Body-brain-avatar Interface: a tool to study sensory-motor integration and neuroplasticity

Doctoral Paper

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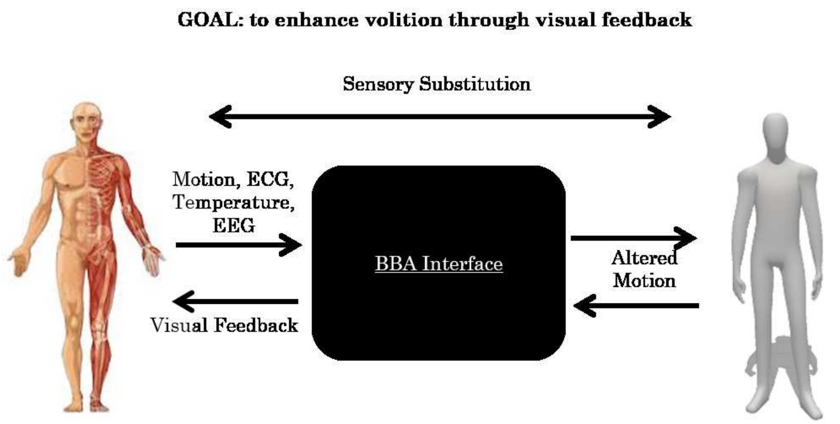

Figure 1: Schematic of the closed loop communication between the subject and the avatar established through the BBAI. Loop of dual-learning: Step 1. The interface collects the physiological signals of the subject. Step 2. It applies real-time analytics and estimates the personalized statistics. Step 3. It endows the avatar with noise and displays the visual feedback 4. The subject receives the feedback. Step 5. The subject reacts on the feedback. Step 6. Loop in closed form.

ABSTRACT

We introduce a body-brain-avatar interface (BBAI), which integrates physiological signals from multiple layers of the peripheral nervous system (brain, heart rate, temperature) collected in real time. Within this concept, we also present new analytical methods amenable to selectively enhance motor control. More specifically, we first characterize the stochastic signatures of biorhythms harnessed from the nervous systems of the individual end user employing a unifying statistical platform for personalized analyses and inference. Then, we pair the end user with an avatar endowed with the person's biorhythms and with their noisy variants. Gradually, we perturb the avatar with the person's noise from different nervous system's levels. We evaluate the outcome of these visuo-motor manipulations in real time to change the noise patterns and inform the interface about the person's nervous systems' reactions. In closed loop, we co-adapt the end user and the avatar driving the coupled performance of their body parts with various noise regimes. We, then, evaluate the person's resting state involuntary micro-movements and iterate the training until we find noise regimes with a tendency to increase the person's bodily awareness leading as well to highly predictive statistical patterns of the involuntary micro-movements across the body. We discuss our results as we further evaluate the person's performance across multiple levels of control, ranging from voluntary to automatic to autonomic.

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CCS CONCEPTS

•**Arts and humanities** →**performing arts;** •**Probabilities and statistics** →*Stochastic processes;* •**Data** →Graphs and networks;

KEYWORDS

physiology, human motion, micro-movements, personalized statistics, dynamics of human motion, body network, avatar, clinical application, training, performing arts, dance, social interaction

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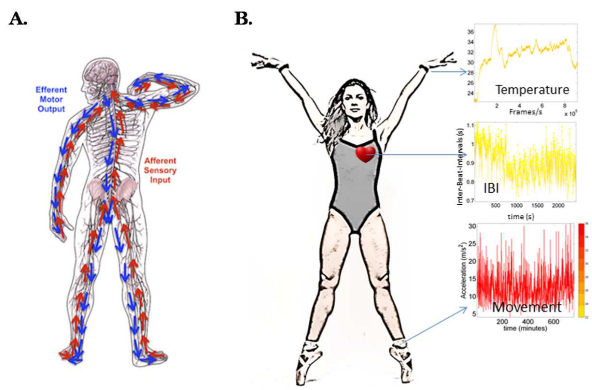

Figure 2: (A) Visualization of the efferent-afferent channels that carry impulses from the CNS to the PNS and from the PNS to the CNS using an enhanced returning signal from the BBAI. These two channels create a "closed loop" of sensations, decisions, and reactions that we can steer by informing the BBAI about the person's biorhythms statistical signatures. (B) Collection of variety of physiological signals (ex. skin temperature, heart rate or inter beat interval (IBI), and movement) to study the integration of micro-movements with other signals and their stochastic processes.

