Human-Robot Kinesthetics: Mediating Kinesthetic Experience for Designing Affective Non-humanlike Social Robots*

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***Abstract*—This paper investigates how a non-humanlike, abstract robot can develop a social presence based on its capacity to move in delicate and dynamic ways. We outline our Performative Body Mapping (PBM) method for robot motion design and report on an audience study of our first robot prototype. These early results indicate support for our hypothesis that movement quality can imbue a robot with a distinct sense of affective agency, without the need for a humanlike or pet-like appearance. The paper embeds these accounts in an exploration of the connections between dance, motion design and knowledge translation along a trajectory of kinesthetic experience.**

I. Introduction

One of the common underlying assumptions for social robot design is that robots appearing humanlike or pet-like are easier for people to relate to [1, 2]. Yet Human-Robot Interaction (HRI) studies consistently show that the more humanlike a robot appears, the more people expect it to also have human-level cognitive and social capabilities [3]. Engaging and interacting with these apparently humanlike social agents thus can result in a frustrating and disappointing experience [3, 4]. In contrast, a non-humanlike, genuinely 'machinic' morphology allows for a robot's behavior, rather than its appearance, to be the predominant factor in a person's response to it, "and only to a much lesser extent any preconceptions, expectations or anthropomorphic projections that can bias the user's attitude even before any interactions have occurred" [5]. A morphology that is not preloaded with familiarity and affect, such as a humanlike or pet-like robot, poses the question of how we relate to abstract or alien-looking robots. This paper examines the potential of movement being fundamental to a robot's capacity to develop a social presence and evoke empathic responses.

Movement and its capacity to evoke affective responses has been explored by a number of artists working with robotics. Simon Penny's *Petit Mal,* resembling a strange, responsive bicycle, according to Penny, takes on the role of "an actor in social space" [6]. *The Table* by Max Dean and Raffaello D'Andrea [7] animates an ordinary looking wooden table that appears to be able to choose visitors to develop a relationship with. The expressive and affective capacity of robots has also been studied in collaborations between robotics and performance domains [8, 9]. While many of these collaborations explore robots' theatrical value, some interdisciplinary research projects have developed a performance-based methodology to investigate human-robot interaction. These include Jochum et al's study of artistic strategies [10], in particular traditional puppetry methods, to inform robot motion design, and Lu et al's approach for human actors to teach robots how to interact socially [11]. Research projects developing robot motion based on human dance commonly focus on humanlike robots learning to move like a human [12]. Notable exceptions include Margo Apostolos' early work on robot choreography [13] and Amy LaViers et al.'s somatic approaches to robot motion design [14].

Our research investigates the hypothesis that movement quality is key to a robot becoming a social agent, without the need for humanlike or animal-like features. To study the potential of movement, our project brings together creative robotics, dance and machine learning to develop an enactive approach that harnesses dancers' movement expertise to inform the robot's non-humanlike mechanical structure, its potential to move and capacity to learn. The project responds to the challenge of designing movement qualities for abstract robots by developing a novel movement learning method, involving the use of costumes, which allows much of the mapping problem to be delegated to movement experts. Our approach simplifies the correspondence problem, by mapping between similar morphologies, while simultaneously allowing only to the most relevant data to be captured from human movement.

This paper explores connections between dance, motion design and knowledge translation along a trajectory of kinesthetic experience. It outlines our robot motion design and an audience study and analysis of non-expert responses to our first prototype and its movement capacity. These accounts are embedded in a wider discussion of human-robot kinesthetics and the potential of kinesthetic experience and empathy to develop highly varied movement qualities and affective, expressive behaviors for non-humanlike robots.

II. Performative Body Mapping (PBM)

Our motion design research methodology, called Performative Body Mapping (PBM), has been developed to harness dancers' movement expertise to inform the shape of a robot and its ways of learning to move and behave. PBM's purpose, in a nutshell, is the development of an autonomous robot with an abstract, non-organic form and a capacity to learn how to move in expressive ways that are unique to its own machine body, based on the movement qualities it acquires from human dancers. The innovation of PBM lies in the enactive acquisition of movements and their fine-tuned qualities, which relies on the dancers' kinesthetic ability to

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embody another, nonhuman body. At its core, PBM deploys a robot 'costume', i.e., a wearable object inhabited and bodily animated by a dancer. The costume stands in for the robot's morphology, extending the dancer's body. The full PBM approach comprises four stages: bodying, grounding, imitating, and improvising. The project is still ongoing, and, in this paper, we focus on the bodying stage, which includes motion design and movement mapping, and aspects of the imitating stage that relate to the audience study.

