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From Contact to Communication: Investigating Interpretation of Robotic Nudges

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ABSTRACT

This thesis investigates how abstract, non-humanoid robots can communicate emotion and intent through physical nudges. Moving beyond anthropomorphic cues such as speech or facial expression, the research centers on a cube-shaped robot built on a Stewart-Gough platform with omnidirectional mobility, capable of initiating expressive gestures. The movements were designed in collaboration with an animator, drawing on animation to emphasize affective qualities of motion.

The study was carried out in two parts. In the first, participants engaged in a goal-oriented interaction in which the robot attempted to nudge past their arm using an escalating sequence of movements. In the second, participants observed pre-designed gestures in isolation and interpreted their affective and intentional qualities. Data collection combined questionnaires, open-ended responses, and video analysis to capture both quantitative and qualitative perspectives.

Findings show that even a minimal, abstract robot can elicit clear attributions of agency and autonomy, extending minimal-cue effects into embodied touch interaction. Context was decisive for interpretation: isolated nudges appeared ambiguous, while situated interactions highlighted social meaning and allowed pragmatic intent to surface through reflection. Affect and intent were interpreted jointly, with emotional trajectories often inseparable from the goals attributed to the robot's actions. Including self-reported neurodivergence showed that individual differences shaped both the perception of the robot and the emotions linked to its gestures.

More generally, the findings illustrate that even simple, abstract robotic touch can shape how people understand emotion, intent, and agency, while also raising new questions for the study of embodied interaction.

1 INTRODUCTION

For quite some time now, robots have been increasingly entering human environments, appearing in homes, streets, and public facilities. As robots become more integrated into everyday life, concerns about ethical, social, and environmental implications of their development are also rising. Public discourse often fluctuates between fascination with technological progress and fear of its unintended consequences.

While task performance is key to robotics, some robots need more than just excellent success rates in functionality. These are social robots. According to Dautenhahn [23], there are various definitions of social robots that include socially evocative, socially situated, sociable, socially intelligent, and socially interactive robots. What brings them all together is the environment they must navigate and its almost unbearable complexity. From the perspective of human-centered HRI, the main goal of robots is to fulfill their task specifications in a manner comfortable to humans. This is usually done by means of carefully designed interaction.

In HRI, communication is no longer limited to linguistic exchange. Social robots increasingly rely on non-verbal cues such as gaze, posture, gestures, motion dynamics, proximity, and overall spatial behavior to engage users. Embodiment—the physical form and movement of a robot—plays a central role in how these cues are produced and interpreted. Therefore, the expressiveness of the robot's body, even when minimal or abstract, shapes how humans perceive its social presence. This is heavily supported by research on human–human interaction and the importance of non-verbal cues, which often communicate more than language [82, 42]. In the context of this thesis, non-verbal communication channels, such as body movement and especially touch, offer yet an underexplored interface for interaction.

The inspiration for this research was sparked by the Pixar movie WALL-E. Despite limited language and simple shapes, the robots in the film communicate affectively through expressive movement, proximity, and subtle touch. WALL-E and EVE's interactions, such as hand-holding and forehead-touching, represent emotionally rich, intentional, and embodied communication. These robots, although non-humanoid, display a wide range of affective behaviors through carefully designed movement and tactile interaction. Their emotional expressiveness is grounded not in human-like faces or voices, but in timing, rhythm, and gentle physical contact.

My first real-life experience with a robot occurred in Moscow with the Yandex.Rover. These delivery robots operate autonomously in complex urban environments and have been deployed across the USA, UAE, and Russia. Despite their strictly functional appearance, they often elicit strong emotional responses from bystanders. I witnessed people helping the robot when it got stuck or reacting with amusement when it navigated around them. These brief encounters often included accidental or cooperative physical contact, prompting users to interpret the robot's actions socially, even attributing intention and emotion to the device. These experiences led me to consider the communicative potential of physical contact, particularly when accidentally initiated by the robot.

The interest of this study then lies in the mystery of the robot, in how people, drawing on complementary reasons, come to define it as a life-like entity. In other words, how do people empathically react to robots and how do they reflect on this reaction?

While touch is gaining attention in HRI, most studies focus on human-initiated touch, haptic sensing, or pattern recognition. Robot-initiated touch remains underexplored, with research falling into three areas: functional use, affective touch for emotional support or behavior guidance, and perceptions of touch-capable robots.

Robotic hugs and hand-holding have been studied for emotional relief, with preferences for soft, warm, brief interactions [39, 27, 100, 8]. Warmth and tactile expressiveness also show therapeutic potential [73, 107, 108]. Robots used include teddy bear-like forms, humanoid arms, and Nao.

Touch defines how people perceive robots, their warmth, emotion, or agency [20, 81, 113], though such studies rely on humanoid or zoomorphic platforms using familiar gestures.

Overall, robot-initiated touch is still largely tied to anthropomorphic designs and gestures like hugs or handshakes. Few studies examine touch as an independent communication channel, beyond anthropomorphogenic comfort. Expressive, intentional touch from abstract or non-humanoid robots remains largely unexamined.

Since touch is a non-verbal communication channel, the use of humanoid and zoomorphic robots in research seems to be limiting. Non-humanoid robots proved to be successful in social interactions [102, 56, 57, 98, 3]. Research has been conducted on robots with both abstract (an abstract ball rolling on a dome [3]) and instrumental appearance (a car seat [102], a footstool[98], an automatic door [56] and other [63]). In both cases, these non-humanoid robots successfully conveyed non-verbal cues that were clearly understood as social gestures. These studies are initially build on the finding of a well-known work by Heider and Simmel [45], which shows that people attribute social meaning to simple movements even from geometrical shapes as triangle.

According to Anderson-Bashan et al. [3], non-humanoid robots offer great design freedom and lower productions costs. Abstract design additionally avoids unrealistic human-like expectations, which when unmet can lead to users frustrations or even feelings of unease and revulsion (e.g. Uncanny Valley effect [71]). Non-humanoid robots allow researchers to study movement in isolation from form, revealing how motion alone can convey social cues.

Saunders and Gemeinboeck [91] are strong advocates for the use of abstract, non-humanoid robots in social robotics research. Across multiple studies [38, 36, 33, 37, 34, 91, 32], they consistently argue that moving away from human or pet-like morphologies allows researchers to study interaction in its purest form, free from the anthropomorphic expectations that often bias user perception. Rather than aiming for mimicry, they emphasize the generative and expressive potential of movement itself, proposing that social agency emerges through the encounter and not from a robot's resemblance to human traits. Their work positions abstract design as a deliberate strategy to explore how movement, gesture, and embodied interaction alone can produce meaningful and emotional connections between humans and machines.

The above-mentioned studies deploy abstract robots to interact with users by the use of movement alone. This thesis, however, builds on the findings of the research and takes a step further to investigates how non-humanoid robots can use physical nudges, movement with touch, to communicate emotion and intent, and how humans interpret these interactions in terms of emotional content and perceived agency. The research addresses the question: how do people perceive and respond to robot-initiated touch in the form of nudges? It examines whether such interactions influence emotional state, the extend to which agency is attributed to the robot, and whether particular perception attributes influence the ability to decode the intent and emotion behind a nudge. The study additionally focuses on the accuracy of interpreting emotion–intent gesture pairs, contributing to the understanding of touch as a communicative modality in non-humanoid social robots. An abstract, cube-like robot was developed for this purpose, built on a Stewart-Gough platform with an omnidirectional base. Drawing from animation principles and affective computing, the study combines design and empirical evaluation to analyze the role of brief, intentional contact in shaping social perception.

The paper begins with background and related work, then details the design process, implementation, and methodology, before presenting the evaluation study, findings, and discussion, and concluding with limitations, threads to validity, future work and acknowledgments.

2 BACKGROUND

This section outlines the theoretical and empirical background that informs the study. It reviews prior research, key concepts, and related approaches to situate the work within the broader field.

2.1 Theoretical and Functional Groundings of Touch

Touch is considered the most essential medium for interacting with the world [30, 18, 47]. In addition to developing ahead of all other senses, it plays a crucial role in influencing and managing human cognition and emotion.

Nonhuman primates use touch to maintain social structures, convey hierarchy, reduce stress, and build alliances [48]. Grooming in rhesus macaques and chimpanzees acts as both a dominance and reconciliation strategy. Dunbar's social brain hypothesis [26] further links grooming to the evolution of large brains and social cognition.

From an evolutionary standpoint, primate hands transitioned from tools for locomotion to instruments of nuanced interaction and communication[64]. These developments underline the importance of touch as both an emotional and functional tool in human and non-human societies.

Saluja, Croy, and Stevenson [89] categorizes existing research based on emphasized aspects of the tactile system, such as: (1) agency (active vs. passive touch), (2) afferent type (discriminative vs. affective), (3) interpersonal function, and (4) sub-modalities (e.g., temperature, texture). While rich in communicative capacity, touch remains under-researched due to its methodological complexity — factors like speed, placement, and temperature influence perception [47]. However, touch gestures, in particular nudges, have generally been ignored in HRI. Nudging combines elements of active touch with minimal duration and localized contact, making it an efficient yet underexplored communicative act. Within human-human interaction, behavioral nudging is the researched in depth, while in the context of physical touch, it is underexplored.

2.2 Embodied AI and Applications of Social Robots

Dautenhahn [23], in the search for an embodied artificial intelligence (AI), developed a 'robotiquette' that is a set of heuristics and guidelines for development of social robots which are not only desirable but also crucial for the acceptance of a robot companion. Combining the social brain hypothesis and Gigerenzer's idea of a later knowledge transfer from social to non-social domain, Dautenhahn argues that to the social factor cannot be disregarded when talking about artificial intelligence, since social intelligence is a particular and essential aspect of human intelligence. The author states that social intelligence is key ingredient of human intelligence. When developing embodied artificial intelligence, the social aspect cannot be considered an add-on. Rather, Dautenhahn believes that developing an intelligent robot actually means developing a socially intelligent one.

Designed for smooth human interaction, social robots aim to naturally communicate and facilitate positive human-robot interactions [11]. There are many applications of social robots [46]. Healthcare, being the main area of application, greatly benefits from the use of social robots [87]. The research is usually divided into providing assistance to elderly [54, 12, 41], people with disabilities or mental health issues [70, 109] and children [67, 24, 15, 61, 65]. Another prominent area of social robot application is education[7]. All of the applications so far correspond to the specialized application class of social robots[44]. However, advances in machine learning brought a significant change to the field of robotics[99]. The field of social robotics now observes a steep increase in research and commercial projects on individual [51] and public application of the social robots [111, 98, 3, 60]. Robots with such application can be regarded as socially intelligent and socially-situated robots respectively [67] and act as service robots.

