EXPLORING THE FEELING OF TOGETHERNESS IN VIRTUAL SPACES

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ABSTRACT

Togetherness is a broad concept, with distinctive research fields focused on moving (i.e., synchrony and imitation), feeling (i.e., affective empathy) and thinking together (cognitive empathy), challenging our understanding of the experience of "being with". Furthermore, the traditional scaffolding of face-to-face human-human interactions is nowadays disrupted by human-computer interactions. Consequently, the present thesis explored (i) the overlap between moving, feeling and thinking together and (ii) their translations into virtual spaces. During this PhD, a systematic literature review was conducted, providing an overview of behavioural synchrony, understood as an emergent coordination pattern, studied through the lenses of physics and social sciences. Online and in-laboratory studies investigated the association between synchrony, imitation, and affective, cognitive and motor facets of empathy using autonomous agents. **Experiments I** and **II** used self-reports of affective, cognitive and motor empathy, and social bonding combined with behavioural assessments of synchrony and economic games, confirming (i) an association between goal-oriented motor synchronization and cognitive empathy but (ii) questioning the credibility of virtual agents for eliciting social bonding. **Experiments III** and **IV** used self-reports of affective, cognitive and motor empathy combined with an automatic imitation and second-order theory of mind tasks coupled with electrophysiological recordings, revealing (i) a negative association of affective and motor-related empathy facets with behavioural accuracy and (ii) the role of predictability on tendencies for anthropomorphism. This thesis has fundamental and applied implications for improving our understanding of the feeling of togetherness in human-computer interactions. By merging the theoretical frameworks of moving, feeling and thinking together, this thesis (i) highlights their respective and overlapping contributions, (ii) provides a systematic investigation of their association by taking into consideration their multidimensional components, and (iii) highlights the limitation of virtual agents in fulfilling human needs for belongingness.

Keywords: *Togetherness*, *Synchrony*, *Imitation*, *Empathy*, *Human-computer interactions*, *Anthropomorphism*, *Theory of Mind*.

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"Life is a movement. We call it death when it comes to a standstill."

- Jón Kalman Stefánsson

"It takes a village to raise a child" is a well-known quote that accurately captures my gratitude towards the global community that helped me through the process of this thesis. I want to thank my supervisors from **Nottingham Trent University** (**NTU**) and **Auckland University of Technology** (**AUT**) for allowing me to build this tailor-made project and for their patience in following my convoluted thoughts.

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Part of this thesis was conducted during the global COVID-19 pandemic, reminding us that togetherness also entails ethical considerations associated with scientific inquiries. I thank all the participants who completed my studies.

Finally, I would like to conclude with particular thoughts for my father, Sam André Ayache (1949 - 2021) and grandmother, Léone Bouleau (1930 - 2023), who sadly passed away during this project. Thank you for giving me the sparkle for science and the strength to fight for a better world.

FOREWORD

"Oh, wonder! How many goodly creatures are there here!
How beauteous mankind is! O brave new world, that has such people in 't!"
- William Shakespeare

During the last four years, I had the privilege of exploring the territory of "togetherness". I thank the **DTA3 COFUND** program for funding this project. However, I often stumbled upon the inquiries of its impact, and I would like to take the opportunity to introduce and highlight its fundamental and practical implications for society. By doing so, I would like to acknowledge the influence of the British scientist and mathematician Alan Turing, the father of a discipline nowadays known as computer sciences. Although Turing's works may seem remotely related to the study of "togetherness", his influential works provide the scientific foundations of the present manuscript.

(i) Where do patterns come from?

Although Alan Turing is mostly known for his work on theoretical computer sciences, Turing was also a pioneer in computational biology. His works on morphogenesis provided a mathematical description of pattern formations in biological organisms (Turing, 1952). Although initially restricted to cell differentiation processes that shape our bodies through reaction-diffusion mechanisms, this approach can be extended to the formation of behavioural patterns. Patterns are indeed everywhere, distinguishing life from death and order from disorder in a so-called "broken symmetry", where the emergence of a structure breaks perfect homogeneity (i.e., noise) - see Anderson (1972).

Based on self-organisation principles, the concept of morphogenesis set the stage for the interdisciplinary research field of synergetics, founded by Hermann Haken (Haken, 1987). Translated from the Greek "working together", synergetics focuses on the spontaneous emergence of new qualities, such as structures, processes or functions, through interactions. Therefore, synergetics provide a relevant theoretical framework for exploring togetherness. However, pattern formation can be more controversial in social sciences and offer a fruitful area for heated debates.

(ii) What is it like to be human?

Turing is probably most well-known for the Imitation Game, nowadays known as the Turing test, attempting to distinguish humans from machines (Turing, 1950). Although this question is often understood as a technical problem to be solved, it also reminds us that the definition of humanness is far from being settled and sparks fierce debates. Humanness is indeed a characteristic not acquired from birth but part of a process where boundaries of humanness are shifting with technological advances and social norms (Christian, 2011; Rochat, 2006).

The present thesis suggests that togetherness entails the fundamental question of defining humanness: being recognised as human by another human and being treated as such. Mutual recognition of humanness lies in the definition of togetherness by nurturing respect and protecting one's dignity despite inter-individual and inter-cultural differences. Dramatically, Alan Turing suffered from a narrowed definition of togetherness, experiencing ostracism due to his sexual orientation. Social rejection is a painful experience that denies a human being to be recognized as such. Turing's experience of ostracism should not be forgotten, and this manuscript will hopefully participate in fostering a society where differences are acknowledged and respected.

In **Chapter 1**, the key concepts used in this thesis are introduced, namely interpersonal coordination and empathy, stressing their multidimensional facets and possible translations in human-computer interactions.

Chapters 2 and **5** introduce the methods and challenges in measuring these two facets of togetherness.

Chapters 3 and **6** report online and in-lab experiments exploring the association between interpersonal coordination and empathy.

Chapters 4 and **7**, report experiments exploring the mechanism of anthropomorphism in human-computer interactions.

Chapter 8 summarises the main findings of this thesis and paves the way for future research exploring the notion of togetherness.

In those times of social and ecological crises, I let the taxpayers judge the relevance of these research questions in understanding the mechanisms underpinning our capacity to live together.

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CHAPTER 1

INTRODUCTION

"History doesn't repeat itself, but it rhymes"
- Mark Twain

What binds individuals together is a research question at the crossroads of various disciplines in social sciences. Nevertheless, the nature of social connectedness still eludes a clear conceptualisation. Social bonding is a fundamental aspect of human cognition, and survival relies on our social environment (Fotopoulou and Tsakiris, 2017). Consequently, regulating our internal states (i.e., homeostasis) requires developing mutual understanding from the beginning of our lives (Tronick et al., 1998). Yet, despite decades of research, the conceptualisation of togetherness has not reached a consensus. As noted by Friedan (2010), togetherness was first coined by McCall, an editor of feminine magazines in the 50's, to promote happiness in American families. Therefore, togetherness is a relatively new concept that suffers from a broad definition, often relying on an implicit social contract that defines who is included or excluded from this shared experience. Togetherness can be understood as "being with", conceptualised as sharing spatial co-location or being mutually aware of each other (Darwall, 2011; Durlach and Slater, 2000). However, the mechanisms underlying togetherness are unclear, and the nature of social connectedness remains the "dark matter" of social interactions (Schilbach et al., 2013). Furthermore, the impact of Computer-Mediated-Communication (CMC) on togetherness needs to be clarified, and more investigations are required to unravel its impact on social interactions. This chapter will introduce mechanisms sustaining social bonding, such as Interpersonal Motor Coordination (IMC) and empathy, to understand the nature of the social glue binding individuals together and how these mechanisms can be translated and investigated in CMC.

Part of this chapter has been published as a book chapter titled *"Feeling Closer Despite the Distance: How to Cultivate Togetherness Within Digital Spaces"* in the **Handbook of Research on Remote Work and Worker Well-Being in the Post-COVID-19 Era** published by IGI Global (Ayache et al., 2021).

1.1 Togetherness, an important but ill-defined concept

The need for belonging is a core and fundamental aspect of human psychology. The Bowlby-Ainsworth attachment theory illustrates the importance of early social connections in human life, stressing the role of infant-parent affective bonds in shaping later adulthood relationships (Bowlby and Ainsworth, 2013). Humans are indeed social beings, evolving in complex social environments that require developing cognitive skills for fostering social belonging (Heyes and Frith, 2014; Parkinson and Wheatley, 2015; Rochat, 2005). Furthermore, developmental and philosophical accounts of consciousness suggest that self-awareness arises from social interactions (Fuchs, 2017; Rochat, 2009; Trevarthen, 2011). Consequently, human psychology is shaped by social interactions and cultural evolution.

However, these social influences are often neglected in studying and determining individual behaviours. Furthermore, social interactions are often studied from a first (i.e., recording of elicited behavioural or physiological response) or a third perspective (i.e., picture or video depicting social interactions), leaving the dynamics of social interactions as uncharted territory (Schilbach et al., 2013). Therefore, there is a need for a paradigm shift in social neurosciences and recent approaches, such as the "second-person" or "two-body" movements, advocate new experimental methods, such as the use of autonomous agents, for investigating the "dark matter" of social interactions (Dumas, 2011; Konvalinka and Roepstorff, 2012; Gallotti and Frith, 2013; Schilbach et al., 2013). However, to what extent these methods are deemed appropriate for capturing the experience of togetherness remains debated.

This subsection reviews the literature on social connectedness, underlying its contribution to human well-being. Theoretical and empirical evidence associated with the belongingness hypothesis are reviewed, stressing the affective and cognitive consequences of belongingness on individual psychology (Baumeister and Leary, 2017). The intertwining of individual and collective psychology is exposed, starting with the "group mind", developed in the early 20th century, a notion that regained attention in modern philosophical and experimental works conducted on shared cognition, sometimes labelled as the "We-mode" (Pacherie, 2014). Finally, this section concludes with the challenges in fostering social connectedness and belongingness in Human-Computer Interaction (HCI) settings (Billinghurst and Kato, 1999; Rudnicki, 2017; Slater and Sanchez-Vives, 2016).

1.1.1 Belongingness, a fundamental human need

According to the belongingness hypothesis from Baumeister and Leary (2017), social connectedness is a fundamental psychological need and a prerequisite for individuals' survival. The need for social connectedness has affective, cognitive and behavioural consequences, and its fulfilment is crucial for human psychological well-being. Yet, the feeling of belongingness requires specific types of interactions that offer both frequency and intimacy. Thus, social interactions characterised by strong ties such as romantic couples, family or friends can fulfil our need to belong by providing mutual support (Valentine et al., 2020). However, when intimacy or frequency is lacking, individuals are more likely to reconnect with ex-partners (Spielmann et al., 2012) or seek new relationships (He et al., 2013). This phenomenon is not restricted to friendship or romantic relationships. Still, it is also observed in organisations such as workplaces, schools, or universities, where the feeling of belongingness is crucial for workplace satisfaction and cohesiveness (Estlund, 2003; Mohamed et al., 2014). A lack of social connectedness among colleagues or fellows can lead to detrimental outcomes such as impeding team performances associated with altered academic and health outcomes and, to some extent, to life-threatening situations (Gkorezis et al., 2016; Walton and Cohen, 2011). Consequently, the experience of belongingness is a core aspect of human psychology.

The sociometer theory from Leary (1999) suggests a direct association between self-esteem and social integration, where self-esteem is conceptualised as a barometer that fluctuates according to the beliefs about how someone is evaluated by others and socially integrated. According to this theory, social connectedness predicts high self-esteem, associated with positive outcomes such as team commitment (Jelil Ladebo et al., 2008). In contrast, the lack of social integration (i.e., thwarted belongingness) predicts lower self-esteem and social isolation associated with adverse outcomes, including suicidal behaviours (Van Orden et al., 2010). Experimental protocols such as the Cyberball Game can induce the experience of ostracism by neglecting participants' need for social inclusion (Williams and Jarvis, 2006), and neuroimaging studies using this paradigm observed that social rejection activates similar brain areas involved in the experience of physical pain (Eisenberger and Lieberman, 2004). Thus, social rejection hurts, and this painful experience affects individuals and society in general (Bastian and Haslam, 2010). Indeed, by neglecting humans' need for belongingness, social rejection denies the recognition of shared humanity, leading to dehumanization and its harmful consequences.

1.1.2 From "I-mode" to "We-mode", a switch of consciousness state

As suggested by the belongingness hypothesis, social connectedness is a core aspect of psychological well-being, reflecting successful social integration (Baumeister and Leary, 2017). However, studies of affective and cognitive mechanisms of human psychology are often restricted to the sole individuals, neglecting the role of social influences on modelling individual human cognition[1]. Consequently, social interaction studies were often restricted to other fields, such as anthropology or sociology, leaving their influences on individuals' psychology unexplored and the experience of togetherness uncharted.

Over a century ago, Gustave Le Bon and Émile Durkheim referred to the concept of "group mind", describing a qualitative switch of consciousness states when individuals engage in collective thinking and goal-oriented actions (Durkheim, 2014; Le Bon, 1896). Whilst Le Bon, inspired by the emergence of psychoanalysis, described the crowd as a psychological entity[2], recalling modern theories of human cognition, such as the extended mind hypothesis or the transactive memory system (Clark and Chalmers, 1998; Wegner, 1987), Durkheim described the collective effervescence emerging from religious rituals, stressing the role of IMC as a social glue, an active area of research exploring mechanisms of joint action (Sebanz et al., 2006). This initial distinction between action and cognition remains vivid in modern investigations of the emergence of the so-called "hive mind", another terminology describing collective thinking.

From a philosophical viewpoint, the "We-mode" can be described as a qualitative change of consciousness state characterised by a shift from a self-focused attentional state to an alter-centric state, including others' mental states (Pacherie, 2014; Southgate, 2020). For example, the sense of agency conceptualised as a multidimensional construct of the sense of intentionality and body ownership (Gallagher, 2000), is experienced differently when acting alone or during joint action (Zapparoli et al., 2022). Nevertheless, despite the growing popularity of research on the "We-mode", the qualitative properties and mechanisms underlying this specific consciousness state are not yet fully understood (Høffding, 2019; Tuomela, 2005). Consequently, the first goal of the present thesis was to clarify how joint action is experienced across individuals by considering inter-individual differences in understanding others' mental states.

[1] Wilhelm Wundt, founder of modern psychology, suggested that collective phenomena were out of the scope of psychology as a scientific discipline - see (Farr, 1983)

[2] Nevertheless, Le Bon had a narrowed vision of this entity, excluding women considered as "the most inferior forms of human evolution" - see (Gould, 1980)

1.1.3 Disembodied communications, a threat to togetherness?

To complicate matters further, communication technologies allow social interactions to take place remotely. Initially pictured by Pierre Teilhard de Chardin as the next stage of human evolution, forming a collective thinking network labelled noosphere (Steinhart, 2008), CMC were cast as a revolution for human-human communications by removing the usual spatiotemporal obstacles for interpersonal communication (Rudnicki, 2017). However, how the disruption of the traditional scaffolding of face-to-face interaction affects the dynamics of social interactions remains unclear.

Despite a tremendous amount of research in this area, the influence of CMC on individual psychology remains debated (Ayache et al., 2023b). On the one hand, studies suggest that CMC offers new ways to connect and foster collective actions through shared online identities, erasing physical distances (Lüders et al., 2022; Rovira-Sancho and Morales-i Gras, 2022). Conversely, other studies suggested that remote communications increase polarization and social isolation by cutting single individuals from the social diversity usually experienced in offline settings (Del Vicario et al., 2016; Nowland et al., 2018)[3]. Consequently, there is a need to understand how the experience of togetherness is translated into CMC and how these remote interactions affect the emergence of the "We-mode".

Several studies have already demonstrated that the lack of subtle behavioural cues in online settings can dampen the effectiveness of interpersonal communications (Binder, 2023; Roos et al., 2022). Interpersonal communications are indeed multimodal, encompassing linguistic and behavioural cues that allow the emergence of mutual understanding (Burgoon et al., 2011; Trujillo et al., 2020). Consequently, CMC that successfully replicate human kinematics, such as Augmented and Virtual Reality, offer new ways of interacting remotely by recreating "seamless" embodied social interactions (Billinghurst and Kato, 1999; Slater and Sanchez-Vives, 2016). Nevertheless, by allowing the reproduction of behavioural cues of human-human communications into CMC, these new technologies also enable machines to mimic human behaviours more accurately. However, to what extent autonomous agents that mimic humans' behaviours can trigger an experience of togetherness remains unclear. Consequently, the second goal of this thesis was to clarify how virtual agents driven by computational models of human behaviours can elicit social bonding in human users.

[3]The weak ties, characterising the social diversity usually encountered in daily life, are indeed crucial for (social) network theories and are also explored in brain neural network - see Granovetter (1973) and Watts and Strogatz (1998)

1.2 Interpersonal motor coordination, an interdisciplinary research area

The previous section emphasised that togetherness is an important concept associated with the fundamental human need for belongingness (Baumeister and Leary, 2017). Indeed, the sociometer hypothesis predicts that failure to fulfil the need for social connectedness is detrimental to self-esteem and activates similar neural pathways as physical pain (Eisenberger and Lieberman, 2004; Leary, 1999). Yet, the experience of togetherness remains a blind spot in social neurosciences.

