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Mobile brain imaging in butoh dancers: from rehearsals to public performance

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Abstract

Dissecting the neurobiology of dance would shed light on a complex, yet ubiquitous, form of human communication. In this experiment, we sought to study, via mobile electroencephalography (EEG), the brain activity of five experienced dancers while dancing butoh, a postmodern dance that originated in Japan. We report the design, methods and practical execution of a highly interdisciplinary project that required the collaboration of dancers, engineers, neuroscientists, musicians, and multimedia artists, among others. We also share the raw EEG data from our live recordings as well as the code we used to generate a live visualization of the dancers' brain activity on a screen, via an artistic brain-computer interface. We describe how we envision that the data could be used to address several hypotheses, such as that of interbrain synchrony or the motor theory of vocal learning. Being, to our knowledge, the first study to report synchronous and simultaneous recording from five dancers, we expect that our findings will inform future art-science collaborations, as well as dance-movement therapies.

Introduction

In the past two decades, there has been a mounting interest in identifying the neural underpinnings of artistic expression, and of dance, in particular. The first endeavors towards this direction have focused on studying the brain responses during dance observation, namely while dancers, or non-dancers, perceive videos of dance movements of themselves or others. Brain perception signals have been studied for a variety of types of dance, including but not limited to jazz[1], ballet[2,3] and tango[4], using either electroencephalography (EEG)[1,3,4] or functional Magnetic Resonance Imaging (fMRI)[2]. Overall, their findings underscore the power of both techniques to capture signatures subserving differences in an array of dance perception settings (e.g., dance perception by expert dancers vs. non-dancers).

Identifying the neural basis of dance performance (i.e., production of dance movements) has been challenging, considering the limitations of neuroimaging techniques that render natural movement in space impractical. Still, researchers have come up with creative ideas to address this question. For instance, Brown *et al.*[5] used an inclined surface in front of the leg room of a Positron Emission Tomography (PET) scanner, where amateur dancers performed small-scale, cyclically repeated leg tango steps while in a supine position. The same group used fMRI to study bimanual partnered movements, with the experimenter sitting next to the lying subject holding hands and alternating between "leading" and "following" joint movements, similar to those used in tango or salsa[6]. In turn, mobile EEG techniques, complemented with motion sensing, have enabled researchers to study brain activity while subjects are dancing freely in the space with the EEG caps on. For example, mobile EEG studies on Laban Movement Analysis (LMA) dancing[7] demonstrated the feasibility of

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classifying specific movements and LABAN effort qualities from specific EEG signals, and proposed a framework for eliminating motion artifacts from dance analysis. EEG has also been proven effective to pick up not only sex-specific effects during thinking of jazz dancing but also sex-independent effects during physically dancing jazz[8].

It is in this context that we decided to study and visualize via mobile EEG the brain activity of five experienced dancers while dancing butoh, recorded simultaneously and synchronously (a process known as hyperscanning), a type of dance and number of dancers that have not been studied thus far, in our knowledge. Moreover, this art-science collaboration allowed us to monitor the creative process through EEG recordings during rehearsals culminating in a theater performance in front of an audience. In this paper, we aim to explain the background, design, neuroengineering methods, hypotheses, and practical execution of the experiment we ran; we share our raw data and code, both for the live recordings and the live visualization of brain activity on a screen, via an artistic brain-computer interface (BCI) while the dancers were dancing. We also report our experience from working as an interdisciplinary team composed of dancers, neuroscientists, engineers and physical therapists. Lastly, we describe how we envision that this work can inform future art-science collaborations, understanding the brain "in action and in context", and therapeutic practices, using dance as a therapeutic modality for improving wellness and motor deficits.

Butoh

Butoh is a Japanese avant-garde dance originated by Tatsumi Hijikata and Kazuo Ohno at the height of the counterculture movement in Japan in 1959[9,10]. Although its definition may vary, butoh has been described as a type of dance that allows the exteriorization of bodily reactions, otherwise suppressed in social settings, such as spasms, involuntary jerks, tremor, facial or bodily distortions, falling down, stamping, and rolling on the floor[10]. Unlike in other dance styles (e.g., ballet), butoh dancers do not pursue high jumping or fast spinning, they rather focus on their breath and subtle body reactions[10].

Butoh has also been seen as a "meditational dance", due to being a contemplative movement practice that includes deep relaxation and meditative calmness[9]. In this, it is similar to other meditative practices, such as Tai Chi or yoga, although, according to Kasai[9], meditation does not picture the essence of butoh as a whole, since the calmness can, in fact, be interrupted by explosive movements. In other words, although butoh is a dance, it falls out of the narrow and western definition of dance, which is mostly focused on rhythmic and dynamic movements[9].

The variety of movements performed in butoh, as well as the extreme, almost imperceptible, slowness of several of the movements, render butoh a great artistic expression that can give valuable insight into the brain mechanisms subserving dance. As butoh is meant to allow the expression of involuntary motor movements, as well as employ voluntary movements, it offers the possibility to disentangle the differences between these two types of movements. Lastly, its contemplative characteristics can be studied in comparison with other meditative practices (e.g., meditation, yoga, Tai Chi) to gain a better understanding on the neurobiology of meditation and contemplation.