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1 INTRODUCTION

Body-machine interfaces (BMI) establishes a closed loop communication between the human body and a variety of devices. Over the years, several applications using this paradigm have provided proof of concept supporting this idea. Through BMI, paralyzed individuals can walk wearing exoskeleton technology driven by brain signals [5], control their wheelchair speed and orientation through shoulder movements [1], and use a prosthetic arm by detecting neural activities in the upper arm/ shoulder [4], just to name a few. These interfaces establish a close-loop communication between the end-user and machine, forming a dual learning paradigm, in which the two (body and machine) would continuously co-adapt to each other. It is remarkable that using the BMI within this paradigm allows an external device to be integrated as an essential part of the body instead of an external object. Indeed, this is possible due to the neuroplasticity of the somatic-motor system. Figure 1 shows our modification of this paradigm where we define the BBAI owing to the proof of concept from BMI research.

In our BBAI version, we incorporate biofeedback from multiple layers of the peripheral nervous systems (e.g., heart rate, temperature, respiration, blood volume, brain waves) where any physiological changes would be detected, while the co-adaptive interaction unfolds between the user and machine, Figure 2.A. We hypothesize that using these types of signals may help enhance the certainty of the bodily rhythms from movements. They may also inform about emotional states and level of stress, fatigue and relaxation, among others. As such, the BBAI may help raise self-awareness and be of use to scaffold social interactions. Given these features, several questions can be addressed in the context of a dual learning paradigm. How can we use the physiological signals obtained via BBAI to drive the flow of co-adaptive interactions between the user and machine? How can we lead the user to reach the physiological state that is desired? Moreover, could this be applied in a clinical setting? For instance, in the case of autism spectrum disorders, it would be challenging to use movement-driven BMI because the moment by moment fluctuations in motor performance are highly noisy and random [7], [8], [10]. However, using the BBAI augmented with other signals from the autonomic system may help us fine tune the motor noise. The autistic signatures of motor variability in isolation lack the type of structure necessary for predictive control, but when they are used in combination with other external signals in the visual or auditory domains, they become useful to enable BBAI

In our lab, we acquired proof of concept that it is possible to build multi-sensory co-adaptive child-computer interfaces driven by the child in tandem with external media. Indeed, in 25 nonverbal children with ASD we were able to induce regimes of highly well-structured anticipatory movements that started from movements with highly random and noisy stochastic signatures [17]. Through a body-machine-interface driven by the hand exploratory motions we witnessed how these children, one by one, bypassed their initial lack of volitional control and turned self-exploratory trial and error motions into systematically controlled purposeful motions. Without instructions, they spontaneously discovered the goal of the task and solved the problem they were faced with to trigger and drive videos, audio and their self-images (from a camera facing them) using their hand gestures.

2 ONE-TO-ONE COADAPTIVE INTERFACE

In my thesis project, I am exploring how to extend this work, where the BBAI would close the loop between the human and an avatar within a full-body interaction, Figure 1 (with the new BBAI concept). This new interface would set a platform for the use of multiple physiological signals generated in real time to selectively enhance motor control. More specifically, instead of using just body motions to control the avatar, we would use physiologically-driven-signal-dependent motions. For example, temperature dependent motion patterns automatically separate spontaneous random fluctuations from systematically predictive ones [15] providing a biomarker that enabled detection of volition in a pregnant coma patient and accurate prediction of the birthday of her son, not only saving her life but also that of her son. Likewise, heartrate variability dependent motions provide a unique signature for each person that permits the tracking of increases in cognitive loads during laboratory experiments [6].