In contrast to projects where the robot's functionality or social role shape its physical form, our project started with the questions (1) what movement qualities allow an abstract robot to develop a social presence, and (2) how to create and capture those movement qualities. This integrated approach to form-finding and motion/behavior design avoids reducing the robot's physical form to a mobile container [15].

In PBM, a costume serves as an embodied interface for mapping between the different embodiments and movement capacities of a human dancer and a robot. In doing so, it

(1) provides dancers with an embodied insight into the morphological characteristics of a specific robot,

(2) supports the development of a repertoire of movements and movement qualities, specific to the robot's morphological form, and

(3) allows the capture of movement data that the robot can learn from, with little or no translation.

A. The Correspondence Problem

HRI has developed a range of methods to design or specify robot motion, from a programmer "imagining a movement executed by the robot's body" [16] to produce a sequence of instructions, to programming by demonstration [17], where human motion is captured for a robot to learn to imitate. The former is challenging because it requires the programmer to translate the (imagined) movement into a precise algorithmic representation. Whereas the challenge of the latter approach lies in the necessary translation between different embodiments and sensorimotor capabilities, i.e., the correspondence problem [18]. In non-humanlike robots, this translation can be particularly complex and result in engineers making assumptions that may or may not be informed by expertise in movement or motion design. Despite this challenge, demonstration learning is a popular approach, because it makes it possible for robots to learn behaviors and skills without every action needing to be explicitly and painstakingly programmed [18].

The PBM approach builds on the core ideas of demonstration learning but delegates much of the difficult morphological mapping to movement experts. Motion capture data of a dancer-activated robot costume is used to expedite imitation learning. By mapping between two (almost) identical bodies, the PBM approach significantly simplifies the correspondence problem, while preserving a high-resolution data set of specifically designed human movement.

B. PBM Movement Studies

During early movement studies, we asked the dancers to inhabit and animate a range of objects and materials, with the objective of narrowing the scope of possible robot forms. To foreground movement over appearance and avoid analogies with living 'things', our exploration was shaped by enabling constraints, including that the form should be simple, without an obvious front or back, head or face, or limb-like structures. It should also be technically possible to construct a robot based on the costume's form and movement capacities, when activated by a dancer. This process filtered out forms that (1) relied too much on the dancer's human body, (2) whose novel, unusual appearance could distract from its movement, or (3) that would be impossible or infeasible to build. A detailed account of this form-finding stage can be found in [19].

Ultimately, our studies led us to perhaps the most obvious, abstract form, yet not the most apparent in terms of its evocative capacity—a box. At first, the dancers inhabited a cardboard box with the dimensions of 150x55x45cm, which we later reduced to cube dimensions of 80cm (Fig. 1), to further distance the form from human proportions. The simple cube quickly demonstrated its potential to being transformed when moving in unexpected ways, perhaps precisely because it is such a familiar, unassuming object. To the dancers the 'box' became particularly interesting when it tilted precariously on one edge or tipped onto one corner, and performed subtle teetering shifts [20]. Confronting our notions of weight and gravity by tilting, swaying and teetering allowed the box to lose its stability and, with it, its 'boxiness'. The second form, whose kinetic capabilities we closely studied with the dancers, was a tetrahedron, which, by a serendipitous accident, turned into a 5-jointed, broken tetrahedron. Our studies with this form are explored in [19].