Benefits and challenges of using EEG while recording butoh dancing

Mobile EEG recordings allow us to study the neural dynamics of dance, individually or in groups, with exquisite temporal resolution (millisecond range) and in ecological settings (e.g., a theater or dance studio) that are not possible to test with other techniques, such as with fMRI, where the subject is constrained to lay down within the confines of the bore of a scanner in a neuroimaging facility. Still, even with mobile EEG recording, there are important challenges that must be overcome by both the researchers and the dancers, and particularly in butoh dance.

First, electrode caps, processing units and WiFi transmitters must be protected from impact during moments of head contact with the floor or during rolling on the floor in butoh dancing (**Figure 1a-b**). Custom shock absorbing caps and neck protection constructs had to be designed and tested not only to

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protect the equipment (**Figure 1a**) but also individually adjusted for the dancer's comfort. A period of acclimatization is necessary to allow for the dancer to become familiar with the equipment, and its proposed setup, as to minimize interference with their dance (**Figure 1b**).

Second, EEG recordings are typically accompanied by different types of physiological and non-physiological artifacts and other sources of noise that contaminate the raw EEG measurements[11,12]. For example, electrode movement artifacts can occur when there is a disruption of the contact of the electrode with the scalp, leading to changes in electrical impedance, and the quality of the recording. To minimize these types of artifacts, an appropriately sized cap must be used, in conjunction with stretchable netting (e.g., medical grade tubular elastic net dressing), to secure the location of all electrodes in the scalp. The netting also helps to secure electrode cables that otherwise may pull down electrodes during head movements, which would also cause artifacts. Viscous hypoallergenic conducting gel, typically used in wet EEG electrode setting, as in this research, also contributes to securing the electrode in place. The gel, however, leaves a residue on the hair that must be fully removed with water and shampoo –an inconvenience to the participant. The type of dance can also contribute to the minimization of motion artifacts. Luckily, the butoh choreography we tested was to a great extent composed of slow movements and stillness, which helped to minimize motion artifacts.

Third, electromyographic (EMG) artifacts originating from the head and neck musculature recruited during head/face and neck movements may also contaminate raw EEG, particularly in frequencies above 12-20 Hz, including beta and gamma waves[13]. Slower brain rhythms in the delta, theta and alpha bands are less susceptible to EMG artifacts, and thus suitable for investigating slow cortical potentials and rhythms. Eye movements and eye blinks also typically contaminate raw EEG recordings and must be identified and removed. Several methods have been proposed to remove the ocular artifacts from raw EEG measurements, both off-line and on-line[14], and thus, they do not pose a major challenge.

Fourth, changes in ambient temperature and the dancer's sweat can also lead to changes in electrode impedance, thereby reducing signal quality. These types of artifacts can be addressed by recording in climate-controlled venues and through careful design of the choreography. The best practice, per our experience, is to record impedances at least twice, in the beginning and the end of recording, so as to assess potential changes or drifts in impedance values. Overall, artifact minimization and removal are critical steps in data preprocessing, prior to functional analysis or neural decoding. Artifact identification and removal is a topic of ongoing research and several sample adaptive algorithms have been proposed in the literature[14–16].

An important challenge when recording brain activity from multiple dancers is the synchronization of the measurement devices with high temporal resolution. In this study, the first, to our knowledge, to conduct hyperscanning of five dancers, we used three different systems (one 128-channel EEG system split into four 32-channel systems with a WiFi transmitter, one 32-channel system with Bluetooth communications, and a distributed system of inertial measurement units (IMU) to track the dancers' head motions). The synchronization must be in the millisecond range when using different measurement modalities and/or equipment to avoid interpretation errors and to render optimal real-time analysis. For example, in our experiment, during dance performances, we used an artistic BCI system to visualize different aspects of the dancers' brain activity, something that required excellent synchronization between the different devices. To further avoid potential software synchronization delays, we used hardware synchronization via a custom cable for wired transmission of Transistor-Transistor Logic (TTL) signals between devices.

Hypotheses to test

Because our team is interdisciplinary, there were different hypotheses that each of us wanted to test when embarking on this project. In what follows, we will explain several of these hypotheses, including the control tasks we used to address these questions.

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Interbrain synchrony

Dance has been posited to have evolved as a form of interpersonal coordination and social communication, which is based on both imitation (matching of movement) and synchrony (matching of time) skills[17]. Different kinds of dances rely on different aspects of interpersonal coordination, including touch, eye gaze, sensory-motor interactions, facial expressions, or even synchronization with other physiological parameters, such as breathing, heartbeat, and sympathetic tone[18]. Thus, EEG recording from different dancers, dancing the same choreography simultaneously, is expected to unravel interbrain neural synchrony in the dance aspects that require interpersonal coordination.

Previous experiments[19] where we examined EEG signals of two dancers while dancing a ballet duet showed high interbrain synchrony in the gamma band of visual brain regions (Broadman area 18) of the dancers. Interestingly, the leading dancer also showed interbrain synchrony between her visual (BA18) cortex and her partner's cognitive (BA31) and premotor/supplementary motor areas (BA6) of the brain. The butoh choreography that we investigated was focused on auditory cues from the music, meaning that the dancers were proceeding from one move to the next in response to specific auditory cues, such as a sound that resembles an owl hooting announcing a specific move. Throughout most of the choreography, the dancers dance with their eyes closed or half-closed with a soft focus[20], something that gives us the unique opportunity to study interbrain synchrony in a type of dance where vision is not expected to be the basis of coordination, reported as the most common form of interbrain synchrony[21]. Lastly, since we recorded both the rehearsals and the final performance, it will be possible for us to assay changes in interbrain synchrony as a function of learning, practice, or the scenic context (e.g., presence or absence of an audience).