Despite an increasing interest in exploring the qualitative changes happening when we interact with others, the qualitative changes associated with the "We-mode" remain to be clarified. Theories and methods investigating this "extended mind" (Clark and Chalmers, 1998; Wegner, 1987) and the mechanisms of joint action (Pacherie, 2014; Sebanz et al., 2006) are often restricted to the observation of an individual's responses or watching others interacting, leaving the dynamics of social interactions unexplored. Therefore, understanding the emergence of the "We-mode" requires the reconsideration of human cognition not as isolated but as a continuous and active process of interactions between the organism and its (social) environment.

By reframing social interaction as dynamic processes, IMC research has established novel methods for exploring the behavioural and physiological components of togetherness (Fuchs and Scott Kelso, 2018; Tognoli et al., 2020). Of particular interest is the phenomenon of synchrony, which has fascinated scientists for centuries, considering its prevalence in living and non-living systems (Strogatz, 2004). In social sciences, synchrony has attracted considerable interest considering its association with affiliative and prosocial tendencies (Hu et al., 2022; Rennung and Göritz, 2016; Vicaria and Dickens, 2016). However, this overgrowing literature based on different conceptualisations and theoretical frameworks of synchrony has led to a scattered vision of the mechanisms underlying this specific pattern of IMC, challenging the emergence of a unitary framework for understanding its mechanisms and pathways linking synchrony with social bonding.

This subsection reviews various conceptualisations of IMC, focusing on behavioural synchrony (Bernieri and Rosenthal, 1991). IMC theories and mechanisms are summarised (Haken et al., 1985; Prinz, 1990; Sebanz et al., 2006), and the hypotheses on its affective and cognitive pathways to affiliative and prosocial tendencies are discussed (Cross et al., 2019; Hove and Risen, 2009; Kirschner and Tomasello, 2010; Machin and Dunbar, 2011).

1.2.1 Interpersonal motor coordination, a quest for a definition

Synchrony is a research topic that has fascinated scientists for centuries. One of the first scientific reports of synchrony can be traced back to Christian Huygens (1665), who observed an “odd sympathy” between two pendulums starting to synchronize when mounted on the same display (Willms et al., 2017). Later, synchrony was described by Durkheim (1912) as a social glue, binding individuals together during collective gatherings (Durkheim, 2014). Accordingly, synchrony as a research topic has attracted tremendous attention from various scientific communities, ranging from physics to social sciences, leading to distinctive conceptualisations of synchrony.

According to Bernieri and Rosenthal (1991), synchrony can be considered as a specific type of IMC, describing tendencies of behaviours to be non-random, patterned and synchronised during social interactions. Notably, IMC distinguishes (i) *synchrony*, referring to the temporal matching or alignment of movements, but also physiological rhythms (Kendon, 1970; Trevarthen, 1999) from (ii) *imitation*, referring to the spatial matching of gestures or mimicry of facial expressions (Blair, 2005). This distinction between temporal and spatial matching nurtured distinctive research fields and experimental methods investigating their mechanisms and consequences[4].

On the one hand, synchrony typically refers to in-phase (e.g., zero lag) but can also refer to anti-phase coordination patterns (e.g., 180° lag or phase shift). Mathematical descriptions of synchrony will be discussed in **Chapter 2**. On the other hand, imitation typically refers to the spontaneous tendency for mimicry (e.g., contagious yawning, Platek et al. (2003)) but can also refer to the execution of spatially congruent movements (e.g., automatic imitation, Heyes (2011)). Conceptualisations and measurements of imitation will be discussed in **Chapter 5**. Additionally, emergent (i.e., spontaneous) and planned (i.e., goal-oriented) motor coordination are often conflated, encompassing coordinated and uncoordinated movement patterns (Athreya et al., 2014; Knoblich et al., 2011). Consequently, IMC is a multidimensional concept, where the spatiotemporal matching that characterises coordination patterns is critical for delineating its multiple facets (Schoenherr et al., 2019). The following sections will refer to (i) *synchrony* as temporal matching, (ii) *imitation* as spatial matching, and (iii) interpersonal motor coordination (IMC) as the umbrella term encompassing temporal and spatial matching.

[4]Importantly, this delineation differs across disciplines - for example, the term alignment is preferred in linguistics as an umbrella term encompassing the notion of convergence (i.e., doing similar things in a similar way) and coordination (i.e., doing something in reaction to the behaviour of the other) - see Pickering and Garrod (2004) and Dumas and Fairhurst (2021)

1.2.2 Theories and mechanisms of interpersonal motor coordination

Experimental investigations of IMC distinguishing synchrony from imitation led to separated streams of research associated with distinctive conceptualisations of human cognition. On the one hand, studies of synchrony are often framed within dynamical system theories, postulating that coordination patterns are self-organised (i.e., emergent) and cannot be restricted to intra-individual mechanisms (Haken and Tschacher, 2011; Kelso, 1995). On the other hand, studies of imitation are often associated with embodied cognition theories or ecological psychology, postulating that capacities for actions (i.e., affordances) shape mental representations of the world (Barsalou, 2010; Gibson, 1977; Lakoff, 2012). Consequently, these distinctive theoretical accounts of human cognition have led to different models of mechanisms underlying IMC.

Inspired by mathematics and physics, dynamical system theories provide a theoretical framework for modelling IMC as coordination patterns resulting from the exchange of information between individuals (Haken, 1987). These models are not restricted to motor components of social interactions and are applied in various domains, from engineering, physics, chemistry, biology, and neuroscience, including hand clapping in crowds or walking on the millennium bridge (Strogatz, 2004). The Kuramoto model and the Haken-Kelso Bunz model (HKB) are particularly interesting for modelling synchrony and describing mechanisms of emergent coordination (Haken et al., 1985; Kuramoto, 1975). However, the Kuramoto model and HKB remain distinct in several ways. On the one hand, the Kuramoto model describes the synchronisation of large populations of oscillators taking place, from disorder (i.e., chaos) to synchrony (i.e., in-phase synchronisation (i.e., order). On the other hand, the HKB describes phase transition between a couple of oscillators (Kelso, 2021). Further details will be provided in **Chapter 2** on the principles and mathematics of the HKB for rendering motor coordination in HCI.

In contrast, the embodied ideomotor theories of human cognition postulate that IMC relies on a shared neurocognitive architecture for the observation and execution of similar actions (Prinz, 1990). In line with these theories, investigations of the monkey and human brains reported the observations of neurons firing while watching or executing the same action (Gallese et al., 1996; Mukamel et al., 2010)[5]. Nowadays referred to as the Mirror Neuron System (MNS) or action/perception matching system, these neurons are widespread in the human brain in areas involved in motor and non-motor functions (Molenberghs et al., 2012).

[5] Mirror neurons were first recorded in the ventral premotor region F5 of monkeys, but their mapping into the human brain areas remain challenging - see Kilner and Lemon (2013)

The MNS is suggested as a central mechanism underlying social behaviours but remains controversial (Gallese, 2001; Keysers, 2009). Whilst nativist views suggest that the MNS is genetically inherited, supporting the great leap in human evolution (Ramachandran and Oberman, 2006), constructivist theories argue that this neural network is developed through learning processes (Heyes, 2010). Furthermore, the MNS can hardly be considered the sole mechanism of IMC that requires capacities to predict others' actions (Sebanz and Knoblich, 2009). Shamay-Tsoory et al. (2019) suggested that IMC relies on three neurocognitive systems: (i) the misalignment detection of motor mismatch, (ii) the perception/action system corresponding to the MNS, and (iii) the reward system associated with its positive outcomes. Consequently, IMC can be understood as an overall optimisation principle, favouring movement matching between self and others for reducing computational cost (Friston, 2010; Hoehl et al., 2021; Koban et al., 2019). Further details will be provided in **Chapter 5** on the putative electrophysiological signature of the MNS and the misalignment detection system.

To summarise, dynamical systems and ideomotor theories offer distinct views on the nature of IMC. On the one hand, dynamical system theories focus on inter-individual processes involved in synchrony without considering cognitive components such as motor programs or anticipatory mechanisms (Schmidt et al., 2012; Vial and Cornejo, 2022). On the other hand, ideomotor theories focus on inter-individual variabilities in imitation by taking into account the intra-individual mechanisms underlying coordination patterns such as anticipatory mechanisms (Hale et al., 2020; Sebanz and Knoblich, 2009).

Whilst these theoretical accounts are not exclusive, they are challenging to merge within a single framework. A recent computational model inspired by the Kuramoto model's principles suggests that IMC results from the coupling mechanisms between and within individuals (Heggli et al., 2019). These models indicate that integrating the 'Other' within the self is a core aspect of interpersonal coordination, underlying its association with social connectedness. Consequently, this thesis will investigate the role of inter-individual differences in self-other integration as a predictor and outcome of IMC.

1.2.3 Prosocial outcomes of interpersonal motor coordination

IMC has attracted increasing interest in social sciences, considering its association with affiliative and prosocial tendencies. Consequently, the spatiotemporal matching of motor behaviours offers an attractive index for assessing the quality of relationships with a wide range of applications for fostering mutual understanding and affiliative tendencies. Nevertheless, the proliferation of paradigms for assessing IMC renders it challenging to identify the mechanisms leading to prosocial outcomes.

Mother-infant interactions revealed that behavioural synchrony is a marker of a secure attachment style, a core feature of healthy psychological functioning, believed to reflect the quality of social interactions during adulthood (Long et al., 2020; Mesman et al., 2009; Tronick et al., 1978). Synchrony is also considered the bedrock for developing the capacity to understand others' emotional states and adjust behaviour accordingly (Feldman, 2007; Tronick et al., 1998; Wheatley et al., 2012). Similar findings are reported for imitation, and the spontaneous tendency to imitate gestures and facial expressions is coined as the "chameleon" effect (Lakin et al., 2003). Behavioural mimicry is observed during infancy for learning motor skills and fostering affiliation, fulfilling the need for belongingness (Over and Carpenter, 2013; Uzgiris, 1981).

In adulthood, synchrony and imitation can also be considered markers of affective bonds and therapeutic alliance (Atzil et al., 2014; Ramseyer and Tschacher, 2011). Furthermore, IMC also increases trust, persuasiveness and altruistic tendencies (Hu et al., 2022; Rennung and Göritz, 2016; Vicaria and Dickens, 2016). Several studies report a greater propensity for cooperation following induced behavioural synchrony or imitation, assessed by helping behaviours (Reddish et al., 2014; Carpenter et al., 2013) or economic games (Reddish et al., 2013; Wiltermuth and Heath, 2009). However, there is a lack of consensus on the mechanisms linking IMC with affiliative and altruistic tendencies - see **Figure 1.1** for a graphical summary.

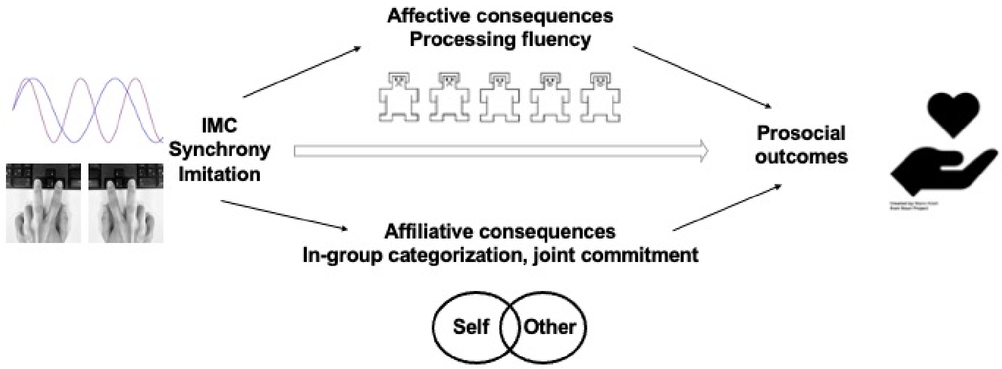

Fig. 1.1 Affective and cognitive pathways linking synchrony with prosocial outcomes

On the one hand, computational models of IMC postulate an affective pathway whereby the spatiotemporal matching of movements is associated with experiences of shared flow, eliciting perceptual pleasure by increasing processing fluency (Hove and Risen, 2009; Zumeta et al., 2016). IMC increases the predictability of others' actions, reducing environmental uncertainty and activating the rewarding system associated with the opioid system, which is involved in pain sensitivity threshold and social bonding (Hoehl et al., 2021; Lang et al., 2017; Machin and Dunbar, 2011; Nummenmaa et al., 2015).

On the other hand, social and anthropological models postulate a cognitive pathway that also shapes the experience of IMC. Prior beliefs in shared intentionality can reinforce its association with rewarding experiences (Kirschner and Tomasello, 2010; Reddish et al., 2013). By extension, this positive association can lead to attentional bias toward coordination (Hu et al., 2022). Finally, synchrony and imitation can promote in-group categorisation by increasing the perception of self-other similarity and altruistic tendencies (Cross et al., 2019). In line with these hypotheses, higher endorphin and oxytocin levels, two hormones involved in attachment and rewards, are reported after synchronous interactions (Feldman, 2007; Lang et al., 2017). Consequently, several hypotheses co-exist in the literature, postulating different mechanisms linking IMC with prosocial tendencies and this thesis considered possible shared mechanisms with empathy.

1.3 Empathy, an elusive concept of mutual understanding

Empathy comes from the German word "Einfühlung" and was introduced by the German philosopher Robert Vischer at the end of the nineteenth century. Vischer conceptualised empathy as "feeling oneself into", referring to the physical responses associated with aesthetic experiences (Freedberg and Gallese, 2007; Vincent, 2012). This initial conceptualisation of empathy captures the mixture of artistic and scientific inquiries conducted in the late Victorian era, and its association with motor responses was simultaneous to the introduction of new techniques of photography that gave rise to the study of movement decomposition (Lanzoni, 2009; Marey, 1894; Muybridge, 1887).

Modern conceptualisation of empathy, likewise interpersonal coordination, suffers from similar theoretical debates concerning its psycho-biological mechanisms and social influences. Neurocognitive and pathological accounts often neglect the multidimensional nature of empathy and its association with social norms (Hall and Schwartz, 2022; Bloom, 2017). Thus, despite its popularity, empathy remains a controversial research topic, prone to a "jingle-jangle fallacy" (Heym et al., 2021). Theoretical accounts suggest that empathy arises from similar mechanisms sustaining IMC, such as the MNS (Gallese, 2001; Prinz, 1990). Nevertheless, clinical conditions associated with empathy deficits, such as autism and psychopathy, cast doubt on the possibility of a unique mechanism underlying empathic abilities (Blair, 2008; Southgate and Hamilton, 2008). Finally, similar to IMC, empathy is often studied in the context of prosocial outcomes such as affiliation and altruism (Batson et al., 2015). However, the systematic association between empathy and prosocial tendencies is questioned and often neglects possible detrimental outcomes, such as poor and unfair decisions or emotional dysregulation (Bloom, 2017; Eisenberg and Fabes, 1990). Consequently, the research field of empathy is currently scattered across different conceptualisations, making it challenging to delineate empathy and understand the mechanisms underlying empathic processing.

The following subsection will trace the origin of empathy as a research topic in the history of psychology as a scientific discipline and summarise its recent development as a multidimensional construct (Decety and Jackson, 2006). Theoretical models of empathy will be introduced and discussed in light of their possible overlap with those of IMC (Decety and Jackson, 2006; Shamay-Tsoory, 2011). Finally, the prosocial consequences of empathy will be introduced, stressing the limit of the empathy-altruism hypothesis and the possible detrimental impact of excessive empathy (Batson et al., 1987; Eisenberg et al., 2010).

1.3.1 Empathy, a multidimensional concept

Vischer's German term "Einfühlung" was later translated by Edward B. Titchener as empathy for the English vocabulary, a word derived from the Greek word "empatheia", meaning feeling, and referring to the ability to "read oneself into a situation, object, or stimulus based on some image of bodily movement" (Lanzoni (2012), p. 311). Initially restricted to aesthetic experiences, empathy was expanded to social interactions by Theodor Lipps, who considered empathy as fundamental in our understanding of other minds (Depew, 2005; Montag et al., 2008). Nowadays, studies of empathy seldomly account for its historical association with arts (but see Gallese (2001) and Fuchs and Koch (2014)) but are inspired by the notion of sympathy developed by Adam Smith and David Hume during the Scottish Enlightenment, linking empathy with ethics (Darwall, 1998; Englander and Ferrarello, 2022).

According to Smith, sympathy is the ability of humans to read other's minds (Fleischacker, 2019). Sometimes labelled as Theory of Mind (ToM) or cognitive empathy, this conceptualisation of empathy characterises the ability to "attribute independent mental states to self and others to predict and explain behaviour" (Frith and Happé (1999), p.2). In contrast, for Hume, sympathy is the capacity to mirror others' mental states, postulating that empathy arises from simulating others' mental states (Morrow, 1923; Tanaka, 2015). This conceptualisation is closely related to the notion of affective empathy, which refers to a vicarious experience of others' emotional state or the ability "to recognise the emotions and feelings of others with a minimal distinction between self and other" (Decety (2010), p. 258). Consequently, Lamm et al. (2016) suggested that empathy is composed of experiences of self-other distinction (i.e., cognitive empathy) and self-other overlap (i.e., affective empathy).