The platform technology that we introduce in our proposal integrates motion and physiological signals (e.g., heart rate, temperature, respiration, brain waves) help track various mental and bodily states during the interaction. Initially, the avatar will be endowed with the use's motions in real time so as to mirror them. Gradually, as the interface learns the user's motion and physiological signal patterns, the avatar will be enhanced with those patterns which will be inserted in the form of noise, Figure 4. Consequently, the avatar's motion will vary according to these enhancements,

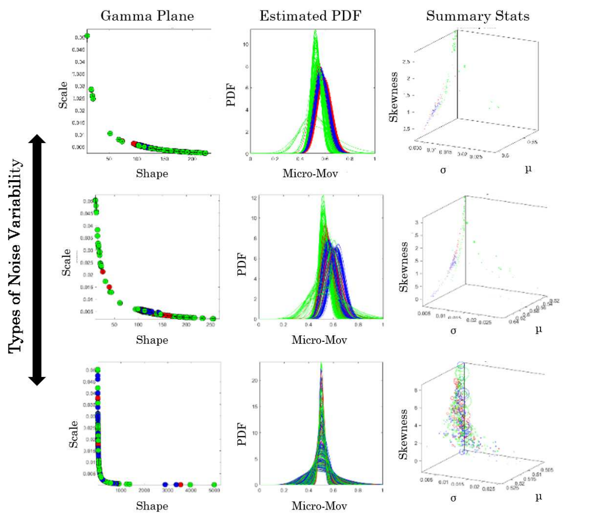

Figure 3: Results of the analysis of the personalized statistical platform. Each row displays different cases of noise variability. For every case, we demonstrate the Gamma plane (shape and scale values), the PDF, and the summary statistics (μ, σ, skewness, and kurtosis (size of markers)).

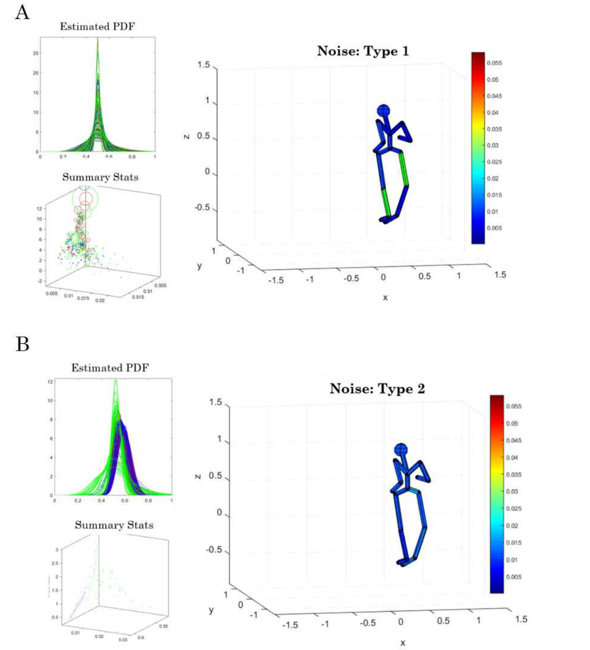

Figure 4: Examples of two users with extreme cases of noise. The left figures demonstrate the statistical estimations of the range of variability of each user; and the right figures show a single frame visualization of the avatar with the estimated noise colored on the corresponding body part. The color-map on the right corresponds to the noise variability.

as the variations will unfold fluidly and accordingly to the flow of the user's adaptation. It is important to highlight that these enhancements (added in the form of noise to the veridical motion), will only be defined by the individual's statistics, thereby establishing a strictly personalized 1-to-1 co-adaptive interaction that is driven by the physiological states of the person that lead the motions towards well-structured and systematic noise regimes. These regimes are well characterized by stochastic anticipatory rules [15].

The main goal of this project is to uncover critical aspects of the co-adaptation process between the human and the avatar. This would involve examining the evolution of how motor trajectories and physiological states (e.g., heart rate, respiration, temperature, among others) unfold in the learning process, and how factors such as noise in the avatar would in turn impact the motion and physiological state. Furthermore, aim at characterizing the extent to which the person becomes aware of the perturbations introduced by the use of noise signatures from physiologically-dependent motions. For instance, would the visual observation of his own distorted motions in the avatar (e.g. motion signatures sampled from a given temperature range and/or range of inter-heartbeat-timing) affect the participant's corporeal awareness? Would this awareness interfere with the co-adaptation process, or would it have a facilitating effect? Indeed, if this interface helps us control the automatic aspects of our body, it would have the potential to accelerate some of our learning processes that we quantified in the non-verbal autistic children. An important question we would like to further address is whether the avatar would be integrated into the person's corporeal self-perception (e.g., as a wheelchair, a prosthetic arm, etc.), or if it would remain in the subject's perception as an external device.