Motor hypothesis of vocal learning

There is a hypothesis[22] that links the evolution of the neural circuit that is responsible for body muscle movement (e.g., head, arm and leg muscles) to the evolution of the neural circuit that is responsible for the movement of the muscles of the vocal organ during vocal communication (e.g., laryngeal muscles in humans). This hypothesis is built on findings[22] showing that in vocal learning birds, all their cerebral nuclei that are devoted to song learning are adjacent to discrete brain areas active during limb and body movements. In other words, the hypothesis states that, possibly, the brain pathways for vocal learning evolved as a specialization of a pre-existing pathway that controls movement in general.

This prediction became even more pertinent after the finding that only species that communicate with complex vocalizations (i.e., humans and parrots) are able to dance (i.e., to entrain their body movements to a beat)[23], pointing to a common neural substrate in both abilities. In humans, this hypothesis has not been tested, meaning that no one has compared in the same subjects the neural pathways underlying speech (i.e., laryngeal movements) and dance movements (e.g., rhythmic arm movements), although a cross-studies' comparison points to an overlap of several of the regions controlling body movements in the primary motor cortex with the regions that control laryngeal movements in the primary motor cortex[24–26]. Further, dance has been found to increase network connectivity between the basal ganglia and premotor cortices[27], with both regions being co-activated during speech[28,29]. To address this question, in our control tasks, we had our dancers produce speech and speech-like vocalizations (e.g., Jabberwocky words), as well as other non-speech vocalizations (e.g., sneeze, laughter, yawn), with the aim to compare their EEG patterns during laryngeal movements vs. movements of other body parts.

Butoh vs. other meditative practices

As aforementioned, butoh embraces in its practice contemplation and meditation[9], offering a comparandum for other meditative practices, where there are already published data on their associated brain activity. For example, Banquet[30] used spectral analysis of the EEG during transcendental meditation, a method described as a mental repetition of a special sound or mantra, to

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show in the early 1970's that meditative states can be distinguished from other states of consciousness based on sequential changes in the alpha, theta, and beta waves in relation to their topographical alterations across the scalp. More recently, EEG recording during meditation in Buddhist practitioners revealed self-induced and sustained high-amplitude gamma-band oscillations[31]. In a different study, meditation training gave rise to increased theta activity in the frontal midline electrodes, which was sustained even during the resting-state following meditation training[32]. Xue *et al.*[33] in a similar experiment on short-term meditation training found increased theta (and some alpha) activity in the anterior cingulate cortex and adjacent prefrontal cortex, which correlated with improved performance on tasks of attention, working memory, creativity and problem solving.
All these studies provide a fertile ground for comparison with the hypothesized meditative aspects of butoh. To make the comparison between butoh and meditation readily possible in our experiment, we included in our control tasks a seated meditation task, which will be compared with the time frames of the butoh choreography that employ contemplative practices. In this way, we will be able to address the question of whether what is happening in the brain during seated meditation bears any resemblance to butoh in the same subjects. Whether the signatures are the same or different, given the evidence showing that meditation-like practices are beneficial in several aspects of human health[34], we hope that our experiment will shed light on the patterns of brain activity underlying these practices.

Butoh in pregnancy

In the course of the experiment, the pregnancy of one of the butoh dancers gave us the opportunity to study brain activity during butoh dancing in a pregnant woman. To our knowledge, this is the first time to run mobile EEG with a pregnant woman dancing butoh, or dancing, in general. Concerning the safety of dancing during pregnancy, there is published evidence that dancing can actually be beneficial in pregnancy, as long as it does not include lifting of other dancers, or high impact activities such as jumping and back flips[35,36]. Considering that, in butoh, such movements are rare to begin with, we deem that this coincidence might uncover butoh's untapped role as a beneficial practice in pregnancy. For the purpose of the experiment, the choreography was specifically altered to suit the movement abilities and safety of the pregnant woman, and the performance was expressly allowed by a doctor.

Regarding the use of EEG during pregnancy, there are already published reports on the safety of this technology in pregnancy[37]. Interestingly, Plamberger *et al.*[37] used a visuo-spatial attention task, where an auditory cue directed the attention of pregnant and non-pregnant participants either to the left or to the right visual hemifield, where, following a variable time interval, they had to discriminate between a "p" or "q" sound on the cued hemifield. Both non-pregnant and pregnant women showed a decrease in the alpha amplitude in the fronto-parietal network, which correlated positively with accurate discrimination, with no significant differences in the cases of pregnancy vs. non-pregnancy. Since our butoh choreography is based on correctly perceiving auditory cues in the music, it is tempting to hypothesize that an alpha band desynchronization, leading to the expected cue and right after the cue is perceived, could underlie accurate choreography performance, and to study whether there are any differences between the non-pregnant dancers vs. the pregnant dancer.

Live performance with EEG-based brain-computer interface visualization

Mobile EEG and BCI techniques allowed us to artistically visualize the interbrain synchrony and other aspects of brain activity of the dancers "in action and in context", during a live dance performance in front of an audience. The artistic design focused on exploring new ways of projecting real-time interactive animated visualizations of EEG data that are both accessible to the lay audience and informative to the audience with scientific background.