However, experimental investigations of empathy do not necessarily distinguish between empathy components, rendering it unclear if experiencing others' states is a prerequisite for mind reading abilities (Zahavi, 2008). Furthermore, the vocabulary used in empathy research does not delineate metaphors from mechanisms, impeding a clear understanding of empathy's components (Lomas et al., 2022). Finally, the lack of consensus on empathy's definition led to the proliferation of terminologies participating in a "jingle-jangle fallacy", where it is unclear if authors are using the same label to describe different things (jingle) or different names to study the same concept (jangle) (Heym et al., 2021). Consequently, some researchers suggest avoiding the problematic terminology of empathy in favour of its components (Hall and Schwartz, 2019). This scattering of empathy as a multidimensional concept led to the proliferation of theoretical models that challenge the identification of empathy's mechanisms.

1.3.2 Theories and mechanisms of empathy

Following the initial association of empathy with aesthetics, the first investigations of empathy focused on subjective accounts of body responses when individuals interacted with their (social) environment (Lanzoni, 2009). These introspective methods remain vivid in artistic and therapeutic settings, with the development of movement therapies such as the Kestenberg Movement Profile (KMP) inspired by the Laban Movement Analysis (Bernardet et al., 2019; Koch and Rautner, 2017), based on the analyses of behavioural and physiological rhythms (i.e., "rhythmanalysis", see Lefebvre (2013)). However, neuroscientific accounts of empathy usually disregard introspection in favour of behavioural and physiological responses. In line with the perception-action model of human cognition initially developed by Prinz (1990), the observations of automatic imitation of facial expressions in newborns suggested that humans develop their body awareness by observing others' actions (Meltzoff and Moore, 1983)[6]. Thus, early imitation and, by extension, the MNS are seen as the core mechanism of empathy.

According to the Perception-Action model, empathy belongs to a super-ordinate class of processes relying on the perception/action system (Preston and De Waal, 2002). Consequently, this automaticity of mirroring, inherited through evolutionary pressure, sustains our ability for empathic skills. This conception of empathy relying on mirroring mechanisms echoes the shared manifold hypothesis, suggesting a joint coding of perception and action, not restricted to empathic processes but widespread in cognitive function, in line with ideomotor theories of embodied cognition (Gallese, 2001).

Although seductive, these theoretical models received harsh criticism for their attempt to summarise the complexity of empathy into a single unitary mechanism. Accumulative evidence suggests specific deficits associated with different clinical conditions, ruling out the possibility of the sole involvement of the MNS, advocating for a "fine-cute" approach (Blair and Perschardt, 2002). Furthermore, its reliance on the MNS gave rise to debates between nativist and constructivist views of empathy (Heyes, 2010; Ramachandran and Oberman, 2006). Finally, the Perception-Action model conflates empathy and its prosocial consequences, such as concerns about others' welfare (Eisenberg, 2002). Therefore, a single unitary mechanism appears insufficient to capture the processes required for empathy, and neurodevelopmental models of empathy suggest different stages in empathy development, underlying the interplay of several neural networks.

[6] Although failure for replications, cast doubts on the existence of early imitation - see Oostenbroek et al. (2018)

According to Decety and Jackson (2006), empathy is an aggregation of distinctive neurocognitive components following the maturation of specific brain areas.

The first developmental stage of empathy relies on the perception-action coding system, supporting a shared coding for action-perception that allows affective resonance and emotional sharing, corresponding to affective components of empathy. Notably, this first stage is not associated with specific brain areas as regions involved vary from assessment methods but overlap with the MNS (Decety and Meltzoff, 2011).

The development of self-awareness characterises the second developmental stage of empathy. It relies on the conflict monitoring system, allowing one to switch from a self-centred perspective to that of others, requiring metacognitive and cognitive control processes. Developmental studies emphasise the altercentric nature of human cognition, arguing that difficulties in considering others' mental states arise with the development of self-awareness (Southgate, 2020). Consequently, the capacity to reflect on one's cognition (i.e., metacognition) and to monitor the conflict between self and others' views (i.e., executive functions) rely on brain areas associated with self-awareness, located in the default mode network with the right temporal junction (rTPJ) as a specific hub for self-other distinction and executive functions controlled by prefrontal areas (Gallese, 2001; Gallup and Platek, 2002; Shamay-Tsoory, 2011).

Finally, Decety and Jackson (2006) highlights a third component, self-regulation, enabling one to maintain a distinction between self and other perspectives and a stable sense of self (i.e., homeostatic state) to avoid personal distress (Eisenberg, 2002). The salience neural network supports this third component, connecting prefrontal areas with limbic structures through the insula and anterior cingulate cortex, associated body awareness and with the regulation of a stable sense of self (i.e., homeostasis) (Uddin, 2015).

Consequently, empathy is an aggregation of distinctive neurocognitive components following the maturation of specific brain areas. However, this mapping of empathy into distinctive neurocognitive components challenges how they interact with each other, echoing one of the major problems of neurosciences, wherein slicing the brain into specific functions loses the complexity of the mental processes initially studied (Pessoa et al., 2022). In an attempt to merge these different conceptualisations of empathy, this thesis investigated the distinctive and complementary roles of empathy facets and their association with IMC.

1.3.3 Impairments and prosocial outcomes of empathy

Evolutionary theories of human psychology conceptualised empathy as a crucial component of psychology, not restricted to humans but widespread in the animal kingdom (de Waal, 2008). Empathy is a pre-requisite for navigating complex social environments prevalent in human society across cultures and civilisations (Dunbar, 1998; Moore, 2021)[7]. Consequently, studying clinical conditions usually associated with difficulties in social interactions could shed light on empathy mechanisms (Blair, 2008).

Autism is an atypical neurodevelopmental condition that attracted considerable attention for its association with global difficulties in social interactions and, more specifically, cognitive empathy (Baron-Cohen et al., 1985; Blair, 2008). According to the broken-mirror hypothesis, these difficulties are rooted in dysfunctional MNS (Iacoboni, 2009; Oberman et al., 2008). Nevertheless, this hypothesis sparked scepticism due to insufficient empirical evidence and its oversimplification of the mechanisms leading to empathy difficulties encountered in autistic conditions (Fan et al., 2011; Southgate and Hamilton, 2008). Furthermore, abilities for empathy are reported in autistic populations, especially when framed in non-social contexts (Atherton and Cross, 2018; Gough, 2021). Consequently, a revised account of the putative empathy deficits in autism is ongoing, and new approaches such as the misattunement hypothesis suggest that the capacity to infer mental states results from interactions and, therefore, cannot be located within individuals (Milton, 2012; Bolis and Schilbach, 2020).

Similar to autism, psychopathy attracted interest in the research field of empathy as a hallmark of affective sharing deficits. Characterised by difficulties in experiencing others' emotions, psychopathy is considered a personality disorder, particularly prevalent in incarcerated populations because of increased antisocial behaviours (Cleckley, 1988; Ellis et al., 2019). This incapacity for understanding others' distress, such as fear, is suggested as a mechanism explaining tendencies for aggressive behaviours (Blair, 2005). Studies indicate a hypoactivation in psychopaths' brain areas involved in emotion processing when viewing others in painful or fearful situations (Arrigo and Shipley, 2001; Deming et al., 2020). Nevertheless, recent reviews cast doubts on these associations, pointing to methodological bias in sampled population (Jalava et al., 2021). Furthermore, some psychopaths display preserved empathy abilities, suggesting a more nuanced vision of this condition (Heym et al., 2019). Altogether, these contradictions highlight the gap in understanding the mechanisms underlying empathic deficits, questioning their origin and role in social interactions.

[7]By framing empathy as a distinctive feature of humanness, the empathy research field participated in the infra-humanization and the stigmatisation of these clinical conditions - see Gough (2021)

Echoing Hume's and Smith's conceptions of sympathy as guiding moral and ethical decisions, empathy is often associated with altruistic behaviours. According to the empathy-altruism hypothesis, feeling empathic toward someone can lead to altruistic tendencies for the sole benefit of the target of empathy (Batson et al., 2015). Nevertheless, the empathy-altruism hypothesis appears modulated by the conceptualisations and methods used for empathy and altruism assessments (Eisenberg and Fabes, 1990). Empathy can indeed backfire, and the emotional arousal experienced can trigger distress, leading to "psychic numbing" and incapacity to engage in helping behaviours (Eisenberg et al., 2010; Västfjäll et al., 2014). Therefore, whilst empathy can lead to positive outcomes, it requires maintaining self-other distinction to avoid maladaptive identification (Decety and Jackson, 2006). Thus, it is unclear whether the association between empathy and altruistic tendencies is a robust and generalisable observation and whether these associations are driven by empathy's cognitive and/or affective components.

Furthermore, studies investigating the association between empathy and prosocial outcomes tend to conflate the processes with its outcomes, sympathy or compassion, referring to the feeling of concern about the welfare of the other (Decety, 2010; Singer and Klimecki, 2014). This confusion can be traced back to the initial difficulties delineating these terminologies. For example, Lipps considered sympathy a form of "positive" empathy experienced when encountering someone triggers positive affect. In contrast, "negative" empathy was understood as an intrusive and unpleasant sensation (Jahoda, 2005). However, for Titchener, empathy was associated with unfamiliar situations, while sympathy referred to familiar experiences (Lanzoni, 2012). Therefore, there is an intertwining between empathy and autobiographical experiences. As such, individuals tend to feel more for those who are similar or from desirable social groups, leading to parochial empathy (Bloom, 2017; Decety, 2010; Fleischacker, 2019). Nevertheless, the initial conflation between empathy's affective and cognitive facets and its outcomes highlights the current lack of understanding of empathy mechanisms.

Consequently, the difficulties in defining and assessing empathy occurred since its earliest conceptualisations, threatening empathy as a research field. Nevertheless, despite a fuzzy definition, empathy still attracts research interests, and empirical evidence suggests its entanglement with body awareness, recalling its initial association with body motion. By exploring the association between empathy facets and IMC, this thesis attempted to reunify their theoretical accounts by investigating their plausible shared neurocognitive mechanisms in the context of non-verbal HCI.

1.4 Research Questions

To summarize, IMC and empathy are two research fields that have attracted interest due to their association with affiliation and altruism. Nevertheless, these two concepts are multidimensional, and their respective facets are often conflated, challenging the emergence of a consensus on the conceptualisation and mechanisms of IMC and empathy (Ayache et al., 2021; Heym et al., 2019). Despite their shared history associated with the tendencies for spatiotemporal alignment in social and non-social contexts, IMC and empathy nurtured distinct streams of research.

Common neurocognitive mechanisms have been identified with the perception/action matching system (or MNS) suggested as a core component of IMC and empathy, associated with the conflict monitoring system, for detecting misalignment between self and others (Gallese, 2001; Decety and Jackson, 2006). Yet, despite their reliance on possible shared mechanisms, the literature on IMC and empathy seldom refer to each other. Consequently, the first goal of this thesis was to explore the association between IMC and empathy by considering their respective contributions to non-verbal social interactions.

The experimental investigations of IMC and empathy also suffer methodological limitations. Psycho-biological mechanisms and social influences are often entangled, and the multiple facets of IMC and empathy are often neglected (Bloom, 2017). This calls for a paradigm shift in social neurosciences to explore the dynamics of social interactions. Virtual agents have been suggested as potential interesting experimental tools for replicating human behaviours (Dumas, 2011; Pan and Hamilton, 2018). Yet, it remains to clarify if they are credible enough to elicit affiliation (Fernández Castro and Pacherie, 2021). Consequently, the second goal of this thesis was to delineate the appropriate use of virtual agents in investigating the dynamics of social interactions.

This subsection will introduce the two main research questions of this thesis, namely (i) **What is the association between motor coordination and empathy?**, with a focus on motor empathy, suggested as a possible overlap with IMC conceptualisations, and (ii) **Can virtual agents replicate non-verbal human social interactions?**, with a focus on investigations using virtual agents, stressing their current limitations and remaining open questions. Finally, a brief overview of the experimental works conducted during this thesis will be provided.

1.4.1 What is the association between motor coordination and empathy?

Interpersonal coordination and empathy share a common history, deriving from sympathy, referring to the affinity between things (Jahoda, 2005). Whilst the mathematician Huygens observed the "odd sympathy" between clocks synchronising, Smith and Hume developed a philosophical conceptualisation of sympathy as holding society together. These mathematical and philosophical accounts of sympathy remain vivid in the modern conceptualisations of interpersonal coordination and empathy. Despite the action/perception system suggested as a plausible common mechanism for mirroring (Gallese, 2001), mixed findings are reported on the association between IMC and empathy, stressing the difficulties in merging these multidimensional concepts.

For example, Preissmann et al. (2016) failed to show any association between empathy and synchrony in implicit and explicit coordination tasks. Still, they did not consider the distinctive influence of affective and cognitive facets of empathy. In contrast, studies using self-report and behavioural measurements of cognitive empathy reported a positive association with goal-oriented interpersonal coordination (Koehne et al., 2016b; Novembre et al., 2019). However, whilst Novembre et al. (2019) suggested that the capacity to attribute independent mental states leads to improved goal-oriented motor coordination, Koehne et al. (2016a) observed that motor coordination training improves the capacity for perspective-taking, usually associated with cognitive empathy. Similarly, studies investigating the association between empathy and imitation failed to provide consistent findings. For example, Sonnby-Borgström (2002) and Drimalla et al. (2019) reported a positive association between facial mimicry and affective empathy measured by self-reports. In their meta-analysis, Holland et al. (2021) provide evidence supporting the existence of a correlation between facial mimicry and empathy, although they acknowledged variabilities and inconsistent findings in the literature. In contrast, Cracco et al. (2018) reported null or weak associations between self-reports of empathy and automatic imitation, measured by stimulus-responses compatibility effects.

These mixed findings highlight the problematic fuzzy taxonomy of interpersonal coordination and empathy measures and the difficulty in mapping the causal mechanisms linking the two concepts. Their common reliance on shared neural networks may support the notion of a domain-general system linking motor coordination with empathy - see **Figure 1.2** for an overview[8]. Consequently, this thesis aimed to clarify the association between interpersonal coordination and empathy by considering their distinct facets.

[8] Although not explored in this thesis, recent studies have also highlighted the role of the cerebellum, a brain area traditionally associated with motor coordination but recently expanded to social cognition (Sokolov et al., 2017; Van Overwalle et al., 2020)

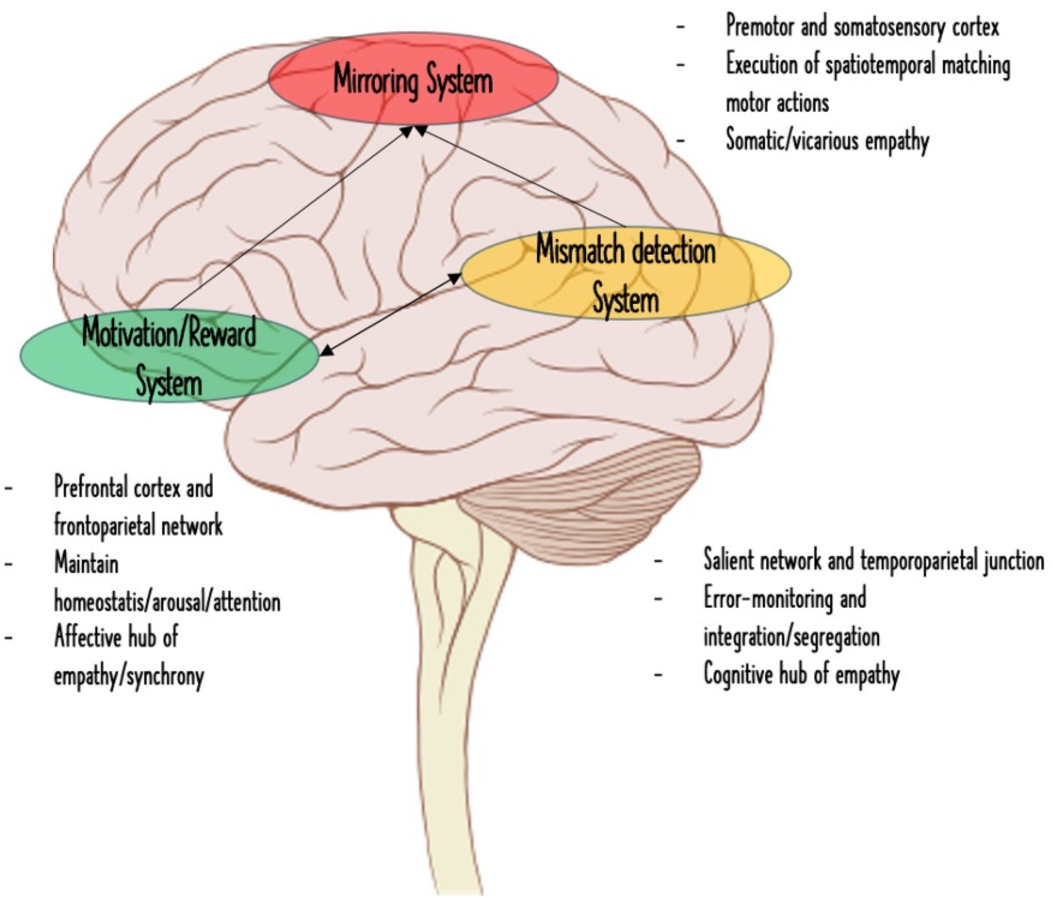

Fig. 1.2 Neural networks involved in interpersonal motor coordination and empathy

The self-other overlap/distinction mechanism is particularly interesting and considered a core component of IMC and empathy (Lamm et al., 2016; Heggli et al., 2021). Self-other overlap is key in predicting others' movements (Novembre et al., 2016). However, perspective taking, and by extension, the capacity to attribute independent mental states (self-other distinction), is also a requirement for achieving goal-oriented motor coordination (Heggli et al., 2019; Novembre et al., 2019). Neuroanatomical accounts suggest that self-other overlap is associated with the activation of the sensorimotor area and the MNS (Cacioppo et al., 2014), whilst self-other distinction relies on prefrontal areas and temporoparietal junction, associated with perspective taking and ToM network, that are also activated during motor coordination (Quesque and Brass, 2019). Consequently, Tognoli et al. (2011) suggested that successful interactions lie between integration and segregation, where self-other overlap and distinction are not contrary but complementary[9]. However, how these subjective experiences of integration/segregation of the other map with effective motor coordination is unclear.