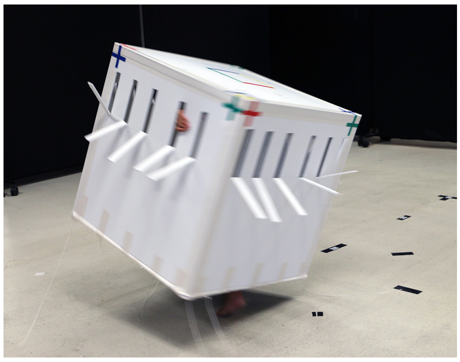

Figure 1. Cube costume, activated by K. Packham

C. Motion Capture and Machine Learning

The motion of the dancer-activated costume was tracked to (1) inform the model for a mechanical prototype resembling the costume and its capacities to move as closely as possible, and (2) provide motion data for the robot to learn from. The cube costume's motion was captured using two HD cameras and colored targets on the cube's surfaces (Fig. 1). The video recordings were analyzed using custom motion tracking software and the resulting 3D points were used to extract the cube's position (x, y, z) and orientation (yaw, pitch, roll). Approx. 15 hours of movement data were captured, involving three dancers over a period of five days. From this dataset, we extracted 5 hours of data representing the types of movement sequences that we wanted to test in the first audience study (see IV). An inverse kinematic model of the robot was developed based on two joints, one to represent the (x, y, z) position of the base of the robot and one to represent the (yaw, pitch, roll) orientation of the top, relative to the base. The motion capture data was processed using the inverse kinematic model to derive the position and orientation of the two joints, the resulting data set consisted of 360,000 joint positions.

For the machine learning, we applied a mixture density LSTM network, previously used to successfully synthesize handwriting [21] and choreography [22]. The inputs and outputs of the neural network were 6-dimensional tensors (x, y, z, yaw, pitch, roll) and the architecture consisted of 3 hidden layers of 512 neurons, a total of approx. 5.3M weights. The synthesized movement sequences were subjectively assessed by experts against the original performances of the dancers before adding them to a catalogue of possible movement sequences. The aim at this early machine learning stage was to produce a baseline result that can be compared with future 'grounded' results, resulting from the imitation learning once the robot has learned to ground its movements and any future learning in its own specific embodiment (grounding stage).

D. Robot Prototype: Cube Performer 1

The robot's required degrees of freedom were determined based on an analysis of motion capture data and documentation materials from our movement studies. To achieve these requirements, the design of the robot (Fig. 2) combines two subcomponents; (1) a 'Kiwi Drive', comprising an omnidirectional wheeled base that provides 3 degrees of freedom (x, y, yaw), and (2) a 'Stewart Platform' that provides 6 degrees of freedom relative to the base (x, y, z, yaw, pitch, roll). The former allows the robot to turn on the spot and move across the ground without having to turn to face its direction of travel. The latter allows the robot to shift, tilt, and rotate in more subtle ways, relative to the base. The use of omnidirectional wheels ensures that the robot design maintains an important initial criterion of not having an obvious front or back, while being able to quickly change the direction of travel. The Stewart platform provides the flexibility necessary to reproduce the range of angles recorded for pan, tilt and yaw, as well as the speed to produce some of the smaller, sudden or subtle movements produced by the dancers inside the costume.

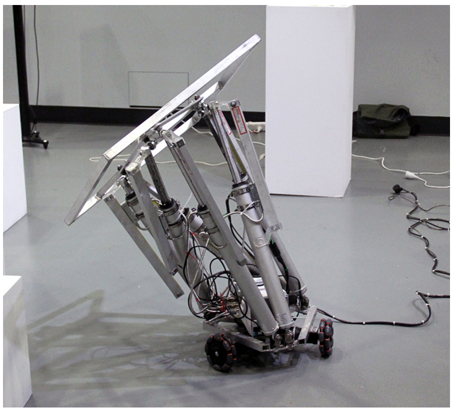

Figure 2. *Cube performer 1*, mechanical frame

III. The Potential of Kinesthetic Experience

Taking a closer look at what happens in the costume-interface, we first need to acknowledge that movement is *not* a change of position. Objects have a position that changes when moving, but movement itself is simply change [23]. To manifest and capture these dynamics of change, we believe that there is a distinct qualitative difference between the embodied unfolding of dancers' movement and vision-focused, keyframe-based animation [24]. In this context, it is also worth noting that we are not interested in imbuing the robot with human characteristics or a narrative character. Rather, our research investigates if seeding the robot's learning with human movement dynamics and their meaning-making capacities—both of which developed in concert with its specific machinic form—can render an abstract machine object affective and intelligible (see IV and V).