The visualization was inspired by the structure of the music composed for the purpose of the study, the choreography itself, and the concept of interbrain synchrony. Since butoh is often made up of slow movements, and in contrast, the music for the project is active and repetitive, the visualization aspired

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to find a middle ground between the physical and sonic rhythms. Overall, the visualization had no identifiable regular pulse but flowed freely in terms of texture, movement, color, and spatialization. It was structured in three sections: a) abstract scenic monochromatic images, b) five 3D brains and brain connections portraying interbrain synchrony, and c) five abstract circles producing a colorful texture (**Figure 2**).

In detail, in the beginning of the music and for the first 20 minutes, the visualization was meant to depict the prevailing sounds of nature with abstract scenic monochromatic images with additive textural visual noise. This noise's amplitude was the result of mapping normalized raw EEG data of the dance leader (Vangeline Gand) (**Figure 2a**). The second visualization of the five 3D brains and their connections reflected the positions of each dancer on stage to help the audience associate the brain visuals with each dancer. The brain synchrony value was mapped in real time with the particle flow level between brains, forming a line between them, so that the higher the value of synchrony, the higher the opacity and thickness of the line (**Figure 2b**). The third visualization of five abstract circles showed the interbrain synchrony between the accompanying dancers and the dance leader. Their interbrain synchrony was mapped to the position of the four circles relative to the central circle, so that the higher the value of interbrain synchrony, the more concentric the circles appeared (**Figure 2c**). We believe that this visualization was crucial in communicating the essence of this collaboration, right at the intersection of art and science.

Live test for interdisciplinarity

As a collaboration studying butoh in the brain, both the art -butoh- and the science -EEG recording- were equally important towards success[38,39]. This live test for interdisciplinarity allowed exploration into understanding the unique opportunities and challenges for such a collaboration, including needs for dancers as athletes and subjects, technical requirements for protecting equipment without inhibiting movement, and for synchronizing brain waves across all five dancers, implications for providing education and working with students, and determination of visual projection based on BCI.

Because this study relied on hyperscanning, the condition of sound was a critical component, not only for live visualization via BCI but also for quality control in the art of butoh dancing and in the science of EEG recordings. The musical score was specifically composed of four specific types of sound based on brainwave entrainment, whereby the brain naturally synchronizes to certain patterns, sounds, and frequencies. Further, the score was intentionally composed without metered rhythm, thus dancers synchronized based on cues such as pouring rain, bleating of a goat, an owl hoot, and other signals. This specificity underscores the importance of the quality and level of sound for the dancers because auditory cues were often the only signals upon which to coordinate motor movements. Thus, any discrepancies or failures in sound quality greatly impeded the dancers' performance, and potentially relatedly, EEG recordings based on ability to enter into anticipated butoh states. As a result, BCI-visual projections based on real-time recorded brain activity were intricately linked to the visualizations of the interbrain synchrony between the dancers.

This collaboration further highlighted that bringing various fields together requires clear communication to understand the various needs and expectations of each discipline[40–42]. For example, for dancers, who are highly skilled athletes[43], a controlled environment, considering aspects of stage size, noise level, temperature, and other factors that may affect the dancers performance, must be considered to minimize stress and maximize ability to perform. For scientists, it is also critical to factor in human fatigue in EEG recordings; simply recording data, if the question at hand is as specific as that we are asking about butoh dancing, will not suffice, and errors in sound production, unnecessary delays lengthening the time of preparation for study, and any other factors that may impede the dancers' ability to perform butoh may lead to poorer data outcomes.

Given that the dancers are the subjects of interest, this collaboration also showed that creative solutions may lie in another's lived experience. One example was that the solution for how to best don

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the EEG caps, which are sensitive both for capturing brain waves and as a piece of equipment, was found by one of the dancers. Another example comes from a dancer who reported that the control tasks are better to be recorded before any butoh dancing takes place, since the butoh (meditative-like) state may linger after the performance and confound results from control conditions. These situations are great examples of the benefits of this multidisciplinary collaboration, in which the perspectives from experts in different fields came into play and merged into a highly unique project.

Ultimately, seemingly competing interests for data needs must all be considered as all interested parties have their own reporting requirements for meeting funder expectations and for future funding: for dancers, a high-quality video; for scientists, robust data collection; for students, time and attention for hands-on learning. The reader is referred to a recently edited book on *Mobile Brain–Body Imaging and the Neuroscience of Art, Innovation and Creativity*[44] that addresses the challenges and transdisciplinary opportunities for transformational and innovative research and performance at the nexus of art and science enabled by emergent technologies .

Dance -and butoh- as movement therapy

Dance-movement therapy is the use of creative movement[45] as a healing tool rooted in the inseparable connection between the body and the mind[46], with concepts of embodiment and attunement affecting human behavior –psychologically, physically, and socially[46]. The therapeutic effect of dance is reported as a modality for health and wellness across the lifespan, including for motor development in children in general[47], with Down syndrome[48], with cerebral palsy[49], and with developmental cerebellar anomalies[50], through the elderly for successful aging, for markers including fitness, functional balance, and mobility control[51–53], as well as for cognition[54]. Overall, dance-movement therapy and dance leads to psychological health outcomes including decreasing depression and anxiety, increasing quality of life, and expanding interpersonal and cognitive skills[55].

Among patients with Parkinson's Disease, music and dance proved to be simple, non-invasive treatment options that promote balance, gait and cognition[56–59], decrease psychological symptoms and improve quality of life[60,61]. For other conditions, such as schizophrenia and psychotic disorders, many studies tend to have small samples, no randomization, and no adequate control[62]. Yet, there is some support that body-centered interventions do alleviate stress, depression, and anxiety as well as facilitate pain reduction in physical and psychological pathologies via a bidirectional pathway between the brain and body[63]. As one creative therapy, dance has been shown to be effective for severe mental illnesses such as trauma-related disorders, major depressions, and bipolar disorder[64,65].