[9]The complementary nature of self-other overlap/distinction is inspired from the complementarity principle suggested by Niels Bohr on quantum mechanics - see Engstrøm and Kelso (2008)

To complicate matters further, IMC sometimes refers to a specific component of empathy, labelled as motor or kinesthetic empathy. Introduced by Bell and Bastian in 1880, kinesthesia was considered a sixth sense associated with muscle sensibility and awareness of motion (Paterson, 2012). This conceptualisation of kinesthesia overlaps with the notion of proprioception, referring to the representation of the spatial and mechanical location of the body. Proprioception is a central element of Gibson's theory of affordances (Gibson, 1977), considered a core mechanism integrating information from other sensory modalities (Stillman, 2002). On the one hand, motor empathy describes a tendency to synchronise or mimic someone else's gestures, such as facial expressions, vocalisations, postures, and movements (Blair, 2005). This conceptualisation matches definitions of IMC but does not distinguish between spatial and temporal matching of movements. On the other hand, kinesthetic empathy refers to the emergence of mutual understanding through perceived changes in body sensations (Foster, 2010; Fuchs, 2017). Echoing initial conceptualisations of empathy, kinesthetic empathy remains restricted to artistic or therapeutic settings (Castro Jaramillo and Panhofer, 2022; Koch and Rautner, 2017). Consequently, whilst motor empathy matches the definition of IMC, kinesthetic empathy refers to the perception and awareness of body sensations. Therefore, there is a need to investigate the association between motor empathy, understood as an objective measure of behavioural motor coordination and kinesthetic empathy, associated with a subjective experience of IMC.

Renewed interest in body awareness paves the way for investigating the association between IMC and empathy. Recent models of interoception suggest adopting a multidimensional approach to disentangle (i) accuracy, the behavioural performance, from (ii) sensibility, the self-evaluated assessment of performance, and (iii) awareness, the congruence between accuracy and sensibility (Garfinkel et al., 2015). Nevertheless, interoception measures focus on visceral sensations and perception of internal bodily changes. Therefore, it is unclear if this model is appropriate for studying the association between kinesthetic and motor empathy and to what extent this can shed new light on their association with affective and cognitive components of empathy. Furthermore, the distinction between kinesthetic and motor empathy could expand recent findings, stressing a potential discrepancy between the "feeling" of being in synchrony and the effective behavioural coordination on affective and cognitive outcomes of interpersonal coordination (Matthews et al., 2022; Noy et al., 2015). Consequently, this thesis investigated how these different facets of motor empathy measured through self-reports and behavioural assessments of IMC are associated with affective and cognitive facets of empathy.

1.4.2 Can virtual agents replicate human social interactions?

IMC and empathy encompass complex layers of psycho-biological mechanisms and tacit collective norms, rendering it challenging to disentangle biological from social influences. As suggested by the "second-person" neurosciences approaches, virtual agents could provide interesting tools for modelling human behaviours by reducing their complexity to delineate variables of interest, providing more parsimonious theoretical models (Dumas, 2011; Pan and Hamilton, 2018). However, there is a need to outline the particular social phenomena in which virtual agents are appropriate for investigating human-human interactions.

Similar to human-human interactions, the experience of synchrony and imitation with a virtual agent can increase trust, closeness, and empathetic concerns (Grynszpan et al., 2017; Hasler et al., 2014). Virtual agents that automatically mimic individuals are rated more persuasive and likeable than those who do not mimic (Bailenson and Yee, 2005). These "digital chameleons" are even more efficient than humans in passing a non-verbal Turing Test (Bailenson et al., 2008). Initially restricted to humanoid avatars, similar effects can be observed with abstract representations (Sun et al., 2019; Tamborini et al., 2018; Tarr et al., 2018)[10]. However, detrimental effects have also been reported; mimicking agents can fail to induce experiences of self-other overlap or likeability, and, when detected, mimicry can reduce perceived trustworthiness (Bailenson et al., 2008; Verberne et al., 2013). These findings suggested that a stereotypical replication of human behaviours can be perceived as robot-like, leading to "phoney" interactions. Nevertheless, it remains unclear if IMC in CMC is sufficient for eliciting the prosocial outcomes usually observed in face-to-face settings.

Consequently, this area of research also raises important ethical considerations regarding their applications for designing anthropomorphic social agents with potentially harmful consequences, such as replacing human task forces or creating deceptive communications (Ruane et al., 2019; Slater et al., 2020). More importantly, virtual agents question the implicit social contract underlying human interactions and challenge our definition of humanness, a core but neglected aspect of the research studies targeting artificial intelligence and empathy (Gough, 2021; Mills, 2014). Consequently, this thesis will also examine virtual agents' ability to elicit a sense of self-other overlap and be perceived as humans.

[10] Visuomotor synchrony can induce body illusions, also known as the "Proteus Effect" - see Botvinick and Cohen (1998) and Yee and Bailenson (2007). Notably, these body illusions increase capacities for adopting others' perspective-taking, illustrating the intertwinement between IMC and empathy - see (Maister et al., 2015)

According to the Computer-As-Social-Agent (CASA) model of anthropomorphism, humans tend to apply social heuristics when interacting with computers (Nass et al., 1994). Therefore, this model suggests that humans behave similarly in human-human interaction and HCI. Alternatively, the 3-factor model of anthropomorphism suggests that the tendency to perceive a virtual agent as a human is driven by the desire to decrease environmental uncertainty, leading to attribute human agentivity when randomness and unpredictability are perceived (Epley et al., 2007). According to this model, the excessive predictability displayed by virtual agents would impede their capacity to be perceived as human and, therefore, buffer affiliative tendencies.

Furthermore, previous studies neglected potential confounding factors influencing the affiliative and prosocial outcomes of IMC, such as shared intentionality. Perceived joint commitment in goal-oriented motor coordination is also a key mechanism associated with prosocial outcomes (Tomasello et al., 2005; Tomasello, 2009). Observing coordinated movements can elicit a sense of a shared goal (Michael et al., 2016). In human-virtual agent interactions, perceived successful goal achievement rather than synchrony per se was associated with increasing trust (Launay et al., 2013). Consequently, the commitment associated with goal-oriented IMC appears more important than the effective completion of coordinated movement. These observations stress the need to delineate effective behavioural synchrony from self-reported experience.

Nevertheless, shared intentionality and joint commitment not only fulfil human needs for predictability and goal achievement but are rooted in our fundamental need to belong and nurture affiliation. Our need for belonging might be absent during human-robot interactions, impacting our ability for joint commitment as a result of their lack of credibility as social agents (Fernández Castro and Pacherie, 2021; Fernández-Castro and Pacherie, 2023). Whilst this statement was initially restricted to human-robot interactions, the tendency for objectification observed during human-virtual agent interactions suggests that this could also be extended to HCI context (Nowak and Fox, 2018). Despite tendencies for anthropomorphism, accumulative evidence highlights that humans tend to reject friend requests from a hyper-realistic avatar because of their feeling of eeriness recalling the "uncanny valley" effect observed in robot interactions (Mori, 1970; Shin et al., 2019). Furthermore, Székely and Michael (2018) reported that participants tended to disengage more often from joint commitment when they believed in interacting with an algorithm. These findings highlight that the implicit social contract underlying human-human interactions is not automatically extended to virtual agents. Consequently, this thesis seeks to disentangle the complex interplay between sensory-motor components and social influences in the context of HCI.

1.4.3 Overview of the experimental protocols

To summarise, togetherness is a vast territory encompassing various definitions and conceptualisations. Often understood as "being with" involving a sense of co-presence and mutual awareness, togetherness can be mapped into moving (i.e., motor coordination) and thinking (i.e., empathy) together. However, despite an initial entanglement with aesthetic experiences, interpersonal coordination and empathy are two segregated research fields that have developed distinctive theories of interpersonal coordination. This thesis aimed to investigate their overlap and distinctiveness across several online and in-lab experiments by answering the following research questions:

(i) What is the association between motor coordination and empathy?

This first research question is addressed in the experiments reported in **Chapters 3**and **6**. **Chapter 2** introduces in more depth the HKB, alongside a brief overview of the theoretical principles of synergetics and its application in describing the emergence of coordination patterns and, in particular, synchrony (Haken et al., 1985; Haken, 1987). This chapter also discusses the initial challenge of measuring empathy, leading to the emergence of psychology as a scientific discipline (Farr, 1983). **Chapter 5** introduces the methods for assessing automatic imitation, another facet of interpersonal coordination (Heyes, 2011). Finally, this chapter introduces electrophysiological measures of the action/perception and conflict monitoring systems involved in imitation and empathy (Hobson and Bishop, 2017).

(ii) Can virtual agents replicate non-verbal human social interactions?

This second research question is addressed in the experiments reported in **Chapters 4** and **7**. **Chapter 2** introduces and discusses the methods for measuring the affiliative and altruistic outcomes usually associated with IMC and empathy. **Chapter 5** discusses the concept of anthropomorphism and the lack of consensus on measuring characteristic features of humanness (Bartneck et al., 2009). This chapter also introduces different cognitive empathy measures, also labelled as ToM, and discusses its application to HCI (Beaudoin et al., 2020).

Notably, the experimental investigations associated with this thesis took place during the COVID-19 pandemic. Consequently, **Chapters 2, 3 and 4** describe the first online data collection. **Chapters 5, 6 and 7** report the second in laboratory data collection using electrophysiological measures.

Complementary investigations were also conducted during this thesis, exploring the "dark side" of IMC and empathy. The literature investigating IMC mainly focuses on spatiotemporal matching. However, mismatched states dominate social interactions, and coordination patterns are dynamic states, changing over time (i.e., non-stationary), allowing for adaptability (Jeon and Kim, 2018; Motter, 2010; Tronick and Cohn, 1989). Consequently, the research field of social neurosciences must move beyond imitation and synchrony (Hasson and Frith, 2016)[11].

Flexibility (i.e., being in and out of matching states) is suggested as a better marker of functional interactions (Dahan et al., 2016; Mayo and Gordon, 2020; Ravreby et al., 2022)[12]. Empathy research also considers similar approaches, stressing the need to distinguish between self and others (Levy and Bader, 2020). Therefore, the capacity to preserve self-boundaries despite environmental changes is a crucial component defining living systems (Maturana and Varela, 1991). Consequently, self-regulation is vital, and failures in maintaining boundaries are usually associated with detrimental outcomes (Coutinho et al., 2019; Galbusera et al., 2019; Zaki, 2014).

In particular, excess of affective empathy can lead to emotional distress when capacities for self-regulation are unavailable (Singer and Klimecki, 2014). Similarly, developmental studies highlight emotion dysregulation in motor-coordination disorders (Rigoli et al., 2012), whereas affect-related disorders are associated with motor-coordination difficulties (Varlet et al., 2012). In turn, motor coordination studies have also reported an effect of spontaneous imitation and goal-oriented joint action on self-regulation capacities (Dalton et al., 2010; Vink et al., 2017). Consequently, the broader literature shows detrimental interrelations between motor coordination, empathy, and self-regulation in behavioural outcomes Cummins et al. (2005).

Possible shared pathways associating IMC and empathy with self-regulation processes were explored during this thesis, such as alexithymia, characterised by difficulties in recognising and labelling emotions, and interoception suggested as potential mechanisms underlying empathy deficits (Bird and Viding, 2014; Fukushima et al., 2011; Grynberg and Pollatos, 2015; Palmer and Tsakiris, 2018). However, these investigations are not reported in the present manuscript, but preliminary findings were presented during scientific conferences - see **Appendices A, B and C**.

[11]The notion of meta-stability describes these transient periods of stability. However, this notion suffers from a clear definition, and several conceptualisations co-exist in the literature - see Hancock et al. (2023) and Kelso (2021)

[12]Flexibility can also refer to the notion of complexity, understood here as Shannon's entropy, where surprise, that is, new information, is conveyed between two systems - see Schwartenbeck et al. (2013)

CHAPTER 2

METHODS - PART I

"What we observe is not nature itself, but nature exposed to our method of questioning"

- Werner Heisenberg

In the previous chapter, togetherness was introduced as a relatively new concept at the crossroads between different disciplines, focusing on Interpersonal Motor Coordination (IMC) and empathy. On the one hand, IMC, encompassing synchrony and imitation, attracted research interests considering its capacity for eliciting affiliative and altruistic tendencies. On the other hand, empathy, encompassing affective, cognitive and motor facets, is viewed as a core component for sustaining our ability to evolve in complex (social) environments, allowing affective sharing and mutual understanding. The two research questions addressed in this thesis are how these concepts are intertwined and how Human-Computer Interaction (HCI) can provide new insights into their associations. In this chapter, methods for measuring empathy and synchrony are introduced.

First, this chapter will introduce the concept of synchrony starting with the Central Pattern Generators (CPG), followed by a focus on the Haken-Kelso-Bunz model (HKB) of motor coordination. Then, methods and indexes used to record and compute synchrony will be discussed - measures associated with imitation will be introduced in **Chapter 5**. Second, this chapter will briefly introduce the history of empathy measurements, focusing on psychometric theories that conceptualise empathy facets as latent variables. Finally, this chapter will present methods and assessments measuring the outcomes of synchrony and empathy, namely affiliation and altruism, through self-reports and behavioural assessments.

Part of this chapter has been published as a systematic review titled **Exploring the "Dark Matter" of Social Interaction: Systematic Review of a Decade of Research in Spontaneous Interpersonal Coordination** in *Frontiers in Psychology* (Ayache et al. 2021).

2.1 Synchrony as a coordination pattern

Behavioural synchrony can be considered as a coordination pattern, an area of research that started in the early 20th century with the development of methods for movement decomposition such as the motion-picture projection or the chronophotography developed by Muybridge (1887) and Marey (1894). These methods gave rise to artistic and scientific investigations of locomotion and coordination patterns that influenced the cinematography industry's development and the workplace's transformation during the Industrial Revolution (Federici, 2020). Simultaneously, motion analyses paved the way for investigating psychiatric conditions, first labelled as psychogenic movement disorders such as hysteria, nowadays known as functional neurological symptom disorders (Miyasaki et al., 2003; Richer, 1895). Consequently, motion analyses attracted considerable attention, coinciding with the simultaneous development of the conceptual framework associated with empathy. Hence, it is not surprising that empathy and synchrony were already entangled.

Whilst the scientific observations of an "odd sympathy" between two pendulums reported by Huygens remained unexplained for centuries, the renewed interest in motion during the Industrial Revolution gave rise to the first attempts toward understanding synchrony of oscillators undergoing a periodic forcing such as Raleigh with vibrating pipes or Appleton and van der Pol with electronic circuits - see details in Pikovsky et al. (2002). Later, the first successful attempts to account for mutual synchronisation between two or more oscillators only appeared within the mathematical models of Kuramoto or HKB (Haken et al., 1985; Kuramoto, 1975). Whilst the Kuramoto model provides a mathematical formulation describing how the synchronisation of large populations of oscillators takes place, the HKB provides a mathematical formulation describing the scenario found in experiments testing the coordination between the periodic flexion-extensions of two index fingers (Kelso, 1984). The model uses a couple of oscillators to describe how the sudden change from anti-phase to in-phase appears, interpreted as a phase transition analogue to physics (Kelso, 2021). In the context of this thesis, the HKB was used to model IMC in the context of HCI. Therefore, the details of the mathematical formula and principles of the HKB will be explained in this section, starting with the conceptualisations of motor coordination as coupled oscillators.

2.1.1 Synchrony as oscillators

An oscillator can be defined as a system that executes periodic behaviour, and its motion can be visualised within a phase space (also called state phase), providing a graphical representation of the state of the system by plotting the evolution in time of its position against its velocity. Whilst oscillators such as pendulums can take any trajectories in the phase space, depending on the initial height from which they are dropped, biological and physical systems such as neurons or cardiac cells are characterised by a stable state, with specific periods and amplitudes, to which the oscillation returns soon after a transient perturbation is applied. Such dynamical systems are also called "life-cycle" oscillators. They are usually considered "open systems" as they require dissipative mechanisms (i.e., inhibition) and a source of energy (i.e., excitation) to maintain and return to their stable amplitude after small perturbations (Strogatz and Stewart, 1993). Although primarily studied in physics, the mathematical descriptions of oscillators provided essential insights for computational synchrony models[1].