2.3 Philosophical and Ethical Context

Touch stands apart from the other senses. It is the way we feel pressure, weight, warmth, and texture, but also the way we know where our body begins and ends. Writers such as Gibson (1966 in [29]) and Olivier and Frédérique [77] argue that this makes touch unusually complex, since it is always tied to movement and to the body itself. Psychology adds a similar point from another angle. In a study using the rubber hand illusion, Crucianelli et al. [21] found that slow, gentle strokes made people feel more strongly that the artificial hand was their own, compared with faster and less pleasant contact. The detail of how the skin was touched changed how people related to their own body.

Drawing on this foundational view of touch, more recent theories of embodiment have increased the scope of the focus beyond tactile sensation alone to include gesture and kinesthetic experience as central to emergence of subjectivity and agency. Noland [74] in her exploration of embodied agency positions gesture as a learned, culturally inscribed act that simultaneously affirms and challenges social norms. Gestures are inscribed techniques of the body that render the subject both socially legible and internally aware, functioning as platforms where agency is enacted through movement rather than intention alone. Building on theories of Marleau-Ponty, Noland emphasizes that gestures are the link between biological movement and cultural meaning. They are not just purely expressive or reactive, but performative, bringing forms of self and subjectivity into being. Importantly, Noland suggests that kinesthetic awareness is not just private, but foundational for intersubject relations, enabling subjects to imagine how another body feels, and to develop a sense of self through bodily variation. This highlights that touch and gesture are not neutral actors but culturally specific practices that carry epistemological and social weight.

Further drawing on Nolan's view of embodied gestures, Bellmer, Graham, and Coleman [6] offers a more fragmented affect-driven account of bodily expression. In *La petite anatomie de l'inconscient physique (Little Anatomy of the Physical Unconscious, or the Anatomy of the Image)*, Bellmer does not treat the body as a communicative agent engaged in clear transmission, but rather as a site where meaning is displaced, and affect emerges through ambiguity. His work emphasizes that gestures and forms, no matter the distortion, can illicit emotional and visceral responses. This unique take on bodily-induced affect supports the idea that robotic gestures can function not only as conveyors of meaning and but also as triggers for felt response.

Complimenting this, Meshcheryakov [69] in his seminal work on the education of deaf-blind children illustrates the radical potential of touch as foundation for both inter-subjective engagement and symbolic thought. His findings affirm that tactile interaction, even without visual and auditory input, can nourish the sense of self, other and communicative structure. These perspectives challenge the traditional assumptions about interpretation, suggesting that communicative value does not have to require language, facial expression or even visual presence.

Together, Noland, Bellmer and Meshcheryakov offer a compelling case that justifies treating touch and gesture as primary channels of robot-human interaction. In the context of this project, their insights ground the design of a non-humanoid robotic system whose expressive capacity lies not in simulating human form, but in evoking affect, agency, and ambiguity through nudging movement alone.

This framing of touch as affective, ambiguous, and deeply embodied also raises important ethical considerations. When a robotic system engages human through bodily contact and movement in abstract, unfamiliar and affectively charged ways, it confronts the participant not only with the machine, but with themselves. Such encounters, while carefully designed, may provoke unexpected interpretations or emotional responses. The ambiguity makes it a rich medium for expression, but also complicates the participant's role as an interpreter. This highlights the need for a careful ethical stance that respects the participant's agency, protects their emotional and physical well-being, and acknowledges that meaning may emerge in ways that are not fully predictable. Therefore, engaging with gesture and touch as sites of affect and subjectivity requires not only design sensitivity, but also ethical attentiveness to the open-ended nature of embodied interaction.

2.4 Motion and Minimal Expressiveness

Although this study focuses on touch, such interactions do not occur in isolation. Physical contact is always mediated by movement — its speed, trajectory, and rhythm. This section explores the expressive role of motion as a crucial component of how touch is delivered and interpreted in HRI.

As mentioned earlier, non-verbal cues act as both main channel, but also as support. Unlike purely verbal exchange that can deceive, non-verbal cues, though not always, present a channel for honest communication, since modalities, such as gaze, posture, gestures, motion dynamics and proximity take place in the unconscious. These cues are central to how humans convey emotional information and intentions. Therefore, social robots must implement such a behavior to comply with the expectations of human interacting with it. Many studies on affective communication via non-verbal cues in HRI have been conducted to satisfy the need for socially intelligent interactive agent.

2.4.1 Kinesics. Starting with kinesics, a work by Hoffman, Bauman, and Vanunu [49] introduced the concept of robotic experience companionship - the idea that a robot's responsive movements to shared stimuli, listening to an audio track, can create a sense of co-experience for the human. The robot used in the study called

Travis is a custom built robot designed to provoke a relation to a pet, rather than humanoid. The outcomes of the study showed that well-timed, context-aware body movements like rhythmic swaying or "dancing to music" can strengthen the robot's social presence and emotional expressiveness, particularly for users receptive to companionship.

A high-profile work recently produced under the research team of Apple presented a framework called ELEGNT [51]. The framework integrates expressiveness and functional movement design for non-biomimetic robot. The robot has a resemblance to the Luxo Junior lamp, the main character of the well-known Pixar's first animation. The lamp-like robot uses motion primitives to convey internal states like intention, attention and emotion, while still achieving functional tasks. The results of the study showed that movements that were expression driven significantly improved user's perceptions of the robotic qualities and overall engagement, unlike the purely function-oriented movements. The study concluded that a robot that not only moves efficiently, but also "with feeling" tends to be received as more lifelike and relatable. In the context of this research, it is important to note that Hu et al. [51] included touch in the interaction, but only human-initiated touch.

While the above-mentioned studies implement robots with human features, bio-mimetic or resembling the famous characters, Sirkin et al. [98] researched the possibilities of expressive movement of a robotic furniture, a footstool in particular. Through careful behavior design, the footstool was able to communicate its purpose without any verbal cues or even any face like attributes. This study concludes that even object-like, minimal robots can coordinate joint action with humans via kinesics, but also proxemics. Similarly, the Greeting Machine developed by Anderson-Bashan et al. [3] revealed that an abstract robot in a shape of a sphere with a smaller one attached on top can effectively take part in opening encounters. The study also found that minimal movement from the robot may elicit positive and negative experiences.

One notable approach to designing expressive movement for non-humanoid robots is offered by Saunders and Gemeinboeck [91], who introduce Performative Body Mapping (PBM) as a method for developing motion vocabularies grounded in embodied performance. In this method, dancers wear sculptural robotic forms that restrict and shape movement, allowing them to explore expressive potential from within the constraints of abstract robotic bodies. These gestures are then transferred to robotic platforms to enable interaction that is interpretable through motion rather than anthropomorphic features. Unlike studies that focus on predefined motion primitives or functional movement, PBM emphasizes embodied improvisation and dynamic qualities—such as rhythm, directionality, and posture—as the basis for communicative behavior. An earlier conceptualization of this methodology is discussed in [38], which outlines the iterative mapping pipeline from performance to robotic embodiment. Building on this, Gemeinboeck and Saunders [37] frame robot–human communication as a relational and performative process, in which agency and meaning arise not from appearance or symbolic clarity but from embodied interaction. This theoretical foundation aligns with the broader framework of relational-performative aesthetics proposed in [33], which emphasizes intra-bodily resonance, emotional dynamics, and the material entanglement of humans and machines as key to designing socially expressive systems.

Overall, the research on kinesics in HRI for emotional information exchange suggests that body language is a powerful channel. By enhancing motion with expressive qualities - Brooks [13]'s long championed concept of behavior-based robotics - robots can project human attributes. However, it is important to note that movement is context-sensitive, where the same gesture can have different polarities in terms of valence or even arousal based on the context it is presented. Therefore, robotic movement should be aligned with the social context and desired affect - findings that echo the disciplines of animation and character design.

2.4.2 Proxemics. Moving on to proxemics, early work by Syrdal et al. [101] observed that humans are comfortable with robots retaining the socially accepted distance, but have limits when robots enter their personal space without an invitation. A more recent research supports the findings [68, 90, 72]. Moreover, the study mentioned in Samarakoon, Muthugala, and Jayasekara [90] found that people tend to physically and psychologically distance themselves more from a humanoid robot that violates their expectations, in contrast to a robot that orients his body in a friendly manner, maintains respectful distance and proper eye contact, mimicking courteous human behavior.

Beyond personal comfort, proxemics can also communicate emotional intent. A robot that comes closer can signal warmth or urgency, while stepping back can indicate politeness, deference or yielding. Coming back to the Mechanical Ottoman of Sirkin et al. [98], the footstool robot used proxemics to effectively ask for permission. The study observed that users found the spacial cues clear and even "considerate", suggesting the robot had social etiquette. Another area of proxemics research involves adaptive spacing - dynamic adjustment of the robot's distance based on the user reactions. The above-mentioned studies [68, 90, 72, 101, 98] recognize distance as communication - it is not just a physical constraint but a channel through which the robot can show respect or attract attention without words.

2.4.3 Appearance. Delving into robot appearance and form factors, it is recognized that the form, aesthetics and anthropomorphism profoundly influence the non-verbal communication and user expectation. The body itself can be considered a communication medium: it can invite or deter interaction, appear friendly or aggressive, familiar or alien. Humanoid appearance can facilitate rich no-verbal communication due to resemblance to the human schema. However, going too human introduces the risk of Uncanny Valley effect, particularly if the robot behavior did not match its human-like appearance [105].This underscores that a congruence between appearance and non-verbal behavior is vital, support to which once again can be found in work by Gemeinboeck and Saunders [37].

3 RELATED WORK

According to De Santis et al. [25], the successful introduction of mobile robots into unstructured anthropic environments depends on their ability to rely on a comprehensive set of sensors, including proximity, vision, sound, and touch. Such multimodal sensing directly supports the reliability of robotic manipulators in interaction contexts. This reflects a human-centered perspective in human-robot interaction (HRI), where any form of interaction must be perceived as safe, comfortable, and appropriate. As a result, considerable research has been devoted to the development of touch sensors and technologies [80, 5, 83], complemented by surveys that review tactile sensing and acceptable practices in physical HRI [104, 53, 85, 25, 22, 58].

Building on this foundation, the following section turns specifically to the role of touch in HRI. We first consider human-initiated touch, where physical contact originates from the person and the robot must interpret and respond appropriately. We then move to robot-initiated touch, in which the robot deliberately employs physical contact as part of its interactive repertoire.

3.1 Human-initiated touch

An importance of touch for conveying affection to the robot has been researched with positive outcomes that suggest that in the communication of affection from a person to a robot capable of multi-modal cue recognition, touch has an integral part [19].

Delving deeper into the inter-agent touch, human-initiated touch has been the center of attention. Many such studies use Paro seal robot[40, 39, 57, 112]. Paro is a medical device that has been developed as a therapeutic robot for use with older people [93]. Studies using Paro as experimental platform have shown that interactions with touch reduce pain perception [40], alleviate stress [39], improve mood and stimulate social interaction [112].

Another widely used robot in HRI touch research is toy humanoid called Nao. Here, more attention is paid to communicating affect to Nao through touch [4, 1, 66]. Studies on human perception of touching Nao have been conducted [110] as well as research on perception of the robot that can react to touch [62, 76].