Because butoh dance is a psychosomatic exploration method[9], this study holds implication for further understanding the healing effects of dance, particularly how dance-movement can be prescribed as a form of therapy by selecting the emotional or physical level of involvement, or dose-response, based on the patient's condition. For example, there may be a relationship between some mental aspects of schizophrenia and butoh performance in terms of the state of consciousness and body-mind vulnerability[66].

Conclusion

The art-science collaboration that we reported here was a unique, complex, multidisciplinary experiment that required the coordination, managing, and execution of several dancers, engineers, neuroscientists, musicians, multimedia artists, logistic personnel, facilities' management crew, and students. In addition, securing funding for the travel expenses and artists' fees were critical to the success of the project. Last but not least, trust and respect for each other was essential to conduct the project in an accelerated timeline. The resulting data, best practices, approach, code and audiovisuals present a unique opportunity for the scientific and artistic communities to harness the data, knowledge and lessons learned from this project, to answer novel questions, deploy new algorithms or computational methods, and create new art-science works.

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Methods

Artistic brain-computer interface

The visualization was designed by TouchDesigner (TD, Derivative, Toronto, CA), a visual programming environment aimed at real-time 3D rendering, combined with high-resolution real-time compositing (https://derivative.ca/). MaxMsp, a visual programming language for music and multimedia developed and maintained by San Francisco-based software company Cycling '74 was used in this project for data filterings and mathematical operations such as normalizing, scaling, averaging, and calculating min. and max. of input data. Additionally, MaxMsp was used for optimizing the computation and construction of the user interface for the change of the visual scenes.

In order to establish a mechanism to translate the EEG data to artistic visualization (BCI), the science team and multimedia artist established a communication system between MATLAB (The Mathworks Inc., Natick, MA) and TD. Two data packets were transferred from MATLAB to TD using the networking protocol TCP/IP (https://docs.derivative.ca/index.php?title=TCP/IP_DAT) via a direct Ethernet connection. The first packet of data is the raw EEG data of the dancers with a frequency of 100 Hz. The second packet is the interbrain synchrony with a frequency of 1 Hz. The received data transfers to MaxMsp via Open Sound Control (OSC), a protocol for network communication among computers, sound synthesizers, and other multimedia devices (https://www.cnmat.berkeley.edu/opensoundcontrol). MaxMsp filters/calculates the data and sends them back to TD via OSC.

[We confirm that consent to publish identifiable images of research participants was obtained through the Informed consent form of the study and the specific for this purpose Nature Portfolio participant release form.]

Figures

Figure 1: Customized head and neck protectors used in the experiment. a, Shown are scientists carefully placing the electrode caps, processing units and WiFi transmitters into a neck pillow we customized with zippers (left and right images), as well as three dancers (right image) with custom caps on, which we used as shock absorbing caps to protect the equipment. **b,** Shown are the dancers while dancing in standing (left image) and lying (right image) positions, with their equipment, and head and neck protectors on. (Dancers' names: Azumi Oe, Kelsey Strauch, Margherita Tisato, Sindy Butz, and Vangeline Gand).

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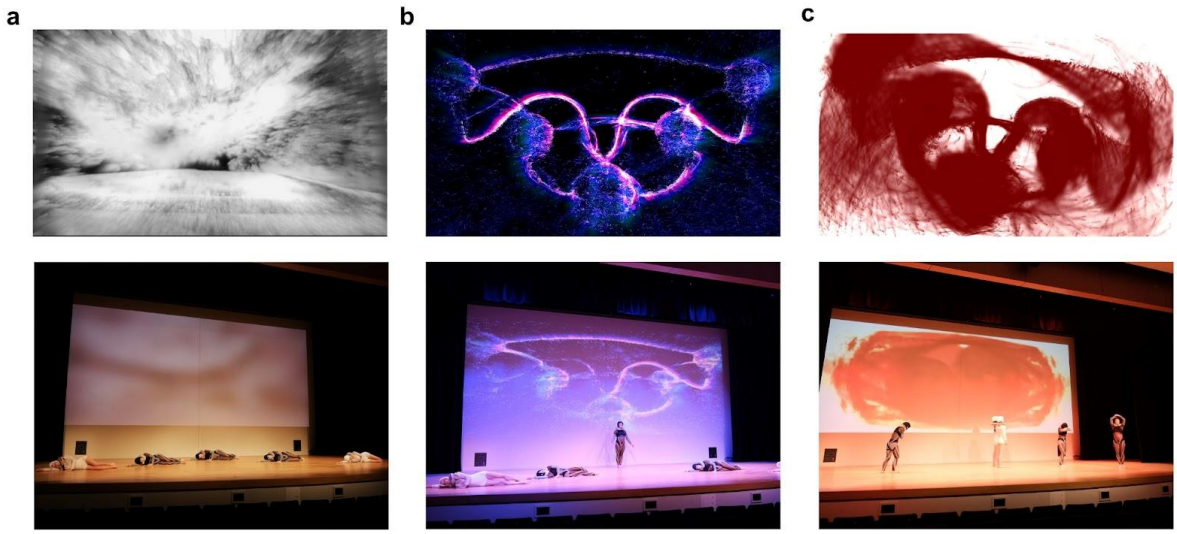

Figure 2: Real-time interbrain synchrony visualization via brain-computer interface. a, Abstract scenic monochromatic images, with additive noise, whose amplitude was the result of the leading dancer's normalized raw EEG data. **b,** Five 3D brains and their connections reflecting real-time brain synchrony. **c,** Five abstract circles showing the interbrain synchrony between the accompanying dancers and the dance leader. In all cases, top images show computer examples from the type of visualization described, and bottom images show real instances of how these visualizations unfolded during a live performance. (Dancers' names: Azumi Oe, Kelsey Strauch, Margherita Tisato, Sindy Butz, and Vangeline Gand).