Investigations of the neurophysiological basis of locomotion in vertebrates revealed the existence of the Central Pattern Generators (CPG), a population of self-organised neurons described as oscillators, characterised by periodic variation of their electrical activity around an equilibrium point (Grillner, 1985). Initially observed in decerebrate cats (Brown, 1914; Sherrington, 1906), the CPG are also present in the human spinal cord and composed of motor neurons and interneurons located in the spinal cord and brainstem generating rhythmic motor behaviours such as locomotion, breathing or mastication through a combination of hard-wired neural circuits and principles of natural selection (Dimitrijevic et al., 1998; Golubitsky et al., 1999; Minassian et al., 2017; Yuste et al., 2005)[2]. Consequently, it is unsurprising that the oscillator models inspired computational synchrony models such as Kuramoto or HKB models.

2.1.2 The Haken-Kelso-Bunz model

Inspired by the theory of coupled oscillators, the HKB was driven by Kelso's observations (1984) and the interdisciplinary research field of *synergetics* (Haken, 1987). Synergetics (i.e., working together) constitutes a set of principles and mathematical tools to explore the formation and self-organisation of patterns in so-called complex systems. Through the resolution of sets of differential equations, synergetics aims to identify the dynamics of a system and predict its evolution in time.

[1]Oscillators can model discrete and rhythmic behaviours for describing circadian rhythms with multiple external and internal oscillators - see Dijk and von Schantz (2005) and Jirsa and Scott Kelso (2005)

[2]Although it remains unclear if the CPG networks are generating rhythms through "pacemaker neurons" or "pacemaker networks" (Guertin, 2013; Harris-Warrick, 2010; Hooper, 2000; Katz, 2016).

More specifically, synergetics seeks to identify the conditions required for maintaining stability, when patterns can maintain their shape and behaviour despite some perturbations, referred to as attractors. Haken proposed to describe the dynamics of systems employing order and control parameters, where the order parameter is the dependent variable capturing the pattern observed at the desired scale, whilst the control parameter is the independent variable that influences pattern formation. Applied to motor coordination, this approach led to the formulation of the HKB model, in which the order parameter, capturing the timing between two fingers oscillating, is the difference between the phase of each of those oscillations (annotated with the letter phi ϕ). The control parameter is the frequency of the oscillations, represented by the ratio between b/a. According to this mathematical model, the motor coordination pattern is bistable when b/a is $< .25$ (i.e., low frequencies), with in-phase ϕ = 0 and anti-phase ϕ = ± π as attractors (i.e., stable solutions), where π radians correspond to 180°, and is monostable for b/a > 0.25 (i.e., high frequencies), with ϕ = 0 as the sole remaining attractor – see Equation 2.1:

$$d\phi/dt = -a\sin\phi \; - 2b\sin\; 2\phi \tag{2.1}$$

Predictions formulated by HKB were initially applied to intrapersonal motor coordination (Kelso, 1984) and expanded to human-human (Schmidt and Richardson, 2008) and human-animal (Lagarde et al., 2005) coordination, but also between brain regions (Bressler and Kelso, 2016). Based on the HKB, a Virtual Partner of Interaction (VPI) reproduces IMC in controlled experimental settings (Dumas et al., 2014a; Kelso et al., 2009), and has been applied to study difficulties in motor coordination in autism and to identify the neural networks of motor coordination (Baillin et al., 2020; Dumas et al., 2020).

2.1.3 Indices of synchrony

For the aims of this thesis, the VPI has been used to assess the association between synchrony and empathy and their association with prosocial outcomes in the context of HCI. HKB offers a model predicting the relative phase between two oscillators, considered as an index of synchrony, measuring the latency between the oscillators' life cycles, determined by peak-to-peak displacement (Kelso et al., 1987). The relative phase is usually expressed in terms of the circumference around the unit circle, where two oscillators perfectly aligned in time will display a relative phase of 2π equivalent to 0° or 360°, whilst two oscillators that are anti-phase will display a relative phase of ± π, equivalent to 180°.

This thesis computed the relative phase from the movements extracted from the 2-D trajectories recorded while participants performed a motor coordination task with the VPI. The relative phase (i.e., the difference between the participant and VPI's phase movements) was calculated based on Baillin et al. (2020)'s formula by a mathematical function returning the phase angle in radians as a complex number, using the analytic signal concept based on the Hilbert Transform - see **Figure 2.1** for a graphical illustration and more details see Pikovsky et al. (2002).

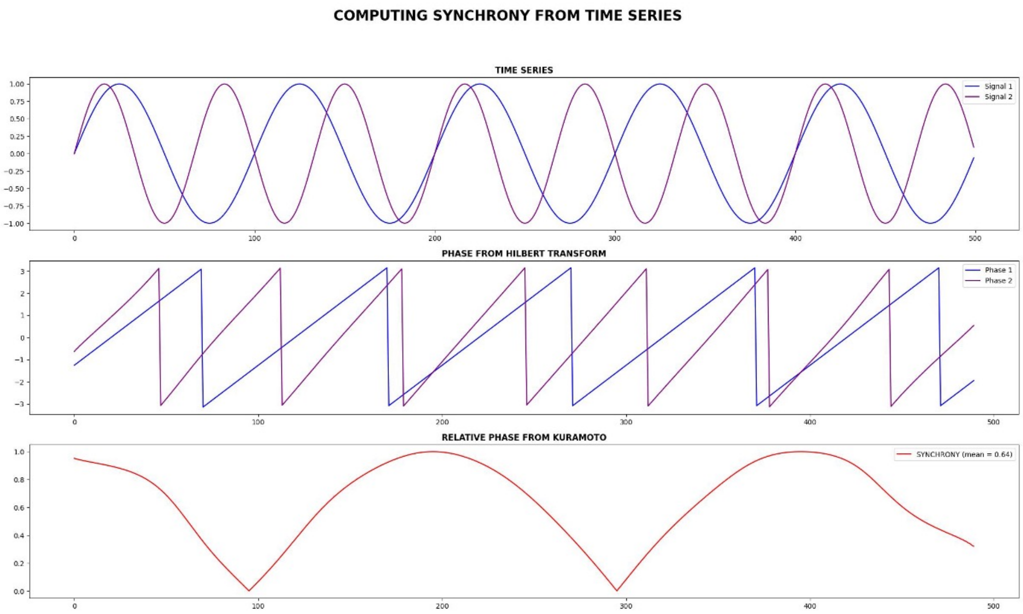

Fig. 2.1 Illustration of the extraction of synchrony scores from individual trajectories

Importantly, the relative phase is not the sole measure of synchrony. Synchrony indexes are method-dependent and often vary from one study to another. The recent development in motion tracking systems offers a wide range of apparatus for recording body movement, ranging from low-cost equipment, such as standard video recordings (Abney et al., 2015; Fujiwara and Daibo, 2016; Wiltshire et al., 2019) or Kinect cameras (Galbusera et al., 2019; Papadopoulos et al., 2014) to more expensive technologies such as accelerometers (Cheng et al., 2017; Varlet et al., 2014) or infra-red cameras (Varlet et al., 2011). However, the variation of methods for recording body motion has led to the multiplication of synchrony indices, rendering it difficult to compare results across studies.

Video recordings, for example, do not allow precise measurement of synchrony but coarse-grained evaluation of motion by extracting movement from pixel frame differences (Paxton and Dale, 2013; Ramseyer, 2020). However, machine learning can now be applied to video recordings, allowing more precise tracking of limb movements with techniques such as DeepLabCut (Mathis et al., 2018) or OpenPose (Cao et al., 2017). Yet, these methods involve high computational costs and require computers powerful enough to extract meaningful information from video recordings. On the other hand, infra-red cameras or accelerometers allow more precise tracking of movements by reconstructing their trajectories in 3-D spaces, allowing the computation of more fine-grained measures of synchrony such as cross-wavelet coherence (Hale et al., 2020) or recurrence quantification analysis (Shockley, 2005). Nonetheless, it is important to acknowledge that synchrony comes with different flavours. As pointed out by Delaherche et al. (2012) and Schoenherr et al. (2019), a more careful assessment of synchrony indices is required, and indices reported in the literature are not necessarily converging. As the next section will demonstrate, the research field of empathy shares similar difficulties with its measurement methods.

Moreover, synchrony can be assessed through various behavioural tasks involving rhythmic activities such as walking (Cheng et al., 2017,0), rocking chairs (Demos et al., 2012), finger flexion (Nordham et al., 2018), finger tapping (Heggli et al., 2019), body-conversation (Galbusera et al., 2019), or simply requiring participants to stay near each other (Varlet et al., 2011). More naturalistic paradigms are also developed thanks to new technologies allowing the recording of body movement outside the laboratory, such as in concert halls (Bishop et al., 2021) or during mother-infant interactions (Long et al., 2020). Combined with eye-tracking (Bishop et al., 2021) or electrophysiological recordings such as cardiac activity (Konvalinka et al., 2011) or neural activity (Nguyen et al., 2020), these methods offer new ways for exploring the sense of togetherness through multimodal measurements.

Nevertheless, the multiplication of paradigms renders it challenging to disentangle the role of synchrony from its context. For example, it is unclear if synchrony is the sole driver of social bonding or the performance of enjoyable activities such as listening to music (Demos et al., 2012), practising sports (Cohen et al., 2010), music (Gordon et al., 2020b), or collaborative team problem solving (Wiltshire et al., 2019). Recent studies reported indeed opposite results regarding the impact of synchrony on affective state, and it is unclear if synchrony is a facilitator or an outcome of emotional alignment (Smykovskyi et al., 2022; Tschacher et al., 2014) - for further details, see **Section 2.3.1**. Consequently, the VPI could also help to disentangle behavioural synchrony from its social context and provide new insights into its impact on affective states.

2.2 Empathy as a multidimensional personality trait

Contrary to synchrony, empathy is difficult to reduce to a physical phenomenon. Psychological states such as empathy are inherently "private" and can be assessed only by indirect measurements (Boring, 1953; Brock, 2018; Lang, 2010). Therefore, the history of empathy measurement is closely intertwined with the development of psychology as a scientific discipline. The first accounts of empathy were based on introspective methods combined with physiological recordings of muscle activity (Kroker, 2003; Lanzoni, 2009). Labelled as descriptive psychology, these methods were inspired by the phenomenological approach developed within the Act Psychology, investigating the process of thoughts rather than their structure (Hackert and Weger, 2018). This method was later promoted by Husserl and Merleau-Ponty, suggesting phenomenology as a suitable methodology for scientific endeavours and exploring consciousness states (Varela, 1996).

Nevertheless, disagreements emerged among the first scientific psychologists. For example, Wilhelm Wundt, described as the father of experimental psychology, restricted introspection to study "inner perception" (i.e., sensations), complying with the scientific criteria for replicability (Asthana, 2015; Boring, 1953). However, the conceptualisation of introspective methods diverged among researchers and this lack of consensus culminated with the "Imageless thought" controversy, opposing Titchener and the Würzburg School on the existence of thoughts without mental imagery, a clinical condition nowadays known as "aphantasia" (Arcangeli, 2023). According to Wundt, introspective methods were unsuitable for investigating higher cognitive functions such as empathy or religion, contributing to the segregation of psychology from sociology and inspiring Durkheim's works on collective representations instead of individual experiences. Although introspection persists in therapeutic settings and has been reintroduced for investigating consciousness states, it was discredited as a method for scientific investigation in favour of quantitative approaches such as psychometrics.

This section briefly reviews the development of statistical methods for the systematisation of inter-individual difference measurements, focusing on factorial analyses used in this thesis for investigating the structure of the affective, cognitive, and kinesthetic components of empathy. Finally, a short review of the questionnaires used for assessing empathy as a personality trait is presented, highlighting their current strengths and limitations.

2.2.1 The birth of psychometrics

Departing from introspection, the introduction of quantitative methods in psychology can be traced back to the history of applying statistical methods in social sciences. The Industrial Revolution in Europe led to a drastic shift in population demographics, and technological advancement was associated with a sudden rise in population (Khan et al., 2008). Population censuses were scrutinised, and mathematical methods were introduced for monitoring population demographics, leading to the incursion of politics and social policies in psychology. Echoing the former association suggested by Smith and Hume between sympathy and ethics, the history of psychology, and by extension empathy, is entangled with the establishment of social norms, where the crude cut-off between pathological and normal behaviours remains controversial (Foucault, 1988; Bracken and Thomas, 2005). Nevertheless, quantitative personality trait assessment remains the most widespread method for investigating stable behavioural patterns that capture and delineate inter-individual differences.

For example, Adolphe Quetelet used statistics to model antisocial behaviours and developed the idea of an "average man" as a model for society (Quetelet, 1835). A similar approach was adopted by Sir Francis Galton, who founded anthropometry, a discipline dedicated to measuring humankind (Lundgren, 2013). Importantly, anthropometry came with different flavours[3], as illustrated by the work done by Charles Roberts, who underlines the environmental exposure to pollution and adverse environment as a factor of malformation and diseases in working-class populations in industrial areas (Smith, 2020). Nevertheless, the development of statistics participated in developing methods such as psychometrics, also known as "differential" psychology, for investigating inter-individual differences in personality traits.

Traditional trait theories have often adopted the scientific positivism approach or nomothetic, attempting to unravel general or universal laws of human psychology in contrast to psychoanalytic approaches that focus on idiographic approaches trying to explain the specificity of individual trajectories (Barone and Kominars, 1998; Zuroff, 1986). Developed by Allport, Cattell and Eysenck, trait theories postulate that personality is a stable tendency to display patterns of behaviour, thought, and emotions manifest in various situations (Costa and McCrae, 1998). According to Allport, personality can be understood as "dispositions" for actions. Yet, these dispositions can be understood as central that are more or less present in every individual from secondary dispositions activated in specific context (Novikova, 2013).

[3]Important figures of anthropometry and psychometrics were the focus of controversies considering their acquaintance with eugenism, setting the goal to improve mankind through genetic selection - see Gillham (2001), Tucker (2010) and Winston (2020).

Traits can be assessed solely by questionnaires measuring respective observable behavioural tendencies (or habitual responses) and with behavioural measures and electrophysiological recordings (Boyle et al., 2016). According to Cattell, one can distinguish between "surface" traits, clusters of observed variables, and "source" traits underlying behaviour causes. Furthermore, Cattell delineated source traits as constitutional from environmental traits, paving the way for studying the interaction between genetic inheritance and environmental influences (Revelle, 2009)[4]. Consequently, personality traits can be understood as underlying traits that are not directly observable but estimated through latent variables, that is, concepts not directly measured but inferred from the structure of a dataset[5]. The following section reviews the various statistical methods that are relevant in the measurement of traits and identification/extraction of the latent variables.

2.2.2 G-Theory and factorial analyses

Contrary to the classical theory of measurement postulating a single source of residuals as an error of measurements, psychometrics is inspired by the Generalizability Theory, postulating that errors can be traced back in inter-individual variability (Vispoel et al., 2018). This approach, also known as G-Theory, provides statistical tools for assessing the scalability of results, assessing their reliability and generalizability to other sampled populations. The reliability or consistency of questionnaires can be assessed by calculating Cronbach alpha (denominated by the Greek letter α), written as a function of the number of test items (N), the average of inter-item covariance (c) and the average variance (v) – see Eqn. 2.2:

$$\alpha = Nc/v + (N-1)c \tag{2.2}$$

Lower Cronbach alpha values indicate low reliability, values ranging from 0.6 to 0.8 indicate good reliability, whereas higher values (>0.95) can indicate redundancy. Cronbach alpha values are sensitive to the number of items and sample size. Therefore, questionnaires composed of a limited number of items tend to have lower reliability. In those cases, mean inter-item correlations indicate the internal consistency of the questionnaires (Hulin, 2001).

[4]Cattell also developed the concept of "syntality" conceptualised as a measure of "group personality" echoing the concept of group mind developed by Gustave Le Bon - see Cattell (1948)

[5]Alternative theories of personality are developed within the dynamical system framework, conceptualising personality traits as "attractor states" that ensure the stability of behaviours - see Richardson et al. (2014). However, these approaches require specific experimental methods, such as the Experience Sampling Method that allows repetitive measures of the same construct for quantifying its evolution over time - see Csíkszentmihályi and Larson (2014).

Alternatively, factorial analyses are designed to identify latent variables of a dataset. On the one hand, Exploratory Factor Analysis (EFA) is a data-driven approach, attempting to estimate the communalities in variance, that is, the latent factors shaping the dataset but not directly measured, without pre-existing assumptions about the structure of the dataset (Taherdoost et al., 2022). EFA has been traditionally used while initially developing and validating questionnaires to identify subscales and facets. This method is closely related to Principal Component Analyses (PCA), another statistical approach for reducing the number of variables. However, contrary to EFA, PCA does not assume the existence of underlying causes (i.e., latent variables) and does not distinguish between common, unique and error variance.