In terms of instrumental touch, research on human-initiated contact focuses on how people can communicate with robots via touch-based interfaces [59].

3.2 Robot-initiated touch

The above-mentioned robot-initiated touch, which is the main topic of this thesis, has so far received little amount of exposure in the research community. Overall, there are three main research areas: instrumental touch, touch for emotional soothing and behavior nudging and perception of robots capable of touch.

3.2.1 Instrumental Touch. A study on functional touch by Chen et al. [17] explores the human response to a robotic nurse that autonomously wiped and touched a participant's forearm. The study found that, on average, participants had a favorable response to the first time the robot touched them. Additionally, the perceived intent had a significant influence on the responses—when instrumental intent was presented instead of an emotion one, participants preferred the former, even when the robot's behavior remained the same. The robot used in the study, Cody, consisted of an omnidirectional base with a body and two anthropomorphic arms.

In a different domain, Shomin [97]'s ballbot demonstrated how robot-initiated physical contact can be applied to guide people through space. By using compliant 2-DOF arms, the robot conveyed directional cues via haptic interaction, showing how instrumental touch can support navigation and assistance rather than emotional communication [97].

3.2.2 Affective touch for emotional soothing and behavior nudging. On the other hand, affective touch has been getting much more recognition within HRI research. Robotic hugs received some exposure in contrast to other touch gestures [78, 79, 95, 96, 55, 8]. Another study looking into the temperature of touch by Nie et al. [73] revealed that experiences of physical warmth and hand-holding increase feelings of friendship and trust toward the robot. Overall, studies on emotional soothing by active robotic touch showcase the potential for a calming and familiar medium and provide a knowledge base for selection of materials, mechanical appearance and behavior [107, 108, 31, 94, 43]. Studies on behavior nudging by robots also received attention from researchers worldwide. For example, a study by Fukuda et al. [28] revealed that a sense of unfairness may be inhibited by a robot touch, as well as the general conclusion that touch can enhance positive affect to the robot via HRI. Another study on behavior nudging showcased the potential of robotic touch for compliance[50].

3.2.3 Perception of robots capable of touch. Finally, the last research area of active robotic touch focuses on how the robot is perceived when touch is involved. For example, the study by Cramer et al. [20] delved into the implications of watching a toy humanoid robot interacting with a person with and without touch as well as with proactive and reactive robotic behavior. The results show that communicative touch can be applied to proactive robots to influence the perception of the robots as machine-like and dependable. Park and Lee [81] examined the effects of robotic skin temperature with a dinosaur-like robot. It is important to also mention a study conducted by Zheng [113]. The research delves into how a humanoid android capable of facial expressions should touch a person to convey a specific emotion. By systematically varying the type of touch, duration and the body part touched, the study found that a brief pat was perceived for a "happy" robot, while longer and more gentle hold best fit the "sad" robot. More recently, Ren and Belpaeme [88] demonstrated that the interpretation of robotic touch is not only shaped by the qualities of the touch itself but also by the surrounding context. Their findings underline that affective perception emerges from the interplay of haptic cues and situational framing, highlighting the importance of embedding touch within interactional settings.

3.3 Research Question

Despite growing interest in affective robotic touch, existing research has largely focused on anthropomorphic robots and morphology-specific gestures, leaving brief, directional nudges underexplored. A nudge is a gentle push, often with the elbow in human interaction. Yet it is a social gesture that does not depend on humanoid form. Its potential as a minimal communicative act, absent of linguistic, facial, or hand-based cues, has received little systematic investigation, though it is conceptually rooted in both philosophical discourse and artistic practice

This study investigates how robots that are devoid of facial features, screens, or speech can still communicate meaning through nudges. In this context, communicating meaning refers primarily to conveying intent and signaling social presence. Prior work has shown that movements designed with expressive qualities, rather than purely functional efficiency, can enhance users' perception of the robot and increase engagement [51]. Building on this, the present study considers not only how nudges convey intent but also how they may be interpreted affectively, capturing a broader spectrum of responses to robot behavior. The research question is as follows:

How are affect, intent, and agency perceived in nudging gestures initiated by a non-humanoid robot?

Studying abstract nudging offers a compelling case for a unique contribution to HRI because it pushes the boundaries of how robots can communicate without relying on human-like form or language. This paves the way for new directions for understanding how minimal, embodied cues like nudge can still elicit rich social meaning. It also provides insights into the above-mentioned 'robotiquette', and focuses on socially intelligent systems that are materially simple but communicatively expressive, making them potentially more accessible, acceptable and versatile in everyday environments. Such research expands the scope of social robotics by decoupling social interaction from anthropomorphic, encouraging designers to focus on the core dynamics of interaction, rather than mimicry.

4 DESIGN PROCESS AND IMPLEMENTATION

To fulfill the goals of this study, we developed a custom robotic platform on which the research was conducted. The platform was guided by the following design questions:

- What appearance and functional attributes does a robot need to be capable of delivering nudges?
- How can the robot's motion be designed to communicate both emotion and intent through nudging?

One of the crucial attributes of a robot capable of touch is its morphology, as shape dictates how physical contact is perceived. Since the robot was designed as an abstract form, any appearance could have been developed. We focused on simple geometrical shapes because they allow a wide range of projections and anthropomorphic attributions, while also aligning with the morphology of many existing robots, such as delivery robots and vacuum cleaners.

A simple geometrical shape was therefore chosen. Curved solids (sphere, cylinder, cone) would restrict physical contact, whereas polyhedra provide both edges and sides. Among these, the cube was selected for its simplicity and ease of implementation, offering sufficient internal space for hardware placement.

The present research builds directly on the lineage of Performative Body Mapping (PBM) by Saunders and Gemeinboeck [91]. The robot developed for this study shares the same underlying design as the one used in [91, 37, 38, 36], both in form and purpose. Developed under the supervision of Rob Saunders, co-author of PBM, the platform was created as a smaller-scale, portable version of the original robotic form used in PBM experiments. The physical structure is a geometric, non-humanoid body capable of expressive movement, retains the emphasis on abstraction and body constraint as generative design elements.

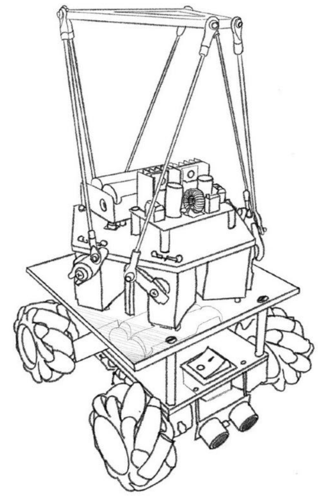

Figure 1: Technical drawing of the robot's internal design without the outer shell, showing the Stewart platform structure mounted on an omnidirectional wheeled base.

4.1 Physical structure

The robot was designed to satisfy two requirements that follow the design question:

1. enable controlled, safe touch gestures against the participant forearm; and
2. render expressive motion cues that remain legible at a tabletop scale.

As shown in Figure 1, a Stewart-Gough platform actuates a 25 cm cubic shell, providing 6-DoF for local expressive movement (x-y-z translation, pitch, roll/yaw), while a four-wheeled omnidirectional base supplies global x-y translation and yaw for precise approach. The simple geometric form and uniform, smooth, white surface are deliberately neutral when static, yet highly projectable during motion, encouraging diverse anthropomorphic readings without prescribing any specific character. Although texture can meaningfully shape human–robot touch perception [52], it was excluded here to narrow scope and is discussed as a future design direction. For consistent execution of touch gestures across trials, we integrated a front-facing ultrasonic sensor, which necessitated designing a "front" on an otherwise symmetric body (full technical specifications are provided in Appendix A).

4.2 Software development and user interface

The development of the software and user interface was guided by the two goals:

1. nudges have to appear organic and natural within the constants of the robot morphology; and
2. the gestures have to be digitalized in a way that enables accurate and repeatable robotic movement.

For the most part, Arduino runs a software that includes only pose-to-actuator inverse kinematics mapping and real-time velocity control for the omnidirectional base. During the initial development phase, the robot's movement parameters were mapped to a joystick connected to the laptop, which transmitted axis values to the Arduino; these values were linearly scaled to control the speed and direction of the omnidirectional base. However, drawing on the methodology of Saunders and Gemeinboeck [91], Anderson-Bashan et al. [3], Sirkin et al. [98], and Hu et al. [51], achieving an organic interaction between the abstract robot and a human requires expert knowledge of movement. This knowledge is best communicated through means that allow the expert to express motion naturally, thereby preserving the intended quality of the gesture.

Saunders and Gemeinboeck [91] invited professional dancers to wear a simple cube-shaped costume. This method resulted in highly expressive motion. While the robot's cubical shell in their study measured 75 cm, the robot used in the present study is one-third that size. As such, the design no longer accommodates this approach.

While dancers are trained to project kinesthetic expression through their own bodies, designing movement for a non-humanoid tabletop robot requires expertise in animating an external object. For this reason, specialists such as puppeteers or animators, who are skilled in giving expressive motion to inanimate forms, are more appropriate. A 3D animator was therefore recruited, contributing both technical knowledge and creative insight to the development of expressive movement for the abstract robot.

Following an initial meeting with the designer, during which the goals of the project were outlined, an appropriate user interface was selected to facilitate the seamless transfer of movement knowledge from the expert to the robot.

4.2.1 User Interface system. To achieve the set goal of accurate translation of expert model manipulation into repeatable robotic movement to accommodate the high sensitivity of touch, the interface required precise motion tracking. For the movement design process, the expert had to manipulate a physical model of the robotic shell, while both its position and orientation had to be recorded. Rotational values were reliably obtained from the IPad's motion sensors, while translational data was estimated using a computer vision system. A ChArUco board [2] was selected for this purpose,[1] as it supports robust and accurate estimation even when partially occluded.

To make the interface comfortable for the expert, the camera was mounted on the underside of the model, facing downward at the ChArUco board placed beneath a glass surface, as shown in Figure 2. This ensured tracking continued even when the model was resting on the table. To ensure feasibility, the animator was provided with defined movement boundaries representing the robot's maximum range of motion.

Although the initial plan was for all gestures to be executed using only Stewart-Gough platform alone, the expert found that the wheel movements were necessary to create more natural and contextually realistic touch gestures. To achieve this, joystick control was added for the mobile base and operated by an assistant under the animator's instructions.

[1] A ChArUco board combines ArUco markers with a chessboard layout. The markers uniquely identify each square, while the checker pattern provides precise corner detection. This hybrid design enables robust calibration even when parts of the board are occluded or viewed under perspective distortion.