In PBM, involving dancers' bodily imagination [25] and kinesthetic experience [26], the costume becomes an efficient instrument, not only for mapping between two different embodiments but also for capturing a dancer's creative ideas. To facilitate this knowledge translation, PBM exploits dancers' finely attuned kinesthetic experience and awareness to channel their creative bodily process. Maxine Sheets-Johnstone argued that "kinesthetic experience is not a matter of sensations, but a matter precisely of dynamics. … When we move, we feel the dynamics of our movement kinesthetically; we feel the dynamics of an unfolding form" [26]. The costume then not only provides new material sensations for the dancers to work with, but, similar to a prosthesis, significantly affects how they kinesthetically feel the dynamics of their movement. Indeed, in our movement studies, the dancers often reflected on the different forces and resulting tensions they felt and negotiated *with* when moving with various wearable objects or materials. When encountering a new form, the dancers first explored its kinetic capabilities from the outside, moving and puppeteering it with their hands, which, according to them relied more on their visual sense. Once they stepped inside the object, however, they used their whole body, and a range of reconfigurations and dynamics to feel into, reshape and move *with* the object [20]. The wearable costume not only 'filters' the dancers' movements but also serves as a mediator between their own kinesthetic knowledge and that of observers. Seen through the lens of human-robot kinesthetics, it can be argued that the dancers' internal "distinctive spatio-temporal-energic dynamics" [23] translates into the costume's (external) kinetic dynamics, which in the audiences' "kinetically-sensitive eyes" [23] translates back into internal kinesthetic empathy (see V).

Importantly, the dancers' kinesthetic communication brings with it social synergies [23] and cultural dimensions of meaningful movement that co-shape our social relations. Manifest in the intrinsic qualities and dynamics of the movements they produce, they resonate in the movements we capture from the dancer-activated costume. In one movement study, for instance, the choreographer asked the dancer to express a question mark. When the dancer responded to the prompt, we witnessed the box performing a shape, seemingly positing layers of hesitation, inquiry and alertness along its movement trajectory. What we experienced was the unfolding of a movement, starting off with a hesitating twist that accelerated upwards with a slight inclination before it came to a sudden halt [19]. This was not a visual representation of a question mark, but the bodily processing of what a question mark *means*, i.e., what it *does* or *feels like* when we experience it. Working with dancers in such closely embodied, kinesthetic ways thus may achieve to embed non-humanlike robotic forms in our social world [see 23].

IV. AUDIENCE STUDY

The public exhibition Re/Pair [27] provided us with the first opportunity to study audiences' responses at an early stage of our robot prototype, *cube performer 1* (Fig. 3). The exhibition engaged audiences in Creative Robotics and was part of The Big Anxiety Festival, Sydney.

Staging the Prototype: The mechanical structure (Fig. 2) allows us to change the robot's outer 'shell' to take on different identities as an object and integrate in different ways in various contexts. The context in which a human-robot encounter takes place, naturally co-shapes people's experience of the robot and their ability, and perhaps even willingness, to make sense of it. For Re/Pair, we decided to integrate *cube performer 1* into the gallery context by staging the prototype as a gallery plinth, disguised amongst a group of other plinths (Fig. 3). This 'humble' staging suited the early prototype and its limited sensing capabilities. The plinth 'coming alive' also aligned with studying audience responses to a simple but delicately moving object.

Figure 3. *Cube performer 1*, shown at RePair 2017

A. Evaluating the Audiences' Perception

Our goal for exhibiting the robot prototype at this early stage was to survey audience perceptions of the moving cube-like robot. At this stage, the robot did not respond to the audience and performed a series of movement phrases that we captured in the movement studies, without performing a specific task (see II). We were particularly interested in the robot's affective qualities and if the audience would attribute agential capacities to this early prototype, and whether this would, in their eyes, render the robot more humanlike. We were also interested in how 'readable' the robot's behaviors were perceived, and whether they gave it a sense of intelligence. It is worth noting, however, that at this early stage the robot had neither the capacity to sense its environment, nor the ability to adapt its behavior, so any sense of intelligence could only arise in the eye of the beholder.

Our survey is inspired by the Godspeed Questionnaire Series (GQS), which addresses five key concepts; Anthropomorphism, Animacy, Likeability, Perceived Intelligence, and Perceived Safety [28], and Jochum et al's extended GQS, which incorporates additional concepts of Entertainment, Atmosphere, and Robots on Stage [29]. Aligned with our research questions, our survey addresses the key concepts: Affective Capacity, Perceived Intelligence, Perceived Agency, Intelligibility, and Anthropomorphism (Table 1). To confirm the internal consistency of our questionnaire, a reliability test was conducted. Table 1 includes Cronbach's Alpha values for each concept, all of which meet or exceed the standard 0.70 threshold [30].