Data availability statement

The datasets generated during the current study are available in the Figshare repository (under the terms of Attribution 4.0 International Creative Commons License), the music in Soundcloud, and the dance videos in Vimeo (video links: 1, 2, 3).

Code availability statement

The underlying code for this study is available in the Figshare repository.

Competing interests' statement

All the authors declare no competing interests.

Ethical compliance statement

We have complied with all relevant ethical regulations. The study was approved by the institutional review board at the University of Houston, Texas, USA.

Author contribution statement

CT, SP, JCV and VG conceived the study. CT, SP and JCV designed and co-supervised the study. DH, ET and MRM ran the mobile EEG recording. BK ran the artistic BCI. AMS created all Figures. VG was the artistic director, choreographer and dancer of the Butoh choreography. CT led the writing of the manuscript, with section contributions by SP, JCV, DH, and BK, while all authors read and gave feedback to the final version of manuscript.

Acknowledgements
CT wishes to thank The Rockefeller University, Hunter College (City University of New York), the Center for the Ballet and the Arts (New York University), and Gibney Dance.

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VG wishes to thank the New York butoh Institute, the Mellon Foundation, Triskelion Arts, Gibney Dance, Hector Perez and the House of Hallucination, The New York Department of Cultural Affairs, New York Council on the Arts, and the National Endowment for the Arts.
SP wishes to thank The Rockefeller University, the Center for the Ballet and the Arts (New York University), and Gibney Dance.
JCV wishes to thank the NSF IUCRC BRAIN University of Houston Site Award # 2137255, the BRAIN Student Group, and the Noninvasive Brain-Machine Interface Systems Laboratory.
MARM wishes to thank the Associate Dean of Research Office, and the Mechatronics Department at the School of Engineering and Sciences, Tecnologico de Monterrey, and the Noninvasive Brain-Machine Interface Systems Laboratory.

References

1. Orlandi, A., Zani, A. & Proverbio, A. M. Dance expertise modulates visual sensitivity to complex biological movements. *Neuropsychologia* **104**, 168–181 (2017).

2. Calvo-Merino, B., Grèzes, J., Glaser, D. E., Passingham, R. E. & Haggard, P. Seeing or Doing? Influence of Visual and Motor Familiarity in Action Observation. *Curr. Biol.* **16**, 1905–1910 (2006).

3. Poikonen, H., Toiviainen, P. & Tervaniemi, M. Naturalistic music and dance: Cortical phase synchrony in musicians and dancers. *PLoS One* **13**, 1–18 (2018).

4. Amoruso, L., Pusil, S., García, A. M. & Ibañez, A. Decoding motor expertise from fine-tuned oscillatory network organization. *Hum. Brain Mapp.* **43**, 2817–2832 (2022).

5. Brown, S., Martinez, M. J. & Parsons, L. M. The Neural Basis of Human Dance. *Cereb. Cortex* **16**, 1157–1167 (2006).

6. Chauvigné, L. A. S., Belyk, M. & Brown, S. Taking two to tango: FMRI analysis of improvised joint action with physical contact. *PLoS One* **13**, 1–28 (2018).

7. Cruz-Garza, J. G., Hernandez, Z. R., Nepaul, S., Bradley, K. K. & Contreras-Vidal, J. L. Neural decoding of expressive human movement from scalp electroencephalography (EEG). *Front. Hum. Neurosci.* **8**, (2014).

8. Wind, J. *et al.* Sex-Specific Brain Responses to Imaginary Dance but Not Physical Dance: An Electroencephalography Study of Functional Connectivity and Electrical Brain Activity. *Front. Behav. Neurosci.* **15**, (2021).

9. Kasai, T. A Butoh Dance Method for Psychosomatic Exploration. *Mem. Hokkaido Inst. Technol.* **27**, 309–316 (1999).

10. Kasai, T. & Parsons, K. Perception in Butoh Dance. *Mem. Hokkaido Inst. Technoloy* 257–264 (2003).

11. Reis, P. M. R., Hebenstreit, F., Gabsteiger, F., von Tscharner, V. & Lochmann, M. Methodological aspects of EEG and body dynamics measurements during motion. *Front. Hum. Neurosci.* **8**, (2014).

12. Bulea, T. C., Kilicarslan, A., Ozdemir, R., Paloski, W. H. & Contreras-Vidal, J. L. Simultaneous Scalp Electroencephalography (EEG), Electromyography (EMG), and

bioRxiv preprint doi: https://doi.org/10.1101/2023.02.26.530087; this version posted February 26, 2023. The copyright holder for this preprint (which was not certified by peer review) is the author/funder, who has granted bioRxiv a license to display the preprint in perpetuity. It is made available under aCC-BY-NC-ND 4.0 International license.

Whole-body Segmental Inertial Recording for Multi-modal Neural Decoding. *J. Vis. Exp.* (2013) doi:10.3791/50602.