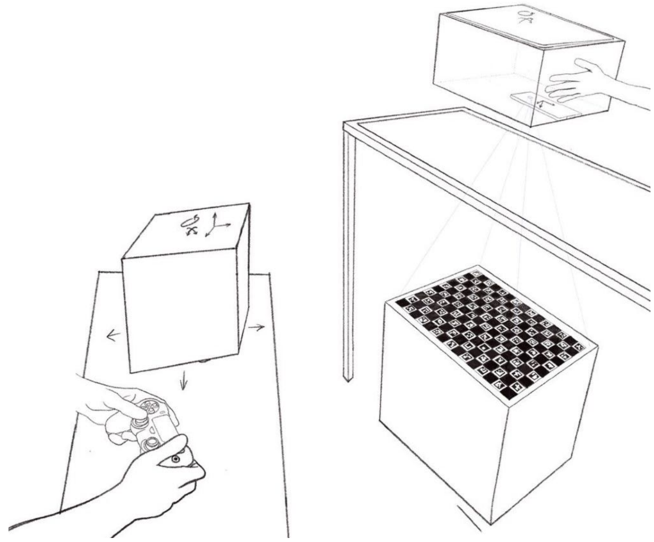

Figure 2: System setup showing the cube-shaped robot controlled via joystick (left) and the camera-based tracking system using a ChArUco calibration board (right).

The final interface thus combined computer vision (translation), motion sensing (rotation), and joystick input (base control). This allowed the robot to replicate the expert's manipulation of the model in real time and enabled recording of the expressive gestures for later replay during the experiments in the form of serial data stream, with each line containing 10 control values (six for the platform and four for the base). For full implementation details of the UI system, see Appendix B.

4.3 Gesture design

To develop gestures that enable the interpretation of intent and emotion, they must be designed with such qualities in mind. This is not strictly necessary, as prior studies have demonstrated that abstract touch can also invite interpretation [113]. However, in order to investigate the potential of touch as a communication channel, it is important to encode certain information into the gestures, so that the degree of congruence between what is expressed and what is interpreted can be examined.

4.3.1 Emotion and intent selection. Several intents were selected based on the communicative nature of nudging. As noted earlier, a nudge is an act of pushing someone or something gently, often with the elbow, to attract attention. Accordingly, the first and most fitting intent is getting attention. A nudge can also signal a need to pass; therefore, taking space was also included, as in the first part of the study. Drawing from animal behavior, domestic animals often use nudges to solicit petting or comfort [92], inspiring the inclusion of seeking comfort. Finally, a no-intent condition was added to serve as a baseline, representing a gesture designed without any underlying communicative goal.

When selecting emotions for the robot to express, the goal was to minimize confusion between different emotional states. To achieve this, five emotions were chosen based on the valence–arousal model of emotion, representing points that are furthest apart in this space. These are: excited, content, angry, and sad. This provided four emotions that are equally distinct from one another, plus a fifth that serves as a baseline: neutral. In the context of neutral or absent emotion, the movement can also be classified as functional or instrumental. Bossema, Saunders, and Allouch [9] make a similar distinction in their methodology, separating expressive and functional movements. In their design, functional movement differed from expressive movement by restricting the robot's motion to linear speed and straight paths. A comparable approach is applied in the present study.

4.3.2 Design sessions. An animation designer with expertise in 3D animation was recruited for the study. Following an initial meeting in which the designer was briefed on the research goals and session tasks, a total of five sessions were conducted. The first session was primarily devoted to training, familiarization with the interface, and gaining an understanding of the robot's capabilities. To accommodate the four selected intents across the five affect categories described above, a total of 20 gestures (5 affects × 4 intents) were developed. Each gesture was discussed and rehearsed before recording, with additional discussion focusing on their characteristics in terms of Laban Movement Effort qualities.

All gesture testing and recording was carried out using the system described in Section 4.2.1. The designer manipulated a physical model of the robot's shell to control the Stewart platform, while instructing an assistant to operate the wheel base via joystick. The robot reproduced these combined movements in real time. For emotionally neutral movements, only base navigation with linear speed was employed. For no intent gestures, the robot would move around the participant arm and occasionally bump into it a few times (once or twice, depending on the emotion).

During the design process, the animator did not have an object to touch with the model, as this would have restricted the possible range of movements. Instead, while manipulating the model, the animator simultaneously observed the full-scale robot performing the corresponding motion, including making physical contact with the researcher's arm. The researcher acted as a stand-in participant, providing immediate feedback on the tactile qualities of the robot's touch (e.g., presence, lightness, strength). This ensured that the gestures were refined based on the robot's actual physical output. Once the designer was satisfied with a gesture, it was recorded and replayed for final quality evaluation.

4.3.3 Laban Movement. Developed by Rudolf Laban, Laban Movement Analysis (LMA) is a system that offers a comprehensive and structured approach to the representation, analysis, and interpretation of movement [14]. LMA's components make movement qualities accessible both to movement experts and researchers.

As Burton et al. [14] note, LMA serves as a bridge between human emotional movement and computational movement recognition and generation, providing a way to translate subjective, artistic descriptions of movement into a structured framework that can be implemented in code. Building on this approach, a large language model (LLM) was prompted with descriptions of all 20 gestures in Laban terms. These outputs were then compared with the animator's own descriptions, and any inconsistencies were discussed and resolved through reasoned argumentation, ensuring that the final movement specifications were clear and consistent.

5 EVALUATION STUDY

This section describes the methodological approach of the study, detailing the development of the experimental design, participant recruitment, materials, and data collection procedures.

5.1 Study overview

Since this study focuses on the role of robot-initiated touch, it is important to account for the many overlapping factors that shape perception in human–robot interaction. In the case of an abstract robot, elements such as appearance, texture, movement, contact location, speed, force, temperature, sound, and proximity all contribute to how touch is experienced and interpreted. These layers offer valuable insight but also present challenges for experimental control.

To balance ecological validity with analytical clarity, the study is structured in two parts. One isolates touch as a designed gesture, while the other explores it as part of a situated interaction. This dual approach allows for both focused examination and contextual understanding of how touch-based behaviors from non-humanoid robots are perceived.

5.1.1 Naturalistic Interaction Study - Situated nudge in interaction. The first part of the study explores situated nudge, where the robot and participant share space for about three minutes while negotiating its use. This part contributes to answering the main research question by addressing the following sub-questions:

(1) To what extent do participants attribute agency to a non-humanoid robot that physically nudges them during an embodied goal-oriented interaction?
(2) To what extent do participants' interpretations of the robot's sequence of gestures, embedded in the broader interaction context,align with the intended design?
(3) Does robot-initiated touch in a nudge interaction result in measurable emotional change in the participant?

5.1.2 Gesture Interpretation Study - Isolated Gesture Evaluation. Isolated touch is explored in the second part. Here, the participant is presented with a touch observation, where context and non-touch-related movement are stripped from touch interaction. This part contributes to answering the main research question by addressing the following sub-questions:

(1) To what extent do participants interpret pre-designed, animation-inspired nudges from a non-humanoid robot as expressing the intended affect and intent?
(2) How do individual factors from Part 1 influence how closely participants' interpretations in Part 2 align with the intended affect and intent?
(3) How does participants' confidence in their interpretations relate to the extent to which those interpretations align with the target affect and intent, and how is this confidence shaped by gesture type and individual factors?

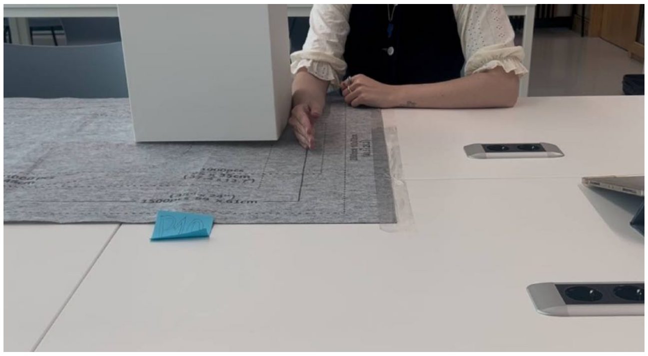

Figure 3: Experimental setup during the evaluation study, showing a participant blocking the cube-shaped robot's movement with their arm.

5.2 Participants

24 participants were recruited (mostly graduate students; aged 20–24: 41.7%, 25–34: 50.0%, and 35–44: 8.3%; 14 female and 10 male). All participants received an information sheet and signed a consent form prior to participation. They completed a demographics questionnaire at the start of the session. The questionnaire included items on age, gender, dominant hand, sensitivity to touch, neurodivergence, and prior experience with robots. At the conclusion of the study, a debriefing form was provided. The entire experiment was conducted in English.

5.3 Materials

Apart from the robot and the communication system used to control it, the setup included a rectangular piece of felt placed on the table, marked with several parallel lines. The lines indicated where the participant's arm should be positioned. A tripod-mounted camera was used to record the interaction for the post-interaction think-aloud protocol. For data collection, a Qualtrics survey was displayed on an iPad, through which participants completed questionnaires and recorded their responses.

5.4 Procedure

5.4.1 Situated nudge. Participants and the robot shared a physical space, with participant's forearm positioned as an obstacle on the table as showing in Figure 3. Drawing on the methodology of Sirkin et al. [98], the Wizard-of-Oz set up was implemented, where the researcher controlled the robot from behind while monitoring the feed of the camera situated in front of the participant. The robot approached along a fixed path and, upon encountering the arm, performed a sequence of three escalated nudges: an introductory content attention-seeking gestures, followed by two space-taking gestures (first content, then angry). These were designed to increase in emotional intensity while decreasing in valence. The sequence ended when the participant moved their arm or after the third gesture, after which the robot navigated around the participant's forearm.

The interaction was video-recorded and used in retrospective think-aloud protocol. While reviewing their interaction, participants first described what they believed had happened, and were later asked in a semi-structured interview about the robot's goals, intentions, and emotions. Pre- and post-interaction questionnaires included demographics, Positive and Negative Affect Schedule (twice) [106, PANAS], Robotic Anxiety Scale (before) [75, RAS] and Robotic Social Attributes Scale (after) [16, RoSAS], allowing measurement of affective shift, social perception and potential influencing factors.

5.4.2 Isolated nudge. This phase isolates touch-based gestures for systematic evaluation. Each participants observed five randomized gestures, drawn from pool of 20 affect-intent pairs, ensuring balanced representation across the 24 participants (120 gesture trials total). After each gesture, participant identified the robot's intent from a multiple-choice options, assessed the affect (inc. dominance) of the robot using an adapted SAM scale [10]. After assessment of each aspect, participants were also asked to rate their confidence in the interpretation.

To ensure validity, intent recognition questions included two distractor options: *trying to guide* and *testing boundaries*. Both are space-related, making them plausible alternatives to the true intents, but differ in meaning, where one emphasizes functional coordination and the other more social probing. Their inclusion hindered the possibility of correct answers achieved through elimination, while enabling stricter testing of whether the robot's intended signal was clearly distinguished from other plausible interpretations.

6 FINDINGS

We conducted a first-person study, combining qualitative and quantitative methods, to evaluate how participants interpret minimal touch gestures from an abstract robotic object in both situated and isolated contexts of touch. The following section details the study results, organized by the type of touch evaluated.

