.2009.21369

Hänggi, J., Koeneke, S., Bezzola, L., & Jäncke, L. (2010). Structural neuroplasticity in the sensorimotor network of professional female ballet dancers. *Human Brain Mapping*, *31*, 1196–1206.

Karpati, F. J., Giacosa, C., Foster, N. E. V., Penhune, V. B., & Hyde, K. L. (2017). Dance and music share gray matter structural correlates. *Brain Research*, *1657*, 62–73. https://doi.org/10.1016/j.brainres.2016.11.029

Keehn, J., Iverson, J., Schulz, I., & Patel, A. (2019). Spontaneity and diversity of movement to music are not uniquely human. *Current Biology*, *29*, R603–R622.

Klug, M. (2019). *Bemobil pipeline*. Retrieved from https://github.com/MariusKlug/bemobil-pipeline Accessed on December 2, 2019

Kullberg-Turtiainen, M., Vuorela, K., Huttula, L., Turtiainen, P., & Koskinen, S. (2019). Individualized goal directed dance rehabilitation in chronic state of severe traumatic brain injury: A case study. *Heliyon*, *5*, e01184. https://doi.org/10.1016/j.heliyon.2019.e01184

Leger, C., Herbert, M., & DeSouza, J. F. X. (2020). Non-motor clinical and biomarker predictors enable high cross-validated accuracy detection of early PD but lesser cross-validated accuracy detection of scans without evidence of dopaminergic deficit. *Frontiers in Neurology*, *11*, 364. https://doi.org/10.3389/fneur.2020.00364

Levkov, G., Di Noto, P., Montefusco-Siegmund, R., Bar, R., & DeSouza, J. F. X. (2014). Global alpha slowing in individuals with Parkinson's disease and dance-induced increases in frontal alpha synchronization. *Neuroscience Meeting Planner*. Washington DC: Society for Neuroscience Abstracts, 437.

Lin, C. T., Chiu, T. C., & Gramann, K. (2015). EEG correlates of spatial orientation in the human retrosplenial complex. *NeuroImage*, *120*, 123–132. https://doi.org/10.1016/j.neuroimage.2015.07.009

Makeig, S., Gramann, K., Jung, T. P., Sejnowski, T. J., & Poizner, H. (2009). Linking brain, mind and behavior. *International Journal of Psychophysiology*, *73*, 95–100. https://doi.org/10.1016/j.ijpsycho.2008.11.008

Margariti, A., Ktonas, P., Hondraki, P., Daskalopoulou, E., Kyriakopoulos, G., Economou, N., … Vaslamatzis, G. (2012). An application of the primitive expression form of dance therapy in a psychiatric population. *The Arts in Psychotherapy*, *39*, 95–101. 101016jaip01001

Müller, P., Rehfeld, K., Schmicker, M., Hökelmann, A., Dordevic, M., Lessmann, V., … Müller, N. G. (2017). Evolution of neuroplasticity in response to physical activity in old age: The case for dancing. *Frontiers in Aging Neuroscience*, *9*, 56. https://doi.org/10.3389/fnagi.2017.00056

Ojeda, A., Bigdely-Shamlo, N., & Makeig, S. (2014). MoBILAB: An open source toolbox for analysis and visualization of mobile brain/body imaging data. *Frontiers in Human Neuroscience*, *8*, 121. https://doi.org/10.3389/fnhum.2014.00121

Palmer, J., Makeig, S., Kreutz-Delgado, K., & Rao, B. (2008). Newton method for the ICA mixture model. In *Conference on Acoustics Speech and Signal Processing*. IEEE pp 1805-08.

Poikonen, H., Toiviainen, P., & Tervaniemi, M. (2018). Naturalistic music and dance: Cortical phase synchrony in musicians and dancers. *PLoS One*, *13*, e0196065. https://doi.org/10.1371/journal.pone.0196065

Pusnick, M. (2010). Introduction: Dance as social life and cultural practice. *NOTEBOOKS Slovene Anthropological Society*, *16*, 5–8.

Rehfeld, K., Lüders, A., Hökelmann, A., Lessmann, V., Kaufmann, J., Brigadski, T., Müller, P., & Müller, N. G. (2018). Dance training is superior to repetitive physical exercise in inducing brain plasticity in the elderly. *PLoS One*, *13*, e0196636. https://doi.org/10.1371/journal.pone.0196636

Thaut, M. H. (2015). The discovery of human auditory-motor entrainment and its role in the development of neurologic music therapy. *Progress in Brain Research*, *217*, 253–266.

Vann, S. D., Aggleton, J. P., & Maguire, E. A. (2009). What does the retrosplenial cortex do? *Nature Reviews Neuroscience*, *10*, 792–802. https://doi.org/10.1038/nrn2733

Ventouras, E. C., Margariti, A., Chondraki, P., Kalatzis, I., Economou, N. T., Tsekou, H., … Ktonas, P. (2015). EEG-based investigation of brain connectivity changes in psychotic patients undergoing the primitive expression form of dance therapy: A methodological pilot study. *Cognitive Neurodynamics*, *9*, 231–248. https://doi.org/10.1007/s11571-014-9319-8

Zilidou, V. I., Frantzidis, C. A., Romanopoulou, E. D., Paraskevopoulos, E., Douka, S., & Bamidis, P. D. (2018). Functional re-organization of cortical networks of senior citizens after a 24-week traditional dance program. *Frontiers in Aging Neuroscience*, *10*, 422. https://doi.org/10.3389/fnagi.2018.00422

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