On the other hand, Confirmatory Factor Analyses (CFA) are theoretically driven when there are pre-existing assumptions about the underlying latent structure of the dataset. Here, a statistical model driven by theory is applied to the covariance matrix extracted from the dataset using Structural Equation Modelling (SEM) and tested against a null hypothesis (i.e., a statistical model where no constraints are applied to the dataset) using a chi-square test assessing the fitness of the statistical model (Taherdoost et al., 2022). The fitness of the model can also be determined by the Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC), that maximizes the likelihood of the data while taking into account the complexity of the model. Consequently, the AIC and BIC are sensitive to sample size and model parameters by weighting models that fit the data but remain parsimonious (Huang, 2017). These methods were used to test the factorial models derived from empathy theory, and further details on sample size considerations will be provided in the next section.

2.2.3 Empathy questionnaires

Empathy, conceptualised as a personality trait, can be measured through various questionnaires. However, consistent with the multiple definitions of empathy co-existing in the literature, Baldner and McGinley (2014) reported a lack of overlap between empathy scales and subscales using EFA, suggesting that these scales did not capture similar constructs. Among the scales tested, the widely used Interpersonal Reactivity Index (IRI) (Davis, 1980) is a questionnaire comprising 28 items (rated on a 5-point Likert scale, ranging from "Does not describe me well" to "Describes me very well"). A four-factor (i.e., latent variable) model was validated initially, distinguishing 4-subscales: (1) *Perspective Taking* (PT), the tendency to adopt the psychological point of view of others; (2) *Fantasy* (FS), the capacity to transpose imaginatively into the feelings of fictional characters; (3) *Empathic Concern* (EC), the tendency to feel sympathy and concern for others and (4) *Personal Distress* (PD), the tendency to experience anxiety and unease in tense interpersonal settings. However, research using the IRI sometimes combines the subscales into a two-factor model distinguishing only between affective (EC and PD) and cognitive (PT and FS) components that do not necessarily fit the datasets (Chrysikou and Thompson, 2016). Furthermore, as noted by Reniers et al. (2011), the IRI subscales PD and EC labelled as affective facets tend to conflate empathy with its outcomes, such as sympathy and emotional distress.

To overcome this limitation, Reniers et al. (2011) developed the Questionnaire of Cognitive and Affective Empathy (QCAE), merging IRI items with other empathy-related scales such as the Empathy Quotient developed by Baron-Cohen and Wheelwright (2004), the Hogan Empathy Scale (Hogan, 1969) and the Empathy subscale of the Impulsiveness-Venturesomeness-Empathy Inventory (Eysenck and Eysenck, 1978). The resulting scale comprises 31 items, scored on a 4-point Likert scale (1 = strongly agree to 4 = strongly disagree), divided into five subscales: (1) *Perspective Taking*, defined as " putting oneself in another person's shoes to see things from his or her perspective" and (2) *Online Simulation*, characterised by an effortful attempt to put oneself in another person's position by imagining what that person is feeling, together measure cognitive empathy. (3) *Emotion Contagion*, referring to the automatic mirroring of the feelings of others; (4) *Proximal responsivity*, the responsiveness aspect of empathic behaviour such as when witnessing the mood of friends or relatives in a social context, and (5) *Peripheral responsivity*, encompassing responses to fictional or detached contexts, together measure affective empathy. Whilst PCA initially suggested a five-factor structure, a CFA suggested a two-factor structure with the distinction of affective and cognitive facets (Reniers et al., 2011). However, the two-factor structure is not always appropriate and Myszkowski et al. (2017) stressed potential inconsistencies across studies and populations. Despite these limitations and inconsistencies already identified in the literature, the QCAE was used in the first part of this thesis, overcoming the limitations previously identified with the IRI. However, as the QCAE captures only affective and cognitive components of empathy, most research to date using this scale (or the IRI) solely does not incorporate assessments of motor empathy. Therefore, more specific assessments of this empathy facet were needed.

Targeting this specific facet of empathy, the Kinesthetic Empathy Scale (KinEmp) developed by Koehne et al. (2016b), composed of 9 items, attempts to assess the spontaneous tendency to mimic facial expressions, body gestures or bodily sensations. Though data associated with the KinEmp questionnaire are scarce, this scale requires further investigation and validation. To the author's knowledge, it is the only psychometric tool available to assess kinesthetic empathy. The study used to validate the KinEmp showed that practitioners of sports requiring higher levels of IMC, such as expert dancers, scored higher on this empathy scale, suggesting a positive association with IMC (Koehne et al., 2016b). Furthermore, this kinesthetic empathy measure was positively associated with affective and cognitive empathy (Koehne et al., 2016b). However, these assessments were performed using the Cognitive and Emotional Empathy Questionnaire, an empathy measurement that has not been widely used in the literature. Another limitation is that the KinEmp items are only formulated in terms of negative affective state. Consequently, although the KinEmp presents potential interesting properties, several limitations already have been identified for its use as a sole measure of motor empathy.

Addressing this limitation, the KinEmp was used in combination with the respective 10-item Somatic subscale from the Cognitive, Affective, and Somatic Empathy Scales (CASES) developed by Raine and Chen (2018). The CASES aims to assess positive and negative components associated with empathy's cognitive, affective, and somatic facets. The Somatic subscale is designed to self-report measures traditionally associated with motor empathy, such as facial mimicry or mirroring behaviours. Initially, CFA suggested a three-factor structure (i.e., cognitive, affective, and somatic) and a fine-grained six-factor structure distinguishing between positive and affective components. Studies using this scale have shown that somatic empathy, alongside the cognitive and affective subscale, was negatively correlated with aggressive behaviours, suggesting a potential negative association with psychopathy (Chen et al., 2021; Raine and Chen, 2018). Therefore, this scale was deemed helpful in overcoming the potential limitations associated with the sole use of the KinEmp. Designed for children and adolescents, this questionnaire has been expanded to the adult population (Raine et al., 2022). However, this data collection took place before this updated version was released.

This thesis used a combination of empathy scales to capture all desired aspects, including affective, cognitive and motor empathy. As a consequence of reviewing the broader psychometric literature, the QCAE, KinEmp and CASES were identified as appropriate measures to map onto the constructs we aimed to assess. However, to harmonise their scoring and allow factorial evaluation, all scales were subsequently scored on a 4-point Likert scale (1 = strongly disagree to 4 = strongly agree) in line with the initial scoring of the QCAE and subscale scores were calculated by summing the associated items. The factorial validation of the combination of these scales is shown in **Chapter 3**, and sample size considerations are discussed further below in the sampling subsection.

2.3 Outcomes of interpersonal motor coordination

IMC and empathy have both been associated with affiliative and prosocial outcomes, making these concepts popular in social psychology in studying altruism. However, what mechanisms drive the association between IMC, empathy, and prosocial outcomes remains unclear. On the one hand, it has been suggested that the positive affective state elicited by synchronous motor coordination drives its association with prosocial consequences (Hove and Risen, 2009). On the other hand, IMC is associated with the blurring of self-other boundaries that can drive prosocial outcomes due to tendencies for in-group bias (Cross et al., 2019; Reddish et al., 2013). Although not exclusive, it is unclear how these two mechanisms are associated and how they can be translated in the HCI context. This section examines the methods for assessing the affective, cognitive and prosocial consequences of IMC with a virtual agent.

2.3.1 Affective state measurements

Synchrony has been consistently associated with positive affective states (Galbusera et al., 2019; Hu et al., 2022; Mogan et al., 2017) and it has been suggested that mood improvement is due to synchrony's capacity to reduce environmental uncertainty, leading to "perceptual pleasure" (Hoehl et al., 2021; Hove and Risen, 2009). According to the opioid hypothesis, synchrony can activate the opioid system and increase the pain threshold following synchronous movement compared to asynchronous movement (Lang et al., 2017). However, other studies suggest that the effect of synchrony on pain may also depend on muscle exertion required to achieve motor coordination (Tarr et al., 2015). Finally, it is unclear if positive affective states increase tendencies for synchronising movements (Smykovskyi et al., 2022) or are an outcome of the execution of interpersonal motor coordination (Tschacher et al., 2014). Positive affective states are indeed associated with biased decision-making processes, leading to tendencies to overrate performance achievement and increased altruistic tendencies (Hommel, 2015). Therefore, a current causality problem must be addressed when investigating the association between affective states and interpersonal motor coordination.

The association between affective states and action lies at the core of emotion theories. As with empathy, the study of emotion has a convoluted history, illustrated by the debates arising about its conceptualisation and methods (Barrett, 2017; Johnston, 1905). First developed by Wilhelm Wundt, the notion of "Gefühl" referred to transient states described by their valence, arousal, and intensity (Barrett and Bliss-Moreau, 2009). In English, the word affect is associated with "producing change", and emotion derives from the Latin word "emovere", meaning "to move", linking affect and action (Bieńkiewicz et al., 2021). Evolutionary theories such as the Thalamic theory (Cannon,

1927) suggest that the physiological changes and subjective feeling of emotion (i.e., affect) are separate. Constructivism theories, such as the James-Lange theory (James, 1894), suggest that affect arises from body sensations, underlying the role of kinesthesia as a core aspect of emotion. Recent theories of emotions, such as the Two-Factor Theory (Schachter and Singer, 1962) or the Conceptual Act Theory (Barrett, 2014), suggest that emotion is the result of physiological arousal and the interpretation of this physiological change in light of environmental cues. Thus, whilst several theories of emotion co-exist in the literature, they all link emotions with body awareness and, by extension, with motion.

Methodologically, the "inner landscape" of emotions cannot be accessed directly but through indirect measurements such as (i) physiological change (e.g., skin conductance, heart rate), (ii) behaviours (e.g., approach, avoidance) or by self-reports, capturing the subjective feeling of emotions (Lang, 2010; Kreibig, 2010). Self-reports of emotions are based on coordinate systems (e.g., arousal and valence as separate dimensions) representing specific affective states such as the Self-Assessment-Manikin (Bradley and Lang, 1994)[6] or based on discrete models, mapping individual emotions (e.g., joy, anger) such as the Positive and Negative Affect Schedule (PANAS) developed by Watson et al. (1988). Previous studies used the PANAS for investigating the impact of synchrony on affective states (Galbusera et al., 2019; Llobera et al., 2016; Tschacher et al., 2014). Consequently, this measure was chosen to enable comparison with pre-existing findings. The PANAS uses a list of twenty words describing discrete positive and negative affective states (e.g., afraid, hostile, happy), where participants indicate to what extent these words describe how they feel this way "right now [...], at the present moment" using a 5-point Likert scales (e.g., very slightly to extremely). Several studies have confirmed a two-factor structure with high-reliability scores (.80). Consequently, this measure was chosen for the first data collection and administered before and after the interaction with the VPI to assess the impact of synchrony on participants' affective states.

2.3.2 Self-other overlap/distinction

Synchronising movements with others during IMC is associated with tendencies for blurring self-other boundaries, leading to experiencing more similarity and interpersonal closeness (Cross et al., 2019). Furthermore, the salience of shared social identity can increase synchronisation tendencies and is understood as a signature of belongingness (Dalton et al., 2010; Levy and Bader, 2020). These observations echo studies on empathy, showing that individuals tend to be more altruistic and empathetic toward

[6]The Self-Assessment-Manikin has been used as effective and quick self-report of affective states for the in-lab data collection conducted in collaboration with EuroMov.

those that are similar (Bloom, 2017; Decety, 2010). Consequently, perceived similarity has been identified as a mechanism driving the association between interpersonal coordination and altruistic tendencies through increasing affiliation.

These experiences of integration/segregation of the other within the self can be measured with behavioural measurements, such as threat avoidance (i.e., participants removing their real hand when a rubber hand falsely induced as their own is threatened), tendencies to extend self-bias recognition or adopt the visual perspective of the other (Botvinick and Cohen, 1998; Bufalari et al., 2019; Bukowski, 2018). However, these measures were not retained considering their difficult implementation in online settings in combination with the VPI. Instead, self-reports measuring perceived closeness and similarity were selected, taken from previous studies investigating their association with IMC (Atherton et al., 2019; Reddish et al., 2013,0). Yet, despite consistent findings across studies linking these measures with the execution of synchronous movement, their potential overlapping construct remains to be clarified. Alternatively, the Inclusion of the Other in the Self (IOS) developed by Aron et al. (1992) consists of a pictorial assessment of the experience of integration/segregation of the other within the self where participants are required to select one of 7 pictures of two circles with increasing degrees of overlap. The IOS is considered a measure of social connectedness and consistently associated with interpersonal closeness measures (Gächter et al., 2015) - see **Figure 2.3** from Aron et al. (1992) for a graphical representation.

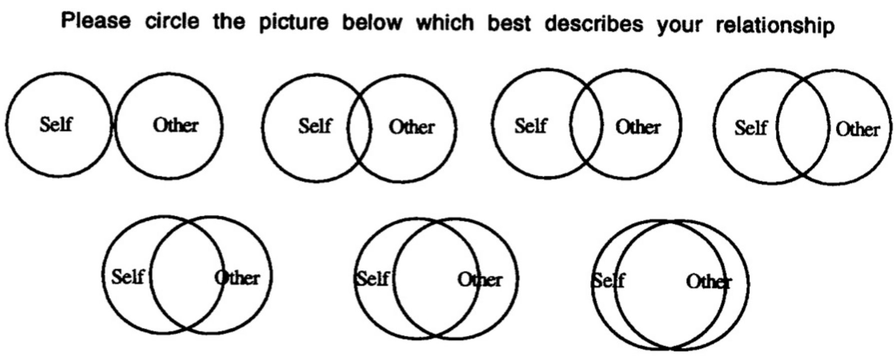

Fig. 2.2 Illustration of the Inclusion of the Other in the Self

However, the IOS scale provides only a coarse-grained assessment of social connectedness, and studies have often used the IOS with self-reports assessing perceived closeness and similarity (Reddish et al., 2013,0; Tarr et al., 2018). Additionally, previous studies suggested that perceived cooperativeness and goal achievement are important factors underlying the association between interpersonal coordination and prosocial outcomes (Kirschner and Tomasello, 2010; Reddish et al., 2013). Finally, the experience of self-other overlap/distinction in the context of HCI remains to be clarified. To the author's knowledge, the role of synchrony in anthropomorphism and prosocial outcomes was only assessed by Heijnen et al. (2019) in human-robot interactions, reporting an association of perceived humanness with altruism but not with the execution of synchronous movements. Considering the potential detrimental effect of synchrony in the HCI context (Bailenson et al., 2008; Verberne et al., 2013), a self-reported measure of perceived humanness was also included for exploring its association with synchrony, experiences of self-other overlap and altruistic tendencies (see **Appendix D**). Consequently, a combination of items was administered for assessing experiences of self-other overlap and perceived humanness with further descriptions in **Chapter 4**.

2.3.3 Economic games

Finally, the role of IMC in tendencies for altruistic behaviours is typically assessed through helping behaviours (Reddish et al., 2014) or economic games (Reddish et al., 2013; Wiltermuth and Heath, 2009). Several conceptualisations of altruism co-exist in the literature, highlighting the multidimensional facets of altruistic tendencies. According to Clavien and Chapuisat (2013), psychological altruism, referring to the motivation to improve others' welfare, should be delineated from behavioural altruism, referring to costly acts that entitle economic benefits to other individuals. Thus, psychological altruism can be understood as a related concept associated with empathy, echoing the conceptualisations of sympathy by Smith and Hume (Darwall, 1998; Fleischacker, 2019)[7]. On the other hand, behavioural altruism is usually investigated using experimental economics, a stream of research dedicated to testing economic theories in experimental settings. In the seminal study conducted by Kahneman et al. (1986), it was observed that individuals tend to deviate from purely self-interested choices, suggesting the involvement of social norms in economic decision-making processes. Consequently, several economic games have been designed to study prosocial tendencies in various contexts.

[7] Adam Smith is also well-known for his fundamental contributions to economics with his book "An Inquiry Into the Nature and Causes of the Wealth of Nations" - see Smith (1776))

For example, the Dictator Game is known to assess altruistic tendencies, where a player (i.e., the Dictator) makes monetary decisions on the distribution of a given number of coins with another player. According to Bohnet and Frey (1999), altruistic tendencies in the Dictator Game are associated with interpersonal closeness, stressing its relevance for IMC. However, some studies failed to report significant associations between IMC and altruistic outcomes (Heijnen et al., 2019; Tarr and Dunbar, 2023). The Dictator Game can indeed be understood as a measure of altruism or fairness, where altruism refers to other-oriented behaviours while fairness refers to the concern for equality, guided by moral considerations rather than other-oriented behaviour (Guala and Mittone, 2010). Consequently, it remains to clarify if the Dictator Game is an appropriate assessment of the prosocial outcomes associated with IMC considering the potential conflation between fairness and other-oriented altruism.

Another example is the Trust Game, consisting of a player (i.e., The Truster) making the decisions on the distribution of a given number of coins. Here, the Truster is also informed that the sum allocated to the other player (i.e., the Trustee) will be tripled, and the Trustee will be free to decide how much to return/send back to the Truster. Several studies have reported a positive association between IMC and subsequently trusting the other player (Lang et al., 2017; Oullier et al., 2010; Tamborini et al., 2018)[8]. These results highlight the role of perceived joint commitment elicited by IMC that could foster a sense of cooperation, inducing reciprocal trust (Tomasello et al., 2005).