3 THE STATISTICAL PLATFORM

To implement our ideas, we are creating a sensory system that integrates sensory and motor information physically coregistered by high fidelity sensors and wearables. Our lab has pioneered new analytical methods to extract natural motions from the physical body in real time, varied by ever-shifting levels of intent and using the output of wearable sensing devices. We have characterized the noise-to-signal regimes in the continuous flow of behaviors across the human spectrum, ranging from pathological signatures (Autism [7], [8], [10] , Parkinson [14] , Schizophrenia [11] , Deafferentation [13] , stroke [16] and post severe Traumatic Brain Injury [15]) to typical signatures in sports [9], [12] and the performing arts, ranging from novices to experts [2], [3]. In addition, we have built analytics that allow us to characterize the states of learning and adaptation in motion within interactions, as well as analytics to detect fatigue in human motion [3]. More recently, we have created a new datatype that integrates motion and temperature signals while parameterizing the statistical signatures of the individual with motion analytics [15], [3]. Specifically, using temperature dependent motions, defined as the moment-by-moment fluctuations in motor performance for each temperature unit (degree) interval, we discovered that we can automatically define boundaries of motor noise, whereby spontaneous random noise (sensory-motor noise that exists in our movement from sensory and motor nerves) can be reliably separated from well-structured systematic noise with high predictive power. Using these analytics, we plan to selectively use motion signals with the lowest noise to signal ratio in the context of stochastic feedback control. This would close the loop between the motions of the human and those of an anthropomorphic avatar endowed with the human's veridical motions added with noise variants. In addition, we have created heart rate analytics that further allow the parameterization of the unique signature of the individual's physiology [18]. The biofeedback of one's heart rate parameter will be used in the interface to indicate how well the individual is physiologically adapting within this co-adaptive interaction.

Finally, it is important to emphasize that one of the most innovative aspects of our work is the individualized analysis of the data. Specifically, the project will focus and utilize the moment by moment fluctuations in performance as determined by the physiologically dependent motor signals separately for each individual, Figure 3 and 4. This is in contrast to current BMI concept that uses only the movement signals from the body. In physiological signal processing, most research studies apply the "one size fits all" approach, where they assume a theoretical normal distribution to characterize motor variability in relation to an assumed mean, often without empirically estimating the probability distributions most likely underlying the random process present in the experimental data. This approach averages out the fluctuations in performance as noise. Yet it is in this "noise" that we have found the signal to aid the autistic children, predict Parkinsonism, save a comma patient and her baby's lives and track the readiness of an athlete for competition. This integrative approach to motor control and body physiology will indeed provide information to help us steer the brain-body co-adaptation process and accelerate the successful blending of the avatar into the human and the human into the avatar, in a truly biologically plausible way. We aim at driving the interaction beneath the subject's awareness to minimize the natural resistance that the avatar may evoke in the subject and the possible interference of this resistance with the adaptation process.

Furthermore, we plan on testing with different populations: healthy controls, children/adolescents with autism, as well as advanced trained ballet dancers. This will allow us to test the interface with individuals with varying levels of motor capabilities and physiological signals -from dancers with well-trained motor capabilities to autistic children/adolescents with limited movement sensing capabilities. Eventually, we plan to build a system which contains information on ranges and proper scales of signals, obtained from characterizing various motor/physiological signals from a wide range of population -healthy individuals to those with pathological conditions.

For our set-up, we plan to simultaneously collect various signals from the body (e.g., brain wave, skin temperature, heart rate, respiration) during the avatar-interaction. Real-time data will be collected from motion capture system and will be mapped onto the avatar. At the same time, real-time analytics produced by the brain and body signals (e.g., brain, temperature, heart rate and respiration) will adjust the feedbacks that run between the user and the avatar within the evolution of their co-adaptation.

4 CONCLUSIONS

Our innovation will involve three main areas of research of interest to both the Computer Science and the Cognitive Science communities. The **first** one is on the design of interactive computer-user interfaces with applications in clinical interventions and physical training. The **second** is on better understanding of the sensory-motor integration process; specifically, motor adaptation patterns due to changes in visual-motor feedback at an individual level for use in personalized medicine. This will provide us with a broadened understanding of our adaptive capacity for the neural control of movements, ranging from intentional to spontaneous to autonomic levels. The **third** innovation will be to create new analytics for wearable devices with applications to physical training and clinical interventions truly tailored to the person -as opposed to be based on an assumed population ideal.

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