6.1 Overall Robotic Anxiety

The average robotic anxiety score was 27.7 (SD $\approx$ 8.8, range 14–41) out of 66, placing participants in the lower-mid range. Subscale means were 7.08 for S1 communication capacity (SD $\approx$ 2.9, range 3–13), 10.71 for S2 behavioral characteristics (SD $\approx$ 4.0, range 4–17), and 9.92 for S3 discourse with robots (SD $\approx$ 4.6, range 4–21), with S1 and S3 both below their respective midpoints.

6.2 Situated nudge

6.2.1 Alignment of Interpretation with Intended Intent. There were five main interpretations of the robot's intent, often overlapping or shifting during the interaction. Many participants saw the robot as attempting to initiate contact (P1, P4, P10, P11, P13, P14, P15, P19), describing it as *"trying to say hello"* (P11, also P12, P19), *"trying to become friends"* (P10), or even *"like a puppy ... trying to understand where the arm was"* (P4). Others felt it was deliberately holding their attention (P2, P3, P5, P6, P13, P19), described as *"light nudges to get a reaction"* (P5) or *"to get my attention ... to build familiarity"* (P13).

A large share interpreted the robot as pragmatically trying to pass their arm. This was conveyed through pushing, climbing, or redirecting strategies when blocked. For some, the goal became clear only after repeated attempts—P17 noted, *"At first I thought it was playful ... but then going around is like, ah, you were trying to go* *around."* Others (P3, P6, P8, P12, P19, P22) immediately recognized the navigational aim.

A smaller but notable theme was boundary testing (P14, P15, P18, P20, P24), where the robot seemed to probe limits or assert its own "personal space." P14 observed that *"when it started to get wild, it felt more like trying out to see what my boundaries are,"* while P15 described the reverse: *"closer to the end ... it made it clear it doesn't want to be touched by me."* Related to this, several participants also framed the robot as curious or playful (P2, P4, P7, P12, P16, P17, P18), sometimes with an ambiguous edge—P7 remarked, *"I feel like it was curious at me and also maybe trying to intimidate me."*

Attribution of the intended design goal (space-taking, obstacle recognition, or prompting to clear the path) was assessed both in interviews and written responses. One third identified the intended behavior in writing, compared to half during interviews, where the navigation goal was more often made explicit. Responses were coded into two categories: those mentioning the target intent and those that did not.

Negative affect (PANAS) correlated with perceiving the robot as trying to pass, both before the interaction ($r = -.43, p = .046$) and after ($r = -.47, p = .027$), although the change in negative affect was not significant. Other measures—robotic anxiety, social attribute scores, prior experience, touch sensitivity, neurodiversity, and demographic variables—showed no significant association with intent attribution or obstacle recognition (lowest $p = .06$).

6.2.2 Alignment of Interpretation with Intended Emotion. Four participants (P1, P11, P16, P20) denied any emotional charge or gave unclear attributions. Most others not only described emotions but also noted shifts in the robot's behavior, from cautious to assertive or from passive to active. Although asked explicitly about emotion, many responses went beyond canonical categories, using broader descriptors such as curiosity, shyness, or caution at the start of the interaction (reported by several participants). P14 observed that the robot *"got a bit more confident... like a baby animal... at first careful."*

Confidence often developed into either excitement and playfulness (P1, P4, P10, P14, P15, P18) or frustration and urgency (P2, P5, P6, P7, P8, P12, P17, P18, P19, P20, P22, P23, P24). Excitement was typically linked to the robot becoming more comfortable through repeated contact, while frustration emerged from unsuccessful attempts to get past the obstacle. This shift was described as a growing insistence: *"more urgency... more insistent"* (P6), *"got frustrated... trembling... more intimidating"* (P7), or *"felt more angry... frustrated I'm not moving"* (P8).

Mentions of aggression were common but usually qualified as non-threatening. For example, P18 remarked the robot was *"a bit upset... but cute, not threatening"*, while P22 noted it was *"frustrated, but not negative... did not try to hurt me."*

6.2.3 Agency Attribution. Agency attribution emerged from both quantitative and qualitative analyses. On the Robotic Social Attributes Scale (RoSAS), participants rated the robot moderately high in warmth ($M = 36$, $SD = 7.23$) and competence ($M = 34.7$, $SD = 8.51$), and low in discomfort ($M = 18.5$, $SD = 6.46$). The highest-rated traits were *interactive*, *social*, and *emotional* (6.7–7.2/9), while *awful*, *dangerous*, and *scary* were lowest (1.2–2.5). Mid-range scores included *strange*, *awkward*, and *aggressive* (4.2–4.6). Demographics showed no significant influence, except that neurodivergent participants rated the robot as warmer than neurotypical ones (Mann–Whitney $U = 27.0$, $p = .0317$, $r \approx .46$ see Figure 4).

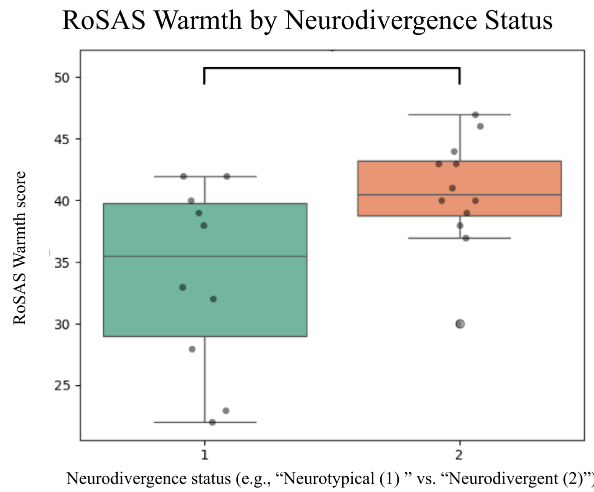

Figure 4: Comparison of RoSAS Warmth scores between neurotypical and neurodivergent participants.

Qualitative analysis focused on how participants described the robot's goals and intentionality. Responses were coded into three levels of autonomy: low, moderate, and high. Only one participant questioned whether a robot could ever have *"its own intention"* (P3) and was coded as low. Thirteen were coded as moderate, acknowledging some autonomy but emphasizing programming limits (P1, P2, P8, P11, P12, P13, P14, P15, P19, P22, P23, P24). For example, P11 noted there were moments they forgot they were *"interacting with a machine"* (similar with P1, P8). Others described *"responsiveness agency"* (P13, similar with P2, P14) or persistence reminiscent of pets or friends (P19, P15). Ten participants attributed high autonomy (P4, P5, P6, P7, P9, P10, P16, P17, P18, P21), often remarking that the robot seemed aware of their position, capable of navigating around them, and responding to gestures in ways that felt *"unpredictable, alive, and organic."*

The autonomy coding showed no significant relationship with robotic anxiety, social attribute ratings, emotional shift, demographics, sensitivity to touch, robotic experience, or neurodiversity.

Animal or child-like framing. Many participants compared the robot to animals — especially puppies, dogs, kittens, or cats — or to children. Some stressed both qualities (P1, P14, P17), framing it as simultaneously pet-like and child-like, underscoring how agency was understood through familiar social categories.

6.2.4 Effect of the interaction on the participants emotional state. On average, overall emotional state measured by PANAS increased by 4 points ($SD = 6.2$, range −6 to +23). A one-sample t-test confirmed this shift was significantly greater than zero, $t(22) = 3.08$, $p = .005$, $d = 0.64$, 95% CI [1.31, 6.69]. Positive affect rose by 1.83 points ($SD = 4.63$, range −8 to +13), but this was not statistically significant, $t(22) = 1.89$, $p = .072$. Negative affect decreased by 2.17 points on average ($SD = 2.96$, range −10 to +3), a statistically significant reduction, $W = 13$, $p = .0014$, with a large effect ($r = -.66$). Because this distribution violated normality, a Wilcoxon signed-rank test was applied.

Demographics and sensitivity to touch showed no effects. Robotic experience was associated with overall emotional change, $H(3) = 9.64$, $p = .022$, though post-hoc Dunn–Bonferroni tests revealed only a difference between participants with some experience (Group 3) and those with extensive experience (Group 4; $p = .022$). Self-reported neurodiversity did not significantly influence emotional balance ($t = -0.66$, $p = .518$) or negative affect change ($U = 81.0$, $p = .053$). Age group was associated with negative affect, $H(2) = 7.42$, $p = .025$, but no pairwise comparisons survived correction (all adjusted $p \geq .075$). Finally, robotic anxiety and social attribute scores showed no significant associations with emotional shift.

6.2.5 Reflections and Decisions Around Touch. Several participants described how the interaction made them reflect on touch and embodiment. P2 wondered *"how fingers would react to the robotic nudge,"* while P6 was struck that *"a simple cube could communicate urgency,"* highlighting the expressive power of touch. P12 asked themselves *"how to deal with this?"* when the robot became more dominant, linking it to agency and aggression. P17 emphasized the importance of touch in general, contrasting robotic contact with human or inanimate touch. P19 reflected on both possibilities and risks, noting the robot's unexpected strength and comparing it to homemade machines or to animals and people. Finally, P21 remarked they would feel less attached if the robot only moved around without touch, since *"it was the barrier that gets broken where you kind of get this sentient attachment."*

Participants also considered whether to move their hand during nudging. Some kept their arm steady, either to avoid interfering or due to uncertainty about what was expected (P4, P6, P7, P17). Others left their hand in place out of curiosity, wanting to see whether the robot would return, how firmly it would make contact, or what it was capable of (P3, P9, P19, P22). A smaller group reported interactive strategies such as mirroring movements or lightly petting the robot (P5, P10, P15), while some actively tested the system by repositioning their hand or pushing back against perceived dominance (P12, P13, P14). One participant compared this choice to interacting with an animal, preferring to stay still and let it *"sniff them out"* (P18). Only P11 explicitly reported removing their hand, describing it as *"a way to test the machine out of curiosity."*

6.3 Isolated nudge

Overall strict accuracy of both intent, valence and arousal is 0%. Strict intent (selected options) accuracy is 22.5% , while strict emotion accuracy (both valence and arousal exactly right) is 3.3%.

6.3.1 Intent accuracy. The confusion matrix (Figure 5) shows that participants most often confused seeking comfort with seeking attention. While seeking attention was recognized relatively clearly, seeking comfort and taking space were frequently mismatched for one another or for attention-seeking. The "no intent" category was rarely perceived as such, with most participants attributing some form of intent to the robot. Responses coded as "other" included interpretations such as *"starting a fight," "explaining something," "dancing,"* and *"playing with me."*

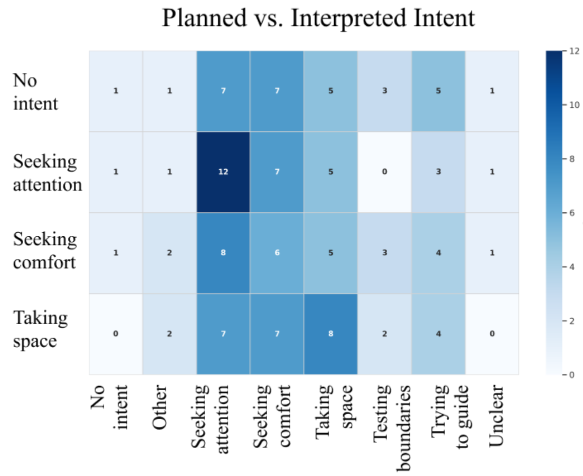

Figure 5: Planned vs. interpreted intent confusion matrix. Darker colors indicate more frequent interpretations.