Finally, reciprocal fairness can be assessed by the Ultimatum Game, where a player (i.e., the Proposer) offers to share a certain amount of money with another player (i.e., the Receiver), who can accept or reject this offer. In the latter case, neither the Proposer nor the Receiver are rewarded. Rejecting the initial offer is considered a form of social punishment against unfairness (Oullier et al., 2008). Whilst the Ultimatum Game could offer an interesting insight into the intricate social norms in economic decisions, to the author's knowledge, no studies have investigated the impact of IMC on a responder decision during an Ultimatum Game. However, studies have previously demonstrated positive associations between interbrain synchronisation in brain areas involved in integration/segregation of the other (i.e., the right temporoparietal junction, rTPJ) and shared intentionality in the Ultimatum Game, suggesting their activation during economic decisions (Tang et al., 2016; Yun et al., 2008). Considering the various possibilities offered by the Dictator, Trust, and Ultimatum Games, they were initially implemented using a one-shot experimental design to assess the impact of executing synchronous movement with a virtual agent on altruism and fairness inclinations.

[8] One of the first hyperscanning studies investigated brain-to-brain coupling during a Trust Game - see King-Casas et al. (2005)

2.4 Sampled population

The first data collection occurred between October 2020 and July 2021 during the COVID-19 pandemic. At that time, face-to-face data collection was initially not possible, and subsequently, access to laboratory facilities was strictly restricted by NTU. Consequently, this data collection was conducted remotely. The online platforms Amazon Mechanical Turk (MTurk) and Prolific were chosen considering their popularity among researchers[9]. However, several concerns have been raised regarding the data quality (Goodman et al., 2013). Therefore, an attentional test and identification codes were implemented to prevent fraudulent behaviours. The overall procedure received approval from the ethics committee of the NTU Schools of Business, Law and Social Sciences (n°2020/11) - see **Figure 2.3** for a graphical illustration of the procedure.

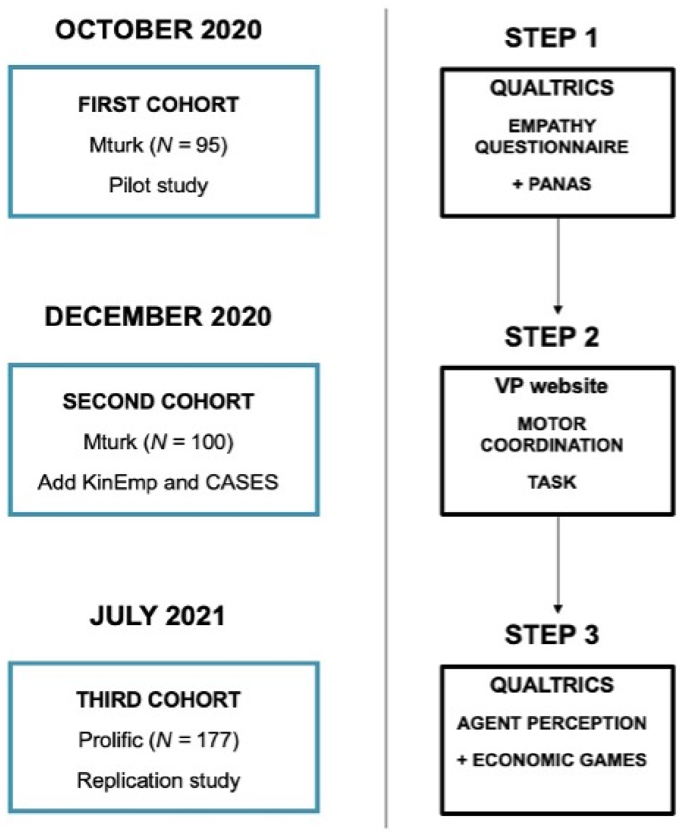

Fig. 2.3 Overall procedure of the data collection for **Chapters 3** and **4**

[9]These platforms question the ethics of scientific research - see Pittman and Sheehan (2016)

Recommendations regarding the sample size required for CFA vary in the literature, with rules-of-thumb suggesting a minimum sample size of 100 to 200, or 5 to 10 observations per parameter or variables (Bentler and Chou, 1987; Bollen, 1989). However, these rules do not consider the role of communalities shared across variables (i.e., the proportion of the variable's variance explained by the factors) and the number of variables for each factor (MacCallum et al., 1999). Prior CFA analyses conducted on the QCAE were administered on large samples ($N > 300$), but recent studies reported smaller sample sizes ($N > 200$ - see Gomez et al. (2022) and Horan et al. (2015)). Thus, a minimal sample size of 200 participants was deemed sufficient to conduct CFA analyses combining QCAE, KinEmp and CASES. In contrast, for the sample size required to detect an effect of motor coordination on prosocial outcomes, Vicaria and Dickens (2016)'s meta-analysis on the prosocial outcomes of interpersonal motor coordination reported a medium effect size of $r = .30$. Consequently, using an $\alpha = .05$ and power of the test $(1 - \beta) = 0.8$, a sample size of 85 participants was deemed sufficient to detect synchrony's effect on prosocial outcomes.

The first research question addressed by this thesis investigated the association between IMC and empathy. Questionnaires measuring affective, cognitive, somatic and kinesthetic empathy were employed, and CFA explored the factorial composition and distinctiveness of self-reports of the spontaneous tendency to synchronise (i.e., kinesthetic and somatic empathy) with affective and cognitive facets of empathy. Additionally, participants performed a goal-oriented motor coordination task using the VPI. Synchronisation scores were extracted by computing their relative phase, investigating the association between empathy traits and behavioural synchrony. Results from this investigation are presented in **Chapter 3**. This research question was also investigated during a second data collection, presented in **Chapters 5 and 6**.

The second research question addressed by this thesis investigated the use of virtual agents for studying human social interactions. The VPI, driven by the HKB model of motor coordination, was manipulated between participants with a cooperative (i.e., in-phase) and a competitive (i.e., anti-phase) condition. The impact of this manipulation was assessed on (i) affective states using the PANAS, (ii) affiliative tendencies using self-reports of self-other overlap/ distinction experiences and (iii) altruism using one-shot economic games (i.e., the Dictator, Trust and the Ultimatum Games). Additionally, self-reports of joint commitment and anthropomorphism were measured using self-reports, investigating their impact on affiliative and prosocial tendencies in the context of HCI. Results from this manipulation are presented in **Chapter 4** and were also expanded in a second data collection, presented in **Chapters 5 and 7**.

CHAPTER 3

EXPERIMENT I - Empathy and Synchrony

"Rather than a feeling of oneness, empathy affirmed difference and connectedness"
- Susan Leigh Foster

In **Chapter 2**, methods assessing synchrony and empathy were introduced, underlying the current pitfalls in the literature to embrace the multidimensional nature of these two concepts. On the one hand, synchrony can be considered as falling under the umbrella term of Interpersonal Motor Coordination (IMC), encompassing synchrony and imitation. On the other hand, empathy is considered a multidimensional concept encompassing affective (i.e., sharing emotional states) and cognitive (i.e., understanding others) components. Whilst synchrony and empathy have nurtured different streams of research, historical and theoretical overlaps have been identified in **Chapter 1**, suggesting potential joint mechanisms. Nevertheless, it remains to clarify how the neurocognitive mechanisms associated with synchrony and empathy overlap and if synchrony is a component of empathy.

An online study was conducted assessing the latent structures of questionnaires measuring affective, cognitive, kinesthetic and somatic empathy using Confirmatory Factorial Analyses (CFA) introduced in **Chapter 2**. This study aims to empirically test (i) the association of motor-related components of empathy with affective empathy; and (ii) the association of empathy facets with goal-oriented motor coordination through a behavioural task involving the synchronisation of movement with a virtual agent, the Virtual Partner of Interaction (VPI) driven by the Haken-Kelso-Bunz (HKB) model of motor coordination. The experimental design of this first study was pre-registered on the Open Science Framework (OSF) developed by Foster and Deardorff (2017): `https://osf.io/apxch`

This chapter has been published under the title **The "jingle-jangle fallacy" of empathy: Delineating affective, cognitive and motor components of empathy from behavioral synchrony using a virtual agent** in *Personality and Individual Differences* (Ayache et al., 2024).

3.1 Summary of the theoretical and empirical gaps

Synchrony and empathy share a common history and theoretical overlap; both have attracted considerable attention considering their association with prosocial outcomes. However, despite decades of research, these two concepts remain studied in distinct streams of research, and it remains to be clarified if they are distinct or overlapping concepts. Theoretical accounts suggest an overlap between neurocognitive components involved in synchrony and empathy, both supported by the perception/action matching system associated with the Mirror Neuron System (MNS) (Gallese, 2001; Preston and De Waal, 2002; Prinz, 1990). Yet, empirical evidence remains scarce, with mixed findings reported in the literature (Koehne et al., 2016b; Novembre et al., 2019; Preissmann et al., 2016). This gap between theoretical and empirical observations suggests that the various conceptualisations of synchrony and empathy currently co-existing in the literature challenge a comprehensive understanding of the possible association between their multidimensional facets. Consequently, there is a need for a systematic investigation of the neurocognitive mechanisms underlying synchrony and empathy for delineating potential distinctive and shared pathways.

3.1.1 Disentangling facets of synchrony and empathy

As exposed in **Chapter 1**, synchrony and empathy share a common history, both starting in the early 20th century with the development of new techniques of motion tracking systems. Whilst scientific observations of synchrony can be traced back to Christian Huygens, the association between synchrony and social connectedness was only introduced by Émile Durkheim and later expanded by Bernieri and Rosenthal to the umbrella term of Interpersonal Motor Coordination (IMC) encompassing synchrony and imitation. The multidimensional construct associated with synchrony makes it difficult to assess similarities and differences between synchrony and imitation, emergent versus goal-oriented motor coordination (Athreya et al., 2014; Knoblich et al., 2011; Varlet et al., 2011). Similarly, various conceptualizations of empathy have flourished since its first conceptualisation associating body sensations with aesthetic experiences (Lanzoni, 2009). Empathy was later expanded to social interactions and is nowadays considered a multidimensional concept encompassing affective and cognitive facets (Decety and Jackson, 2006; Lamm et al., 2016). Nevertheless, the multiplication of assessments and conceptualisations of empathy render it difficult to disentangle these two distinctive or overlapping facets, leading to a "jingle-jangle" fallacy in the literature (Hall and Schwartz, 2019; Heym et al., 2019). Consequently, it is unclear how the multiple facets of synchrony and empathy are associated.

Recent studies suggest the addition of motor empathy as a distinctive component encompassing synchrony and imitation (Blair, 2005). To complicate matters further, another stream of research developed the concept of kinesthetic empathy, associated with the awareness of body sensations, recalling the initial association of empathy with aesthetic experiences and modern conceptions of proprioception (Paterson, 2012). However, it is unclear how motor and kinesthetic empathy concepts are related, considering their association with distinctive levels of consciousness states. Inspired by theoretical models applied to introspection distinguishing effective performance from subjective experiences (Garfinkel et al., 2015), motor components of empathy could differentiate the "feeling" from the "being" of synchrony, already identified as a distinctive component of the enjoyment of music (Matthews et al., 2022).

3.1.2 Shared neurocognitive components of synchrony and empathy

Theoretical models of synchrony and empathy suggest an overlap between their neurocognitive components with ideomotor theories postulating a common mechanism grounded in the action-perception matching system supported by the MNS, associated with experiences of self-other overlap (Gallese et al., 1996; Prinz, 1990). Nevertheless, the sole mechanism of mirroring appears insufficient to capture the full spectrum of the facets associated with interpersonal coordination and empathy. Therefore, theoretical models suggest that the capacity to coordinate movement with others also requires detecting a mismatch between one's own and others' movements, requiring self-other distinction (Sebanz and Knoblich, 2009; Shamay-Tsoory et al., 2019). Similarly, neurodevelopmental models of empathy stress the role of metacognition and executive functions underlying capacities for self-other distinction and conflict monitoring between self and others' perspectives (Decety and Jackson, 2006). This suggests that despite their multidimensional construct, IMC and empathy share common neurocognitive mechanisms.

Nevertheless, empirical evidence remains scarce, with mixed findings reported in the literature. Therefore, it is unclear if the theoretical association between synchrony and empathy can be translated from in-lab controlled settings into real-live social interactions (Wheatley et al., 2019). Social norms and reinforcement learning influence IMC and empathy (Dalton et al., 2010; Levy and Bader, 2020), challenging the capacity to investigate this research question in ecological settings. Consequently, virtual agents could be used as experimental tools, considering their capacity for reproducing human social behaviour and complying with the scientific replicability criteria (Pan and Hamilton, 2018). Nonetheless, it remains to clarify if virtual agents are credible for eliciting affiliative tendencies (Fernández Castro and Pacherie, 2021).

3.1.3 Goal and hypotheses

To summarise, synchrony and empathy have attracted considerable attention in psychology, considering their associations with affiliative and altruistic tendencies. Nevertheless, despite sharing a common history focused on embodied social interactions and theoretical models suggesting their reliance on shared neurocognitive mechanisms, the association between synchrony and empathy remains unclear and has not been systematically investigated. On the one hand, it is unclear how the multiple facets associated with synchrony and empathy are related, with the distinction and potential overlap between affective, cognitive, kinesthetic and motor facets of empathy that must be explored and disentangled. On the other hand, the association between synchrony and empathy is often studied in the laboratory, lacking ecological validity, or in live social interactions, thus lacking controlled parameters that may conflate their association with contextual influences. Consequently, a systematic investigation of the association between synchrony and empathy is required using experimental tools providing ecological validity and replicability.

To address this research question, this online data collection was conducted using the Questionnaire of Affective and Cognitive Empathy (QCAE) developed by Reniers et al. (2011), the Kinesthetic Empathy Scale (KinEmp) developed by Koehne et al. (2016b) and the Somatic subscale from the Cognitive, Affective and Somatic Empathy Scale (CASES) developed by Raine and Chen (2018). The dataset extracted from these empathy-related questionnaires was investigated and compared with theoretical models of empathy employing Confirmatory Factorial Analyses (CFA) and Structural Equation Modeling (SEM). These self-reports of empathy traits were combined with the execution of a goal-oriented coordination task with a virtual agent, the Virtual Partner of Interaction (VPI), driven by the Haken-Kelso-Bunz (HKB) model of motor coordination. The association between empathy questionnaires and effective performances in a goal-oriented motor coordination task were investigated by extracting the relative phase between participants' and VPI's movements.

A first hypothesis predicted a positive association between affective, kinesthetic and somatic facets of empathy, considering their shared reliance on the action-perception matching system supported by the MNS (Gallese et al., 1996; Prinz, 1990). A second hypothesis predicted a positive association between cognitive facets of empathy and goal-oriented motor coordination, replicating in-lab observations that stressed the role of predicting others' movement for achieving interpersonal motor coordination (Koehne et al., 2016b; Novembre et al., 2019). Finally, exploratory analyses investigated the association of affective and motor-related empathy facets with motor coordination scores.

3.2 Methods

3.2.1 Participants

A total of 277 participants were recruited through MTurk and Prolific from December 2020 to July 2021. Participants were compensated $5 for completing the survey. Control checks were conducted, resulting in the exclusion of one participant failing to complete an attentional test. Consequently, a sample size of 276 participants (163 men/113 women; US residents, mean age = 34.40, SD = 10.68, range 18 to 66 years) was included in the CFA analyses. Because of technical incompatibility between the VPI implementation and some web browsers, the dataset including participants' trajectories was restricted to 202 participants (113 men/89 women; US residents, mean age = 34.17, SD = 10.98, range 18 to 66 years), included in the subsequent statistical analyses assessing the association between empathy questionnaires and behavioural scores of motor coordination with the VPI.

3.2.2 Empathy questionnaires

Participants completed the QCAE developed by Reniers et al. (2011), composed of 31 items, with two cognitive subscales (i.e., Perspective Taking and Online Simulation) and three affective subscales (i.e., Emotion Contagion, Proximal and Peripheral responsivity). Additionally, participants completed the KinEmp composed of 9 items, and the Somatic subscale of the CASES, composed of 10 items (Koehne et al., 2016b; Raine and Chen, 2018). All items were scored on a 4-point Likert scale (1 = strongly disagree to 4 = strongly agree) to harmonise with the initial scoring of the QCAE, and scores on the subscales were calculated by summing the associated items[1].

3.2.3 Synchrony

Participants were randomly assigned to one of the two different experimental conditions: *Cooperation*, where participants and the VPI shared a common goal (e.g., being in-phase), or *Competition*, where the participant and the VPI shared an antagonistic goal (e.g., the VPI aims to be in anti-phase). The VPI code was implemented on an NTU server using the modified HKB equation developed by Dumas et al. (2014a), manipulating the VPI's goal for antiphase and in-phase.