B. Survey Results

We collected a total of 48 questionnaires during the Re/Pair exhibition. The majority of participants were between 21 and 55 years old. Participants were asked to fill in a questionnaire, once they had engaged in the performance of *cube performer 1*. The majority of the participants (81%) reported that they engaged with the robot for more than 2 minutes, 50% engaged with the robot for more than 5 minutes. Participants were also given a list of possible reasons for being attracted to the robot including its sound, appearance, and movement: 36 participants (75%) responded that the robot's movement attracted them, 23 (48%) that they were interested in the project, 17 (35%) the robot's appearance, and 5 (10%) the sound the robot made. 10 participants (21%) provided other reasons for being attracted to the robot. Fig. 4 illustrates the participants' responses as box plots of the participants' ratings for each of the five indices, using the Tukey convention with the median values and the box indicating the first and third quartiles, the whiskers indicate the lowest and highest datum within 1.5 IQR (interquartile range) of the lower and upper quartile, outliers are indicated with crosses [31]. A detailed analysis of the survey results shows that this early prototype of *cube performer 1* received high ratings for Affective Capacity (M=3:43), moderately high ratings for Perceived Intelligence (M=3:06) and Perceived Agency (M=2:95), moderately low ratings for Anthropomorphism (M=2:02), and varied responses for Intelligibility (M=2:56; SD=1:21). The latter aligns with our expectations, given that the robot's movements were not yet responsive.

C. Attribution of Lifelike Traits

As sensing and behaving objects, robots are often experienced as something in-between lifelike and non-lifelike. Based on their cognitive psychology studies, Levillain and Zibetti argue that the distinct behavior of objects produces transformations that trigger "the same kind of attributions that would be activated by the motion of a living being" [7]. With *cube performer 1*, we set out to study the relationship between morphology and motion capacity, pushing them as far apart as possible: a simple geometric form with five equal faces and a wide range of finely attuned, expertly developed movement dynamics. According to our survey results, people's primary reason for engaging with the robot was movement (36 out of 48), only 17 participants listed appearance. Audience members were clear that they perceived the robot as non-humanlike (M=2:02), despite rating it as affective (M=3.43), with a surprisingly high agential capacity (M=2:95), given that it was not yet adaptive. These early results indicate support for our hypothesis that movement quality can imbue a robot with a distinct sense of affective agency, without the need for a humanlike or pet-like appearance. Given that the robot prototype did not yet have any relational or adaptive capacities, the high ratings for perceived agential capacity (M=2:95) and intelligence (M=3:06) were higher than we expected. We believe that the surprising span between its simple non-lifelike morphology and its delicate and dynamic movement qualities—and thus the magnitude of its potential transformation—is a sizable factor here.

Attribution	Attributes	Mean (M)	Std. Dev. (SD)
Affective Capacity	Bland — Expressive	3.51	0.81
$\alpha = 0.82$	Forgettable — Memorable	3.34	1.08
$M = 3.43$	Dull — Evocative	3.64	0.93
$SD = 0.97$	Trivial — Meaningful	3.03	0.99
	Boring — Engaging	3.63	0.94
Perceived Intelligence	Incompetent — Competent	2.94	1.17
$\alpha = 0.74$	Unintelligent — Intelligent	2.91	1.07
$M = 3.06$	Aimless — Deliberate	2.92	1.15
$SD = 1.14$	Indifferent — Curious	3.61	0.95
	Scripted — Imaginative	2.94	1.21
Perceived Agency	Simple — Puzzling	2.84	1.33
$\alpha = 0.70$	Predictable — Surprising	3.31	1.10
$M = 2.95$	Scripted — Imaginative	2.94	1.21
$SD = 1.22$	Rehearsed — Spontaneous	3.09	1.20
	Rigid — Elastic	2.58	1.16
Intelligibility	Unintelligible — Intelligible	3.14	0.96
$\alpha = 0.75$	Enigmatic — Understandable	1.95	1.03
$M = 2.56$	Opaque — Readable	2.51	1.19
$SD = 1.21$	Ambiguous — Obvious	1.81	1.04
	Unconvincing — Believable	3.39	0.98
Anthropomorphism	Mechanical — Organic	2.13	1.18
$\alpha = 0.84$	Machine-like — Human-like	2.07	1.16
$M = 2.02$	Non-human — Human	1.75	1.24
$SD = 1.21$	Artificial — Natural	1.79	1.23
	Machine — Performer	2.36	1.19