Seeking attention was the most consistently attributed label (12/30 cases, 40%), yet no single intent was recognized above chance after correction ($p > .20$). To simplify analysis, intents were grouped by goal: navigation-driven (taking space, guiding, testing boundaries), socially-driven (seeking attention, seeking comfort), and no intent (unclear, no intent). Although boundary-testing could be framed socially, it was coded as navigation-driven for clarity.

Accuracy at the group level rose to 43.3%. Socially driven intents were correctly identified 35 times, misclassified 20 times as navigation-driven, and three times as no intent. Navigation-driven intents were almost evenly split (15 congruent, 14 incongruent). Nudges with no intention were never classified as navigation-driven but were more often mistaken for socially driven than recognized as accidental. For confusion matrix of planned vs. interpreted intent gestures, see Appendix C.

Intent accuracy did not significantly relate to the intended valence–arousal targets. However, accuracy varied by emotional state. For the Sad condition (low arousal, negative valence), participants most often aligned with the intended class (54.2%, 95% CI [.33, .74]), significantly above chance ($p = .002$). Angry (45.8%) and other states (Excited, Content, Neutral: 37.5–41.7%) did not exceed chance after correction.

Finally, we tested descriptive factors, including demographics, PANAS change, RAS subscales, and RoSAS dimensions. A moderate association emerged with perceived robot competence ($r = .50$, $p = .012$; $\rho = .53$, $p = .008$), suggesting participants who rated the robot as more competent were somewhat more accurate in intent attribution. This effect did not survive correction, and no other reliable relationships were observed.

6.3.2 Emotion accuracy. Overall, participants' ability to correctly identify the intended emotion was low. Exact-match accuracy was 16.7% for valence, 12.5% for arousal, and 3.3% for both dimensions,

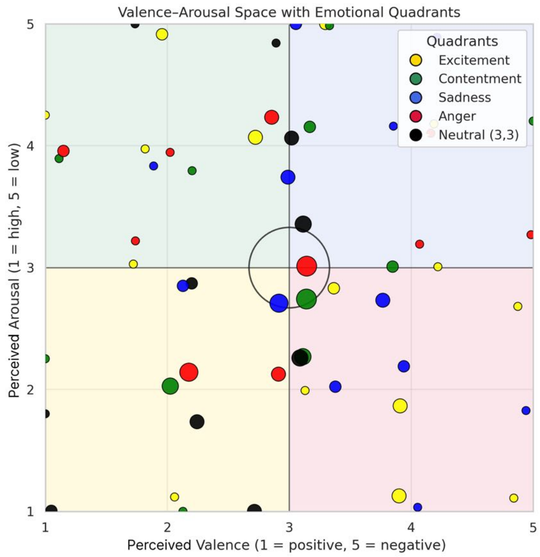

Figure 6: Distribution of participants' perceived emotion in the valence–arousal space. Each circle represents a response, positioned at the participant's reported integer valence and arousal. Circle color indicates the intended target emotion of the robot. To display coincident circles from identical integer responses, a small random jitter was added; as a result, the figure appears continuous, but underlying data are discrete and should be interpreted with this in mind.

with none above chance ($p > .70$). Allowing a ±1 tolerance improved accuracy only modestly (valence = 39.2%, arousal = 40.0%, both = 17.5%), still not significantly above chance. Accuracy was strongly skewed toward the neutral condition (valence = 87.5%, arousal = 70.8%, both = 66.7%, $p < .01$), while recognition of emotionally loaded states remained poor. Figure 6 visualizes this distribution in the valence–arousal space, showing responses clustered near the neutral reference point and dispersed across quadrants for other emotions. To reduce overlap, a small random jitter was added to individual data points, so the figure should be interpreted with caution.

To complement binary accuracy, recognition was assessed using mean Euclidean deviations. Excitement ($M = 3.34$, $SD = 0.82$) and anger ($M = 3.15$, $SD = 0.78$) were least accurately recognized, followed by contentment ($M = 2.97$, $SD = 0.77$). Sadness ($M = 2.71$, $SD = 0.75$) and especially neutral ($M = 1.31$, $SD = 0.83$) showed smaller deviations, indicating relatively higher accuracy. We also examined intent–emotion pairs; the largest mismatches occurred for seeking comfort–anger (Euclidean = 3.66), taking space–excitement (3.31), and seeking comfort–contentment (3.18) (see Figure 7 in Section **??**).

Descriptive factors were also explored. Arousal accuracy correlated negatively with the behavioral characteristics subscale of the Robot Anxiety Scale (S2; $r = -.51$, $p = .011$) and positively with perceived robot competence ($\rho = .51$, $p = .010$). Valence accuracy was positively related to RoSAS Competence ($r = .44$, $p = .030$). None of these effects survived correction for multiple comparisons.

6.3.3 Dominance. We first examined whether dominance ratings reflected the design parameters of the gestures. Correlational analyses showed no association between target arousal and dominance ($r = -.03$, $p = .73$; $\rho = -.03$, $p = .72$) or between target valence and dominance ($r = -.07$, $p = .48$; $\rho = -.09$, $p = .35$). A Kruskal–Wallis test likewise revealed no differences across planned intents ($H = 0.55$, $p = .91$, $k = 4$). Analyses within mapped emotional categories also showed no differences (all $p > .42$). Thus, dominance impressions were not systematically shaped by valence, arousal, or intent.

We next tested whether dominance predicted participants' interpretations. Correlating dominance with emotion recognition error showed no association ($r = -.03$, $p = .76$; $\rho = .02$, $p = .87$). Mann–Whitney U tests also found no differences in dominance for correct vs. incorrect intent recognition, both at the strict intent level ($U = 1153.50$, $p = .51$, $n_{\text{correct}} = 27$, $n_{\text{incorrect}} = 93$) and for broader intent categories ($U = 1486.00$, $p = .39$, $n_{\text{correct}} = 42$, $n_{\text{incorrect}} = 78$, $r = .09$).

At the participant level, aggregated dominance ratings showed no reliable correlations with PANAS change scores, RAS subscales, or RoSAS dimensions (all $|r| < .30$, all $q_{\text{FDR}} > .48$). Demographic variables, including age, gender, robot experience, and background, were also unrelated. The only nominal effect was a positive correlation with self-reported sensitivity to touch ($\rho = .47$, $p = .020$), which did not survive correction ($q_{\text{FDR}} = .49$).

Finally, dominance was related to emotional impressions. Interpreted arousal correlated modestly and negatively with dominance ($r = -.25$, $p = .005$; $\rho = -.28$, $p = .002$), indicating that gestures perceived as more arousing were judged as more dominant. Interpreted valence and dominance were unrelated ($r = .09$, $p = .33$; $\rho = .10$, $p = .27$). Overall, dominance emerged as a perceptual dimension largely independent of design parameters and recognition accuracy, with only limited links to arousal judgments.

6.3.4 Confidence in interpretation. Confidence ratings showed only limited alignment with accuracy. For valence, confidence was marginally higher on correct than incorrect trials ($U = 1251.0$, $p = .073$, $r_{rb} = .25$) and weakly negatively correlated with absolute error ($\rho = -.16$, $p = .079$). Arousal judgments showed no effects (all $p > .50$). Confidence in intent classification likewise did not differ by accuracy ($U = 1489.0$, $p = .409$; AUC ≈ 0.455).

Calibration analyses indicated systematic overconfidence. Mean confidence exceeded observed accuracy by 0.2–0.3, with Expected Calibration Errors from 0.186 (valence, soft) to 0.552 (valence, strict), and Maximum Calibration Errors up to 0.488 (arousal). Regression slopes and rank correlations between confidence and performance remained small and non-significant (all $p > .30$).

Confidence was not influenced by the robot's design parameters. Kruskal–Wallis tests showed no differences across intended behaviors (valence: $H = 1.07$, $p = .586$; arousal: $H = 0.15$, $p = .928$; intent: $H = 2.30$, $p = .316$) or emotional levels (all $p > .52$). Correlations with design values were uniformly weak ($|\rho| \leq .13$). By contrast, confidence measures were strongly interrelated, showing positive correlations across valence, arousal, intent, and dominance ($\rho = .43$–$.61$, all $p < .001$).

7 DISCUSSION

In this work we set out to explore how affect, intent and agency are perceived from a non-humanoid robot initiating nudging gestures. By examining both situated and isolated nudges, our study revealed not only whether participants aligned with the intended design but also how they spontaneously made sense of the rich quality of robotic touch. While our focus was on how participants attributed designed behaviors to the robot's nudges, we position this study as highly exploratory. Philosophical considerations of embodiment remind us that impressions arising from physical interaction are inherently unpredictable, and that meaning emerges in encounter [35] in ways that cannot be fully controlled by design.

Our clearest finding is emergence of agency. Our white box was considered quite warm and competent, while only mildly discomforting (See Section 6.2.3). Participants saw it as an interactive, social and emotional robot, that was a little strange, awkward and sometimes even aggressive. An interesting side note is that neurodivergent participants rated the robot as warmer than neurotypical ones. With our small sample this should be taken cautiously, but it hints that individual differences may systematically shape perception. Initially, self-reported neurodivergence was recorded to explore whether participants with conditions such as the attention deficit hyperactivity disorder (ADHD), post-traumatic stress disorder (PTSD) depression, autism, anxiety or Asperger's differ in how they attribute agency and intention, as prior research shows that people with depression experience a reduced sense of agency [84], those with PTSD show disruptions in bodily self and attention [86], and autistic individuals attribute intent and emotion less automatically [15], while neurotypical individuals tend to ascribe agency more readily and consistently. However, since we did not analyze each subgroup separately and instead treated neurodivergence as an overall influencing factor, the results diverged from the expected direction. It is also possible that self-reported neurodivergence, without clinical verification, limited the precision of this measure. While HRI research often focuses on specific neurodivergent groups, our approach shifted toward tracking neurodiversity as a broader self-reported measure, which makes direct comparisons more difficult but also highlights a less explored methodological direction in the field.

Most participants saw the robot as having moderate autonomy, often due to the incongruence of perceiving an animate object as agentic. A slightly smaller group saw high autonomy in the robot, typically explained through a simple anthropomorphic projection or by the attribution of responsiveness. Strikingly, only one participant denied the cube any autonomy, suggesting that even a minimal abstract robot was generally convincing in projecting independent intention. This is in line with the classic study by Heider and Simmel [45], and with more recent work in HRI [3, 9]. Our work also aligns with recent perspectives that emphasize the relational making of human–robot relationships through embodied encounters, as discussed by Gemeinboeck and Saunders [35]. From this view, the cube's perceived autonomy was not simply designed into it but emerged through the dynamics of interaction. From a design perspective, this highlights both the power and the risk of motion-based cues: minimal robots can project autonomy in ways that exceed designer control, highlighting the inherently co-constructed nature of agency attribution.