13. Brown, P. Cortical drives to human muscle: the Piper and related rhythms. *Prog. Neurobiol.* **60**, 97–108 (2000).

14. Kilicarslan, A., Grossman, R. G. & Contreras-Vidal, J. L. A robust adaptive denoising framework for real-time artifact removal in scalp EEG measurements. *J. Neural Eng.* **13**, 026013 (2016).

15. Kilicarslan, A. & Contreras-Vidal, J. L. Towards a Unified Framework for De-noising Neural Signals. in *2019 41st Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)* 620–623 (IEEE, 2019). doi:10.1109/EMBC.2019.8856876.

16. Kilicarslan, A. & Contreras Vidal, J. L. Characterization and real-time removal of motion artifacts from EEG signals. *J. Neural Eng.* **16**, 056027 (2019).

17. Laland, K., Wilkins, C. & Clayton, N. The evolution of dance. *Curr. Biol.* **26**, R5–R9 (2016).

18. Basso, J. C., Satyal, M. K. & Rugh, R. Dance on the Brain: Enhancing Intra- and Inter-Brain Synchrony. *Front. Hum. Neurosci.* **14**, (2021).

19. Pacheco Ramírez, Maxine Annel, Huber, Derek, Ramirez, Mauricio, Brandt, Anthony, Noble, Andy, Noble, Dionne, Contreras-Vidal, J. Neural Synchrony and Dynamics Present During Creative Movements.

20. Vangeline. *Butoh: Cradling Empty Space*. (Vangeline Theater/New York Butoh Institute, 2020).

21. Kuboshita, R. *et al.* Intrinsic brain activity associated with eye gaze during mother–child interaction. *Sci. Rep.* **10**, 18903 (2020).

22. Feenders, G. *et al.* Molecular Mapping of Movement-Associated Areas in the Avian Brain: A Motor Theory for Vocal Learning Origin. *PLoS One* **3**, e1768 (2008).

23. Jao Keehn, R. J., Iversen, J. R., Schulz, I. & Patel, A. D. Spontaneity and diversity of movement to music are not uniquely human. *Curr. Biol.* **29**, R621–R622 (2019).

24. Glanz, O. *et al.* Real-life speech production and perception have a shared premotor-cortical substrate. *Sci. Rep.* **8**, 1–14 (2018).

25. Belyk, M., Eichert, N. & McGettigan, C. A dual larynx motor networks hypothesis. *Philos. Trans. R. Soc. B Biol. Sci.* **376**, (2021).

26. Gordon, E. M. *et al.* A mind-body interface alternates with effector-specific regions in motor cortex. *bioRxiv* 2022.10.26.513940 (2022) doi:10.1101/2022.10.26.513940.

27. Batson, G., Migliarese, S. J., Soriano, C., H. Burdette, J. & Laurienti, P. J. Effects of Improvisational Dance on Balance in Parkinson's Disease: A Two-Phase fMRI Case Study. *Phys. Occup. Ther. Geriatr.* **32**, 188–197 (2014).

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28. Ghosh, S. S., Tourville, J. a. & Guenther, F. H. A Neuroimaging Study of Premotor Lateralization and Syllables. *J. Speech Lang. Hear. Res.* **51**, 1183–1202 (2008).

29. Longcamp, M., Hupé, J. M., Ruiz, M., Vayssière, N. & Sato, M. Shared premotor activity in spoken and written communication. *Brain Lang.* **199**, 104694 (2019).

30. Banquet, J. . Spectral analysis of the EEG in meditation. *Electroencephalogr. Clin. Neurophysiol.* **35**, 143–151 (1973).

31. Lutz, A., Greischar, L. L., Rawlings, N. B., Ricard, M. & Davidson, R. J. Long-term meditators self-induce high-amplitude gamma synchrony during mental practice. *Proc. Natl. Acad. Sci.* **101**, 16369–16373 (2004).

32. Tang, Y.-Y. *et al.* Central and autonomic nervous system interaction is altered by short-term meditation. *Proc. Natl. Acad. Sci.* **106**, 8865–8870 (2009).

33. Xue, S.-W., Tang, Y.-Y., Tang, R. & Posner, M. I. Short-term meditation induces changes in brain resting EEG theta networks. *Brain Cogn.* **87**, 1–6 (2014).

34. Kaliman, P. Epigenetics and meditation. *Curr. Opin. Psychol.* **28**, 76–80 (2019).

35. Sanders, S. G. Dancing through pregnancy: activity guidelines for professional and recreational dancers. *J. Dance Med. Sci.* **12**, 17–22 (2008).

36. Physical Activity and Exercise During Pregnancy and the Postpartum Period. *Obstet. Gynecol.* **135**, e178–e188 (2020).

37. Plamberger, C. P. *et al.* Fronto-parietal alpha ERD and visuo-spatial attention in pregnant women. *Brain Res.* **1798**, 148130 (2023).

38. Zaelzer, C. The Value in Science-Art Partnerships for Science Education and Science Communication. *eNeuro* **7**, (2020).

39. Warner, D. Hybrid Matters: Art and Science as a New Epistemology. *DNA Cell Biol.* **41**, 16–18 (2022).

40. Rakers, L., Tebben, L. & Glorius, F. co.labore-A Genuine Collaboration between Arts and Science, Reflecting Viewpoints and Merging Skills. *Chem. - A Eur. J.* **23**, 5860–5863 (2017).