Table 1. Analysis of questionnaire responses

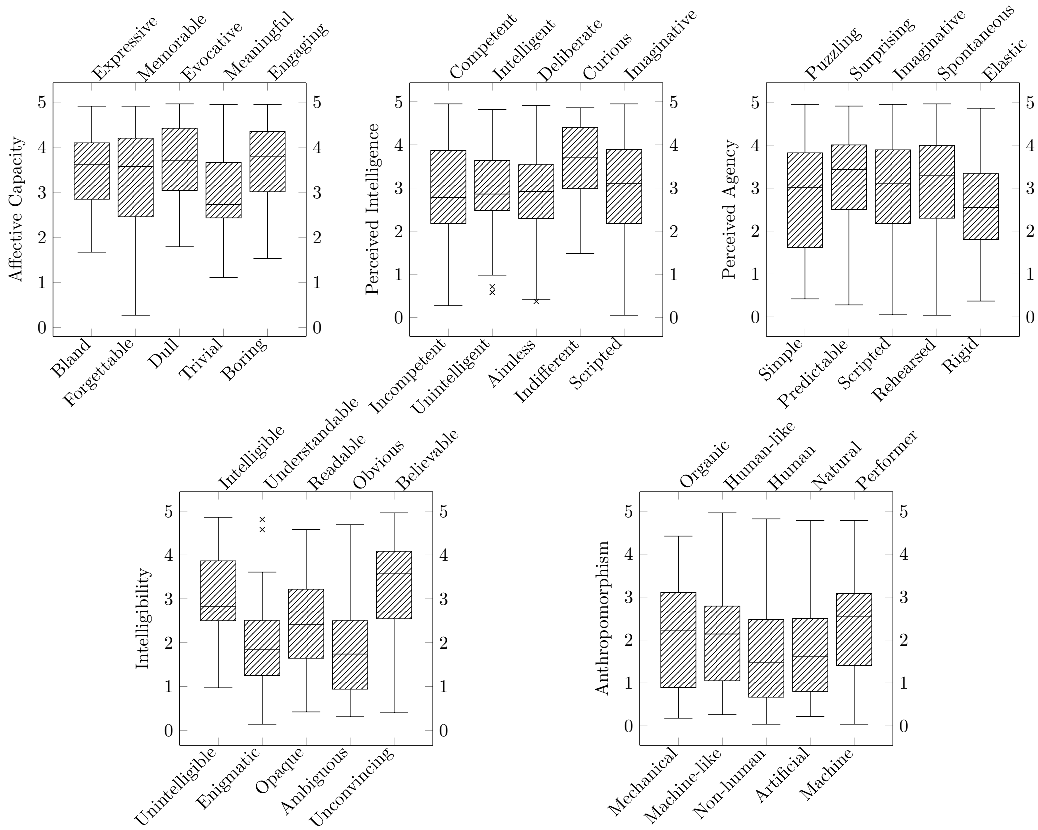

Figure 4. Box plots illustrating analysis of questionnaire responses

V. The Potential of Kinesthetic Empathy

Kinesthetic empathy is an interdisciplinary concept that facilitates our understanding of social interaction and communication [32]. We mostly refer here to participants' embodied affective responses as they encounter and engage with the robot's perceived kinesthetic intentionality [32], before emotions or thoughts are formed. Research on a moving body's capacity to resonate with an observer argues that observed movement literally moves and bodily affects us [33, 31]. For living beings, movement is both a kinesthetic (internal) and kinetic (external) happening [23]. Because of this tight interrelationship, the qualitative dynamics of movement ground our empathy towards other moving beings and things, and, with it, our social interactions [23]. While audiences don't experience these qualitative dynamics in the same tactile, kinesthetic ways as the dancers when entangled with the costume, watching moving objects or robots nevertheless produces kinesthetic affect [31]. As suggested in section III, we believe that PBM's use of a costume, and, consequently, *cube performer 1,* imitating the costume's movements, plays a key role in transferring the dancers' inscription of kinesthetic intentionality. Dancers, being experts in bodily producing and finely modulating affective experiences, thus skillfully 'play' the costume like an instrument, resulting in specific motion dynamics that are empathically perceived by audiences through their sense of kinesthetic empathy. It is worth noting that this transfer and resulting experience is not universal but will be different for every audience member, dependent on their personal and cultural background. Both, the dancers' kinesthetic intentionality and the audiences' kinesthetic affect are embedded in a specific socio-cultural context, which, in turn, grounds the socio-cultural perception of *cube performer 1*. Future PBM movement and audience studies will investigate different socio-cultural encodings and test the connection between dancers' kinesthetic intentionality and audiences' perception in more detail.

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