The attribution of agency was measured during the first part of the study, where a Wizard-of-Oz protocol was used as the main interaction method. Beyond the inherent variability of this approach, stemming from the inconsistency of human opposed to machine behavior, the interaction itself depended on the operator's decisions, which directly influenced participants' experiences. This raises questions about the consistency of the robot's reactivity to participants' actions, as well as the philosophical boundary between the robot's agency and that of the operator, a recurring issue in Wizard-of-Oz research. In this study, the operator was also the researcher, meaning that all non-touching movements were carried out without motion expertise and thus less aligned with the research's focus on expressive movement. This highlights a methodological issue: not only how much "human-in-the-loop" is required in such interactions, but also what expertise that human should bring. In our case, non-touching movements were deliberately constrained to linear speed without tilting or pitching, in order to isolate expressive movement from the influence of touch. Nevertheless, even under such constraints, robotic motion should ideally be guided by a motion expert who can extend their embodied understanding into the robot's form, thereby ensuring more organic and coherent behavior.

Nevertheless, if agency was readily attributed, the next question becomes what participants believed this agency was directed toward, what they thought the robot wanted. In contextualized nudge interaction, about half of the participants eventually recognized the obstacle-passing goal in interviews, compared to one third in short written statements (see Section 6.2.1). Interviews invited richer narratives in which pragmatic intent surfaced over time, whereas the compressed format of written statements led them to foreground social interpretations. This suggests that in situated touch, social meaning was more immediately salient, while pragmatic intent required more reflective elaboration. Our findings complement work on functional robots by showing that while preferences may favor pragmatic intent in those contexts [17], an abstract form without prior framing leads participants to perceive and emphasize social intent instead. The half of the participants that still recognized the design goal indicates that touch can indeed contribute to intent communication when embedded in interaction.

By contrast, when nudges were presented without context, participants struggled to recognize the designed intent (see Section 6.3.1). The most accurate interpretation fell on the attention-seeking intent, which aligns with the inherent nature of a nudge, but overall accuracy was low. Participants were more successful at recognizing coarse categories than fine-grained goals. This suggests that abstract nudges are more effective at conveying general orientations of behavior, though this interpretation requires further testing. Without contextual cues, intentional and unintentional nudges were rarely distinguished. This likely reflects the study design: without preceding or concurrent actions from which accidental contact could plausibly arise, participants had no cues to treat the nudge as unintentional.

While no descriptive data reliably predicted alignment of interpretation with the intended design, a tentative trend suggested that higher perceived competence was linked with greater intent recognition, hinting at basic theory-of-mind processes. Affect also appears to shape intent attribution: gestures designed with sad emotion yielded somewhat better alignment, perhaps because intensity made social and navigational gestures easier to distinguish or because sad emotion is just more appropriate in the context of all intents. These trends, however, require confirmation with a more diverse and larger sample.

Moving on to affect recognition, participants often described the robot's emotions during interaction as evolving from shy to assertive and finally to aggressive, though rarely threatening, or even excited (Section 6.2.2). This trajectory mirrored the designed sequence of two content nudges followed by an angry one: notably, the first intent was attention-seeking behavior followed by two space taking intents. This suggests that perceived emotion was inseparable from the underlying goal of the nudge and shaped by the sequential build-up of actions, aligning with observations of Ren and Belpaeme [88].

In the isolated nudge observation task, affect recognition was generally poor (see Section **??**). Neutral affect was most reliably identified, while high-arousal emotions such as anger and excitement were the least recognized. Sadness was somewhat clearer, which hints at a possible design flaw, in that high-arousal states were not conveyed as clearly as low-arousal ones. At the same time, it may reflect a broader limitation of abstract embodiment, where a cube-like form struggles to map onto highly intense emotions. On the other hand, this finding may also resonate with the work of Crucianelli et al. [21], who showed that slow velocity touch is perceived as more pleasant and increases subjective embodiment during a rubber hand illusion. By analogy, emotion attribution in our study may have been supported by participants' ability to reflect on their own bodily affect; the clearer they could mentalize their own emotional state, the clearer they were able to interpret the emotion of the robot. Considering further that the robot was frequently described as "cute" during the interaction scenario, it is plausible that this perception of cuteness paired naturally with a sad affect, making empathic attributions toward the robot easier for participants.

Intent also modulated emotion perception: incongruent intent-affect pairings reduced clarity, while sadness sometimes improved legibility by allowing participants to imagine plausible scenarios, as mentioned above. The strongest mismatches were found for seeking comfort–anger and taking space–excitement, both of which reflect inherent incongruence between intent and emotion in itself. These findings highlight how affect and intent jointly shape interpretation. By contrast, the case of contently seeking comfort most likely points to a pitfall in gesture design rather than interpretive bias.

Although exploratory, trends suggested that participants who perceived the robot as more competent were also more likely to align with the designed affect, while those with greater behavioral anxiety were less attuned to the arousal intensity (see Section 6.3.2).

Dominance impressions did not track designed valence or intent but correlated with perceived arousal, implying that dominance was inferred from the intensity rather than the direction of the gesture (see Section 6.3.3).

Confidence analysis showed only limited alignment with accuracy: participants were marginally more confident on correct than incorrect trials, though the effect did not reach significance (Section 6.3.4). Across domains, participants tended to be overconfident, with confidence rating exceeding observed accuracy by 0.25 on average. This suggest that while gestures were sufficiently clear to elicit confident judgments, the meaning of nudges could be interpreted in divergent ways.

The interaction led to a reliable overall improvement in participants' affective state, primarily through a reduction in negative affect (see Section 6.2.4). Participants felt less uneasy after the interaction, but not necessarily more energized. The observed reduction in negative affect is consistent with earlier work showing that touch can alleviate negative emotional states and support more positive experiences[112, 73, 8, 113, 40, 39, 110, 27, 100, 107, 108, 31, 94, 43, 28]. Interestingly, the effect was moderated by prior experience with robots: participants with some interaction history reported greater mood improvement than participants with extensive experience, suggesting that the affective impact of the nudges is strongest at an intermediate level of familiarity.

The situated nudge interaction often prompted participants to reflect on the broader meaning of robotic touch, as should in Section 6.2.5. Many were surprised that a simple, abstract cube could communicate emotion and urgency through minimal contact, which led them to consider the expressive potential of robotic touch. Others linked the experience to questions of agency and control, noting how even small nudges could evoke aggression, or care. The robot's unexpected strength was sometimes perceived as both a risk and a source of vitality, highlighting how robotic touch blurs boundaries between mechanical, animate, and social. Participants also actively negotiated their responses to the interaction. Some remained still in order not to interfere, others experimented with testing or mirroring its movements, and a few treated it like an animal to see how it would behave. These strategies reveal both ways of managing uncertainty and moments of play. One participant further remarked that touch, more than movement alone, created a sense of attachment, illustrating how contact can heighten perceptions of social presence or relational significance in a robot.

Taken together, these findings contribute to HRI research in several ways. First, they demonstrate that even an abstract, minimal robot can reliably elicit attributions of agency and autonomy, extending classic insights on minimal cues for animacy into the domain of embodied, touch-based interaction. Second, they show how context critically shapes interpretation; while isolated nudges were ambiguous, situated touch interactions foregrounded social meaning yet also allowed pragmatic intent to surface through reflective elaboration. Third, the results reveal that affect and intent are interpreted jointly, with emotional trajectories often inseparable from the perceived goals of the robot's actions. Fourth, by including self-reported neurodivergence, the study points toward a less explored but important methodological direction, highlighting that individual differences systematically shape perception and affective outcomes. Importantly, the methodology itself constitutes a contribution: the study was developed from scratch, combining the construction of an abstract cube robot with an animator-led movement design process, a Wizard-of-Oz interaction protocol, and a dual-task structure contrasting situated with isolated nudges. Finally, the work underscores that the expressive potential of robotic touch, even in minimal and abstract embodiments, can play a distinctive role in shaping how people perceive affect, intent, and agency, while raising methodological and philosophical challenges for the study of embodied interaction.

A reflection on the study design is necessary here. In the study, the gestures were designed with safety precautions, which reduced the intensity of some high-arousal pairs. While the force of the movements was already surprising and thought-provoking, increasing it could have improved congruence with the intended design but would have raised ethical concerns. This represents an inherent limitation of the research.

Further consequences of the study design include the use of a Wizard-of-Oz protocol, which introduced inconsistency, and the artificiality of a laboratory setting, which was less suited for studying natural interactions. Moreover, the study did not account for unintentional nudges, as the goal was to strip touch of contextual factors. Yet, intention versus non-intention in touch can only be decoded through context. This creates a tension between the attempt to isolate touch for analysis and the reality that touch can only be meaningfully interpreted within its ecological context.

8 LIMITATIONS

The limitations of the study then is encompassed in the methodological goal: to isolate touch from other influencing factors. Since the meaning of touch emerges within context, stripping it in the isolated scenario eventually resulted in insufficient cues for participants to confidently interpret the nudges. While for the interaction scenario, participants had some context to navigate, it is then hard to estimate how much the context influenced the outcome of the nudges.

A more classical limitation of this study is the small and homogeneous pool of participants. As mentioned in Section 2.3, gestures are culturally inscribed, rendering participants both socially legible and internally aware; therefore, including participants from different cultures could potentially shift the results to a large extent. Moving away from the WEIRD (Western, Educated, Industrialized, Rich, and Democratic) population would be highly beneficial in terms of general touch gesture interpretations.

Because the main goal of this study was to examine how the intent and affect of robotic nudges were perceived, participants were explicitly invited to reflect on the robot's agency. This framing means that the findings do not address whether participants would spontaneously attribute agency to the robot, but only how such agency was interpreted once it was made salient. As a result, the study should be read as an exploration of how agency was perceived rather than as evidence for the existence of agency attribution in an unprompted context.

9 FUTURE WORK

To address the limitation of the study in terms of influence of context on the overall results, touch could be studied in comparison with a context-only scenario. This way, the influence of touch can be evaluated in comparison to its absence.

From another perspective, touch could be studied in complete isolation, with participants deprived of sight and other contextual cues. In such a design, the focus would shift away from HRI toward research on touch perception more broadly. The robot's relevance would then lie primarily in its role as the object producing the tactile stimulation—functioning less as a social agent and more as an inanimate medium through which sensations are delivered. It is also interesting to examine differences in participants' interpretations when they are told whether the robot or a human with an external touching element is performing the movement. This would highlight bias and could also perpetuate robotic anxiety in general, as participants then lose almost all control within the interaction. Therefore, such a study should be carried out with high ethical standards.

Looking specifically at affect recognition, a study where one intent is presented with different emotional charges would also help to clarify the influence of affect without intent as a shaping factor.