41. Springs, S. & Baruch, J. Artists on the Research Team: An Interdisciplinary Approach to Team Science, Research Rigor, and Creative Dialogue. *Health Promot. Pract.* **22**, 83S-90S (2021).

42. Cuevas, S. *et al.* How to design an art-science program? Self-reported benefits for artists and scientists in the VI4 artist-in-residence program. *PLoS One* **17**, e0279183 (2022).

43. Koutedakis, Y. & Jamurtas, A. The Dancer as a Performing Athlete. *Sport. Med.* **34**, 651–661 (2004).

44. Contreras-Vidal, J. L., Robleto, D., Cruz-Garza, J. G., Azorín, J. M. & Nam, C. S.

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Mobile brain-body imaging and the neuroscience of art, innovation and creativity. (Springer, 2019).

45. Payne, H. *Dance movement therapy: Theory and practice*. (Routledge, 2003).

46. Levy, F. J. *Dance/Movement Therapy. A Healing Art.* (ERIC, 1988).

47. Anjos, I. de V. C. dos & Ferraro, A. A. A INFLUÊNCIA DA DANÇA EDUCATIVA NO DESENVOLVIMENTO MOTOR DE CRIANÇAS. *Rev. Paul. Pediatr.* **36**, 337–344 (2018).

48. McGuire, M., Long, J., Esbensen, A. J. & Bailes, A. F. Adapted Dance Improves Motor Abilities and Participation in Children With Down Syndrome: A Pilot Study. *Pediatr. Phys. Ther.* **31**, 76–82 (2019).

49. López-Ortiz, C., Gaebler-Spira, D. J., Mckeeman, S. N., Mcnish, R. N. & Green, D. Dance and rehabilitation in cerebral palsy: a systematic search and review. *Dev. Med. Child Neurol.* **61**, 393–398 (2019).

50. Bégel, V. *et al.* Dance Improves Motor, Cognitive, and Social Skills in Children With Developmental Cerebellar Anomalies. *The Cerebellum* **21**, 264–279 (2022).

51. Hwang, P. W.-N. & Braun, K. L. The Effectiveness of Dance Interventions to Improve Older Adults' Health: A Systematic Literature Review. *Altern. Ther. Health Med.* **21**, 64–70 (2015).

52. Rodrigues-Krause, J., Krause, M. & Reischak-Oliveira, A. Dancing for Healthy Aging: Functional and Metabolic Perspectives. *Altern. Ther. Health Med.* **25**, 44–63 (2019).

53. Joung, H. J. & Lee, Y. Effect of Creative Dance on Fitness, Functional Balance, and Mobility Control in the Elderly. *Gerontology* **65**, 537–546 (2019).

54. Menezes, A. C., Drumond, G. & Shigaeff, N. Dance therapy and cognitive impairment in older people: A review of clinical data. *Dement. Neuropsychol.* **16**, 373–383 (2022).

55. Koch, S. C. *et al.* Effects of Dance Movement Therapy and Dance on Health-Related Psychological Outcomes. A Meta-Analysis Update. *Front. Psychol.* **10**, 1806 (2019).

56. Kalyani, H. H. N. *et al.* Effects of Dance on Gait, Cognition, and Dual-Tasking in Parkinson's Disease: A Systematic Review and Meta-Analysis. *J. Parkinsons. Dis.* **9**, 335–349 (2019).

57. Hackney, M. E. & Earhart, G. M. Effects of dance on gait and balance in Parkinson's disease: a comparison of partnered and nonpartnered dance movement. *Neurorehabil. Neural Repair* **24**, 384–92 (2010).

58. de Natale, E. R. *et al.* Dance therapy improves motor and cognitive functions in patients with Parkinson's disease. *NeuroRehabilitation* **40**, 141–144 (2017).

59. Pereira, A. P. S. *et al.* Music Therapy and Dance as Gait Rehabilitation in Patients With Parkinson Disease: A Review of Evidence. *J. Geriatr. Psychiatry Neurol.* **32**, 49–56 (2019).

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60. Sharp, K. & Hewitt, J. Dance as an intervention for people with Parkinson's disease: a systematic review and meta-analysis. *Neurosci. Biobehav. Rev.* **47**, 445–56 (2014).

61. Kalyani, H. H. N. *et al.* Impacts of dance on cognition, psychological symptoms and quality of life in Parkinson's disease. *NeuroRehabilitation* **45**, 273–283 (2019).

62. Helgason, C. & Sarris, J. Mind-body medicine for schizophrenia and psychotic disorders: a review of the evidence. *Clin. Schizophr. Relat. Psychoses* **7**, 138–48 (2013).

63. Tarsha, M. S., Park, S. & Tortora, S. Body-Centered Interventions for Psychopathological Conditions: A Review. *Front. Psychol.* **10**, 2907 (2019).

64. Karkou, V., Aithal, S., Zubala, A. & Meekums, B. Effectiveness of Dance Movement Therapy in the Treatment of Adults With Depression: A Systematic Review With Meta-Analyses. *Front. Psychol.* **10**, 936 (2019).

65. Chiang, M., Reid-Varley, W. B. & Fan, X. Creative art therapy for mental illness. *Psychiatry Res.* **275**, 129–136 (2019).

66. Kasai, T. New understandings of Butoh creation and creative autopoietic Butoh-From subconscious hidden observer to perturbation of body-mind system. *Sapporo Gakuin Univ. Bull. Fac. Humanit.* **90**, 86–141 (2009).