Finally, in this study the robot's material and surface properties remained constant. Earlier work has shown that aspects such as texture, softness and roughness can influence how people form impressions of a robot [52, 103]. Future research could extend this work by examining how variations in texture, softness, or surface quality shape the way nudging gestures are interpreted.

10 CONCLUSIONS

This project examined how people make sense of affect, intent, and agency when an abstract robot initiates touch through nudging. Although the robot was nothing more than a cube, participants often described it as acting with intention. In the interaction setting, social meanings surfaced most readily, while pragmatic goals became apparent only after reflection. When gestures were presented without context, they were far harder to interpret, underscoring the role of situational framing. The interaction also influenced participants' mood, reducing negative affect and showing that even minimal robotic touch can alter the quality of an encounter.

The study contributes through its two-part structure that contrasted situated with isolated nudges, revealing different conditions under which meaning was made. It also included neurodiversity as a factor, with self-reported differences shaping some participants' perceptions, pointing toward an underexplored dimension in HRI. While the small and culturally narrow sample restricts generalization, the findings demonstrate that abstract robotic forms can still guide how people attribute affect, intent, and agency, highlighting the expressive potential of a nudge in human–robot interaction.

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APPENDICES

A Technical Implementation

The robot consists of a Stewart-Gough platform mounted on a four-wheeled omnidirectional base equipped with Mecanum wheels (Figure 1). The platform enables 6 degrees of freedom—translation along and rotation about the x, y, and z axes—while the base provides 3 additional degrees of freedom in the planar workspace (x, y translation and yaw rotation). Combined, the system affords a total of 9 degrees of freedom, enabling both precise local actuation and global mobility. It is powered by an Arduino and two pairs of batteries, which supply power separately to the base and the platform. Communication between the master laptop and the robot is facilitated via a Bluetooth module. Both the base and platform were custom-designed and laser-cut to meet the physical constraints of the intended robot form. The robot needed to support a broad range of expressive movements while remaining compact and tabletop-sized. Accordingly, the platform's dimensions were carefully chosen to match the shell.

The robot's shell is a 25 cm lightweight white plastic cube with one side left open. While the goal was to create a visually cubic robot, the shell had to be short enough to avoid collisions with the floor or internal components during motion, but tall enough to obscure the inner structure.

Just as in the study by Gemeinboeck and Saunders [37], the robot's appearance was deliberately designed to minimize any potential for anthropomorphism when viewed in a static state. Its white shell was chosen for its association with calmness and neutrality, while the yellow-black wheel, though sometimes visible, were not a deliberate design choice but rather a byproduct of the selected components. The shell was 3D-printed using Polylactic Acid, the most lightweight solution available. To ensure that the Stewart platform could lift and maneuver the shell without difficulty, its walls were thinned to the minimum viable thickness. This design decision successfully reduced weight but resulted in visible cracking in the structure after the experiments concluded.

While the tactile texture of robotic surfaces has been explored in prior work [52], this thesis did not incorporate textural variation. The shell was printed with a uniform, smooth surface to reduce the design and experimental complexity.

The robot is not equipped with tactile sensors. Although the initial design considered incorporating conductive paint or pressure sensors to enable more precise control of the touch gesture, this idea was later abandoned due to the complexity of integration relative to their limited utility. In this context, the sensor data would have enhanced the movement quality but would not have influenced the study's primary outcomes. Therefore, to narrow the project's scope and maintain focus, the decision was made to exclude tactile sensors.

However, as the development of the robot progressed, it became evident that some form of sensing was necessary to ensure consistency in touch gestures across experiments. As a result, an ultrasonic sensor was implemented at the base of the robot, positioned as low as possible. Ror the sensor to function properly, the robot's shell had to be raised by several centimeters and tilted to provide a clearer field of view. Although the robot has four identical sides, a defined front was established to accommodate the sensor. Designing the robot to function equally from all four sides would have significantly increased design complexity, without sufficient benefit to justify the added effort.

In the absence of the default pose configuration required for ultrasonic sensing, the robot can move its shell across a total range of 7 cm along both the x and y axes (+-3.5 cm), and 3 cm along the z-axis (+-1.5 cm). The shell is capable of roll, pitch and yaw tilting, although these movements are constrained by the risk of collision with the internal structure or the floor, depending on the configuration.

B User (Expert) Interface System

To manage the complexity of capturing an object's translational and rotational data, existing tracking solutions were evaluated. One such solution was Max, a visual programming environment for multimedia applications, which offers built-in support for the iPad through the Mira extension. Mira enables access to the iPad's inertial measurement unit (IMU), providing comprehensive motion data including acceleration, magnetic field strength, orientation, and raw gyroscope readings.

Initially, acceleration data was used to estimate position, while orientation values were applied for rotational tracking. The setup functioned as follows: Mira on the iPad transmitted motion data to a Max-based server on the laptop, which then relayed the data via UDP to a Visual Studio-based application. This application forwarded the values to the robot over a Bluetooth connection. Despite multiple attempts at filtering acceleration data, including the use of Kalman filters, position tracking remained imprecise. Further filtering improved accuracy but introduced excessive smoothing, which diminished the sharpness of expressive movements that required abrupt or irregular motion. As a result, a more suitable position estimation solution was sought. Retrieval of orientation values from IPad, however, proved to be successful.

The revised solution implemented computer vision based position tracking. Instead of tracking the physical model directly, the decision was made to estimate the camera's pose. A ChArUco board was selected, as it combines the advantages of chessboard corners and ArUco markers. This board supports high accuracy pose estimation due to its fixed reference points, spatial structure, and static configuration. One of its key benefits is that full visibility is not required. As long as a sufficient number of corners remain in view, the pose can still be estimated reliably. This makes the system more robust to tilting or shifting of the camera. To reduce the chance of detection failure even further, both the board and its markers were made relatively large.

To create a system that was both functional and comfortable for the expert, the setup had to allow for moments when the model was not being held. The camera was placed on the underside of the model, facing downward toward the table. This allowed tracking to continue even when the model was resting on the glass surface, as the ChArUco board placed beneath the table remained visible to the camera. Every time tracking is activated, a reference point is defined as the origin, allowing all subsequent displacements to be measured relative to the robot's base rather than a global coordinate frame. To ensure the expert maintains spatial awareness during movement design, a visible frame was drawn on the glass surface to mark this origin. The Z axis is defined relative to the robot's vertical displacement. When the model rests on the table, this position represents the lowest possible Z value. The neutral Z position is reached when the model is lifted off the surface, allowing free movement above the defined origin.

While the pose estimation system provides coordinates suitable for platform control, extending this approach to wheel control poses challenges, particularly in separating local platform movement from global displacement. However, since the aim of the study was to investigate touch not only in isolation but also within a naturalistic context, the robot's wheels had to be included. Initially, all touch gestures were intended to be executed by the platform alone, but the expert later observed that the platform's movement capabilities were insufficient. As a result, the wheels became essential not only for creating realistic scenarios but also for enabling certain touch gestures. It was not feasible to develop a high-usability interface that allowed the expert to intuitively control both the model as a shell and the full robot. Therefore, joystick control was reintroduced specifically for managing the base, and was operated by a second person under the direct instruction of the animator.

The final interface system combined computer vision and motion sensing to provide full six-degree-of-freedom pose estimation. Translational data was extracted using a camera, while rotational values were obtained from the iPad's motion sensors. A laptop ran a script that opened the camera feed, displayed the input alongside additional visual cues, and transmitted the translation values via UDP. Simultaneously, a second laptop ran a Max patch that received the iPad's orientation data and sent it over UDP as well. A separate script merged the two data streams and forwarded the combined pose data to the robot, along with real-time joystick input for controlling the mobile base.

In addition, the script enabled setting a reference point and saving the streamed data as a .txt file when prompted. This system allowed the robot to replicate the expert's physical manipulation of the model in real time, enabling precise and expressive motion replay during the experiment.

C Tables and figures

Planned intent	Target affect	Valence error mean (guess – target)	Valence error SD	Arousal error mean (guess – target)	Arousal error SD	Euclidean error √(Δval² + Δaro²)
Seeking Comfort	Anger	-2.67	0.82	2.5	0.84	3.66
Taking Space	Excitement	2.17	1.47	2.5	0.55	3.31
Seeking Comfort	Contentment	2.33	1.03	-2.17	0.75	3.18
No Intent	Excitement	2.33	0.52	2.0	1.55	3.07
Taking Space	Contentment	1.83	0.75	-2.33	0.82	2.97
Taking Space	Anger	-2.5	0.55	1.5	0.55	2.92
Seeking Attention	Excitement	2.17	0.98	1.83	1.47	2.84
No Intent	Anger	-2.0	0.63	2.0	0.89	2.83
Seeking Comfort	Excitement	2.17	1.17	1.67	1.97	2.73
Seeking Attention	Contentment	1.67	0.52	-2.17	1.17	2.73

Figure 7: Top 10 intent–affect pairs with the largest mean Euclidean deviation between interpreted and target valence–arousal ratings. Euclidean error is computed on the raw SAM scale (1 = positive/high arousal; 5 = negative/low arousal). Thus, negative valence deviations indicate responses judged *more positive* than the target, and positive arousal deviations indicate responses judged *calmer/less aroused*. Larger Euclidean values denote poorer recognition accuracy.

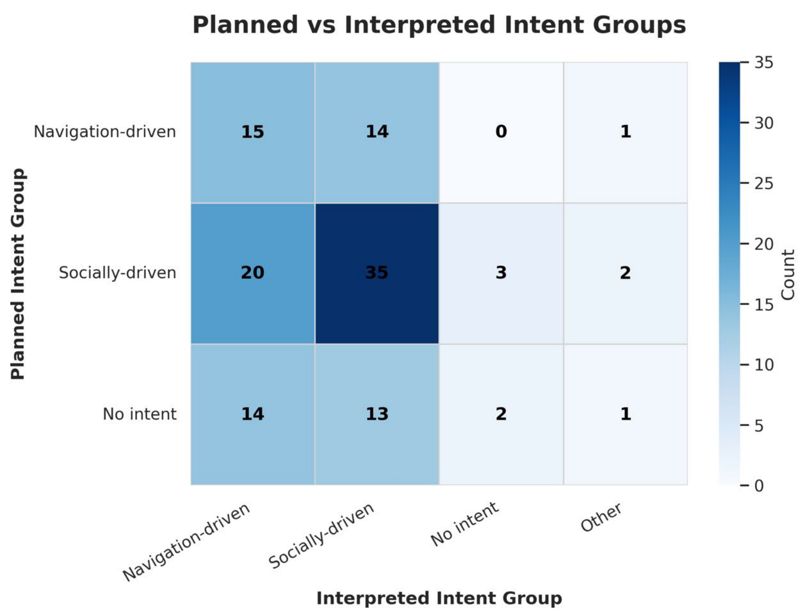

Figure 8: Confusion matrix of planned versus interpreted intent groups. Rows represent the robot's planned intent groups (navigation-driven, socially-driven, no intent), and columns represent participants' interpreted intent groups. Cell values indicate counts of responses, with darker shading reflecting higher frequencies.