[1] Additionally, other empathy-related questionnaires were also completed; namely the Levenson Self-Report Psychopathy (LSRP) from Levenson et al. (1995), the Difficulties in Emotion Regulation Scale (DERS) from Gratz and Roemer (2004), the Autism Quotient (AQ) from Baron-Cohen et al. (2001), the Toronto Alexithymia Scale (TAS) from Bagby et al. (1994), and the Multidimensional Assessment of Interoceptive Awareness (MAIA) from Mehling et al. (2012) - see **Appendices A, B and C**

3.2.4 Procedure

Participants were recruited through the online platforms MTurk or Prolific and redirected to a Qualtrics survey where they provided their informed consent and created a unique participant code. Then, participants were invited to complete relevant demographics (gender, age), followed by the empathy questionnaires (i.e., QCAE, KinEmp, CASES). An attentional test was intercalated to check the accuracy of participants' answers[2]. Participants were redirected to the NTU website hosting the VPI, and participants' unique codes were embedded within the URL and registered in the PHP database to link the data between the two platforms. Participants were randomly assigned to the Cooperation or Competition condition without being aware of the VPI's goal. They were instructed in both conditions to follow a dot on the screen (e.g., with a mouse, trackpad or other means, depending on the device used) and aimed to synchronise their movements in phase with it. At the end of the trial, participants were redirected to a second Qualtrics survey, with additional assessments of the affective and cognitive consequences of their interaction with the VPI (see procedure and results in **Chapter 4**). In total, the procedure took between 15-20 minutes. Participants had to provide a random number generated by Qualtrics at the end of this second survey to claim their payments and avoid fraudulent claims - see **Figure 3.1** for a graphical illustration.

3.2.5 Data analyses

Data pre-processing and statistical analyses were conducted using R (RStudio Team, 2020) and Python (Van Rossum et al., 1995). Manipulation checks controlled the psychometric properties of the QCAE, KinEmp and CASES subscales using Cronbach's alpha and inter-item correlations. Pearson's correlations computed the associations between QCAE, KinEmp and CASES subscales. CFA were conducted with the R package "lavaan" (Rosseel, 2012) using SEM, testing for latent factors associating items from affective, cognitive, kinesthetic and somatic facets of empathy. Scores of motor synchronisation were computed following Baillin et al. (2020)'s formula. Visual inspection of the motor synchronisation scores revealed a bimodal distribution - see **Appendix E** for a graphical representation. A Shapiro-Wilk Test confirmed that motor coordination scores significantly deviate from a normal distribution ($W = 0.90, p < .001$). Consequently, non-parametric tests were performed to compare motor coordination scores across virtual agent conditions and to compute the zero-order correlations with empathy facets. Finally, Holm Bonferroni corrections were applied for multiple comparisons. All scripts and datasets are available in OSF: `https://osf.io/apxch`.

[2]Participants also completed the Positive and Negative Affect Schedule PANAS from Watson et al. (1988) as a baseline for assessing the impact of the interaction with the VPI on their affective states - see **Chapter 4** for further description.

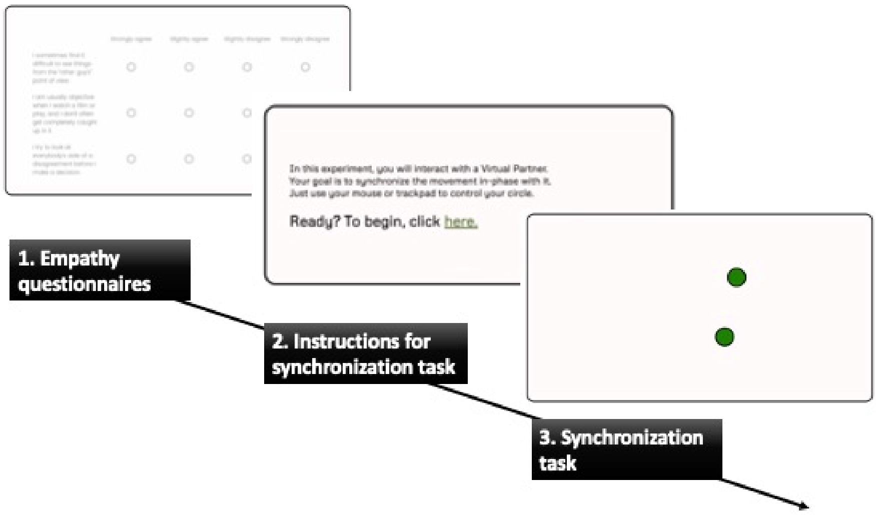

Fig. 3.1 Illustration of the experimental protocol of **EXPERIMENT I**

3.3 Results

3.3.1 Manipulation checks

Consistencies of the subscales were all above $> .60$, apart from the *Peripheral Responsivity* subscale, displaying insufficient Cronbach's alpha score (.52) and average inter-item correlation (.21). After careful examination, item 17 ("*It is hard for me to see why some things upset people so much*") displayed low correlations with items 11 and 29. Removing this item slightly improved the subscale consistency, with Cronbach's alpha score of .57 and average inter-item of .30. Significant positive correlations were seen across all the QCAE subscales, apart from Peripheral Responsivity. The affective empathy-related QCAE subscales were positively correlated with KinEmp and CASES. However, despite a positive and significant correlation between KinEmp and CASES, they displayed distinct patterns with cognitive QCAE subscales. Whilst KinEmp was not associated with cognitive-related facets *Online Simulation* and *Perspective Taking*, CASES was positively associated with these cognitive subscales - see **Table 3.1** for descriptive statistics and correlations with *Peripheral responsivity* reported after removing item 17.[3]

[3]The p-values values reported here might differ from the published manuscript, where p-values were reported without corrections for multiple comparisons.

	Mean	OS	PT	PE	PR	EC	KI
Online Simulation	27.24						
Perspective Taking	30.47	.66***					
Peripheral responsivity	7.73	.16*	.01				
Proximal responsivity	11.65	.53***	.45***	.33***			
Emotion contagion	11.25	.27***	.23***	.18**	.51***		
KinEmp	22.04	-.05	-.02	.21**	.23***	.43***	
CASES	29.46	.18**	.16*	.28***	.44***	.48***	.54***

Table 3.1 Descriptive statistics and zero-order correlations between empathy facets

Adjusted p-values are reported with $*p < .05$*,* $**p < .01$*,* $***p < .001$

3.3.2 Confirmatory Factor Analyses

The latent structure of the QCAE was tested, comparing the 2 and 5-factor structures. Model comparison favoured the 5-factor structure ($\chi^2(395) = 242.21, p < .001$). Second, the latent structure of the KinEmp and CASES were tested, comparing a unique or a 2-factor structure of the two motor-related subscales. Model comparison favoured the 2-factor structure ($\chi^2(151) = 117.64, p < .001$). Finally, the aggregation of the KinEmp and CASES as distinctive or overlapping facets was tested, comparing the 6 and 7-factor structure models. Model comparison favoured the 7-factor structure ($\chi^2(1106) = 150.28, p < .001$). Finally, considering the positive correlations observed between the KinEmp, CASES and the *Emotion Contagion* subscale of the QCAE, exploratory analyses were conducted comparing two models of 6-factor structure, combining KinEmp or CASES items with the *Emotion Contagion* subscale of QCAE with the 7-factor structure. Model comparisons favoured the 7-factor structure ($\chi^2(1106) = 170.13$, $p < .001$ and $\chi^2(1106) = 150.28, p < .001$ respectively) - see **Table 3.2** for a summary of the goodness of fit indices and **Figure 3.2** for a graphical representation where single-headed arrows represent standardized correlations, and double-headed arrows represent covariances.

	DF	AIC	BIC	χ^2	CFI	TLI
Two-factor QCAE	404	18298	18628	1117.5	0.747	0.728
Five-factor QCAE	395	18074	18436	875.1	0.830	0.813
Six-factor QCAE + KinEmp/CASES	1112	30896	31482	2377.3	0.732	0.717
Seven-factor QCAE + KinEmp + CASES	1106	30758	31366	2227.1	0.763	0.748

Table 3.2 Indices of the goodness of fit for factor structure models

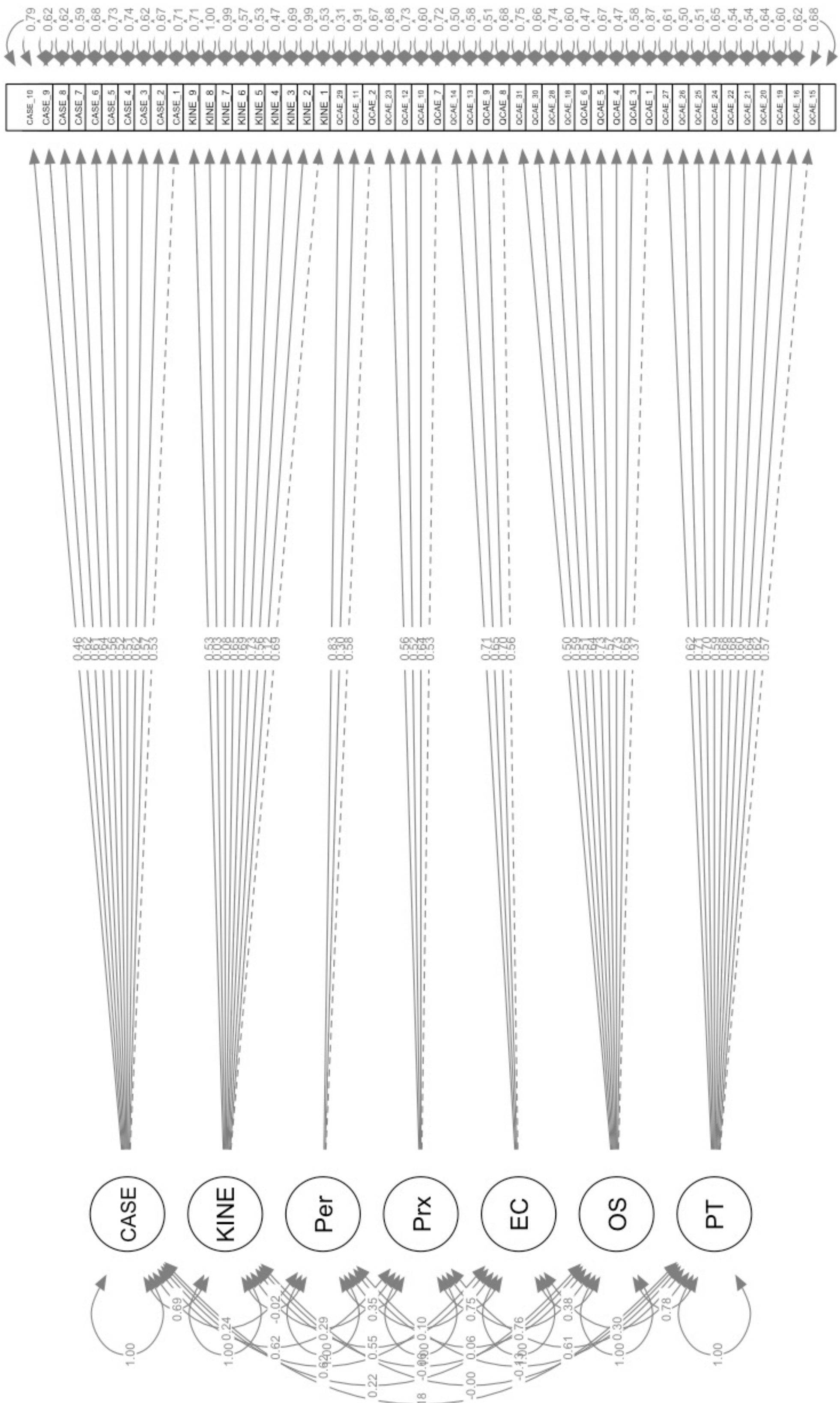

Fig. 3.2 Graphical representation of the seven-factor structure of empathy

3.3.3 Comparison of the VPI conditions

Comparison of the VPI conditions did not reveal any significant differences for demographic properties of the population, including age ($t(200) = 0.58, p = .562$) and gender ($p = 0.778$). Similarly, no significant differences were observed between VPI conditions for the QCAE subscales *Online Simulation* ($t(200) = -0.97, p = .336$), *Perspective Taking* ($t(200) = -1.53, p = .127$), *Peripheral Responsivity* ($t(200) = 0.58, p = .561$), *Proximal Responsivity* ($t(200) = 0.24, p = .812$), *Emotion Contagion* ($t(200) = -0.09, p = .928$). Additionally, there was no significant difference for the KinEmp ($t(200) = 0.36, p = .722$) and the CASES scores ($t(200) = 1.63, p = .105$). Finally, motor coordination scores did not differ across VPI conditions ($W(200) = 5586, p = .235$)- for full descriptive statistics, see **Table 3.3**.

	Cooperation ($N = 105$)	Competition ($N = 97$)
Age	33.73 ± 10.19	34.64 ± 11.81
Gender	60 men and 45 women	53 men and 44 women
QCAE Online Simulation	27.35 ± 4.72	26.69 ± 5.00
QCAE Perspective Taking	30.88 ± 5.40	29.68 ± 5.67
QCAE Peripheral Responsivity	7.66 ± 2.03	7.82 ± 2.06
QCAE Proximal Responsivity	11.49 ± 2.50	11.57 ± 2.36
QCAE Emotion Contagion	11.10 ± 2.81	11.06 ± 2.47
KinEmp	21.80 ± 4.66	22.03 ± 4.55
CASES	28.84 ± 6.28	30.21 ± 5.65
Motor coordination scores	0.47 ± 0.32	0.53 ± 0.32

Table 3.3 Descriptive statistics of VPI conditions

3.3.4 Zero-order correlations

The QCAE subscales *Online Simulation* and *Peripheral Responsivity* were positively associated with motor coordination scores (with $r(200) = .17, p = .017$ and $r(200) = .20, p = .005$, respectively). In contrast, KinEmp scores were negatively associated with motor coordination scores ($r(200) = -.14, p = .043$). However, these associations did not hold significance after Holm Bonferroni corrections, except for *Peripheral Responsivity* ($p = .037$).[4] In contrast, there was no association between motor coordination scores and the QCAE subscales *Perspective Taking* ($r(200) = .01, p = .843$), *Proximal Responsivity* ($r(200) = .04, p = .550$) and *Emotion Contagion* ($r(200) = .05, p = .442$). Finally, there was no association with CASES scores ($r(200) = .06, p = .361$).

[4]This result differs from the published manuscript, where p-values were reported without corrections for multiple comparisons.

3.4 Discussion

The present investigation aimed to disentangle the relationship between self-reports of affective, cognitive, kinesthetic and somatic empathy trait measures and their association with goal-oriented motor coordination skills using the VPI driven by the HKB. Correlations and latent structures of the dataset suggested that kinesthetic and somatic facets of empathy represent distinct constructs from affective and cognitive empathy facets. Moreover, the present study confirmed the association between cognitive empathy and goal-oriented motor coordination scores, offering new insights using virtual agents as experimental tools.

3.4.1 Disentangling empathy

In line with the first hypothesis, self-report measures of empathy traits through QCAE, KinEmp and CASES revealed the positive association between affective, kinesthetic and somatic empathy components, supporting neurodevelopmental accounts of empathy (Decety, 2010), linking tendencies for noticing body sensations with development of affective empathic responses. However, whilst somatic and kinesthetic subscales were positively associated with affective-related facets of QCAE, they display contrasting associations with cognitive empathy.

The somatic subscale of the CASES was positively associated with affective and cognitive empathy facets of the QCAE, reproducing the pattern observed for *Proximal Responsivity* and *Emotion Contagion* QCAE subscales. On the other hand, the KinEmp questionnaire was only positively associated with QCAE affective facets but not with QCAE cognitive facets *Online Simulation* and *Perspective Taking*. Thus, despite their strong and positive correlations (.54), these subscales displayed distinctive patterns. Furthermore, the CFA model comparisons favoured a 7-factor structure, suggesting a fine-grained distinction between affective, cognitive, kinesthetic and somatic dimensions. This result also favours adopting a 5-factor structure of the QCAE, as suggested by previous studies, in contrast with the 2-factor structure initially suggested (Myszkowski et al., 2017). Consequently, whilst somatic and kinesthetic empathy were both conceptualised as reflecting the subjective experience of motor components of empathy, conceptualised as tendencies to mimic or synchronise with others, their conceptualisations appear to differ, underlying a potential "jingle-jangle" fallacy coming from distinctive streams of the empathy literature.

On the one hand, the somatic subscale of the CASES was conceptualised by Raine and Chen (2018) as a self-report measure of the motor-related component of empathy, following Blair (2005)'s definition of motor empathy, usually measured using electrophysiological recordings of muscle and somatosensory cortex activation. This conceptualisation of motor empathy is associated with eliciting a motor act (i.e., smiling when seeing someone happy) or experiencing autonomic and somatic bodily responses to emotional cues (i.e., flinching when seeing a dog run over). Therefore, the items composing the somatic CASES subscale reflect this conceptualisation of motor empathy as body responses to emotional cues, associated with tendencies for emotion contagion and mimicry of positive and negative emotions (e.g., item 30, " When I see children smiling, I smile too"; item 14, "I would get tears in my eyes if I saw my friend cry"). Echoing the theoretical debate between empathy conceptualisations, it is therefore unclear if this conceptualisation of somatic responses to another's affective state of empathy requires the mentalisation and recognition of another's affective state (Zahavi, 2008). Results from this study suggest that the conceptualisation of motor empathy associated with the somatic CASES subscale construct overlaps with the conceptualisation of QCAE cognitive facets and might, therefore, require capacities for mentalizing others' states.

On the other hand, the KinEmp scale developed by Koehne et al. (2016b) inherited from the initial conceptualisation of empathy from Lipps as an "inner mimicry" (Li and Ryan, 2017). Koehne et al. (2016b) conceptualised the KinEmp scale as a self-report measurement of traits (i.e., stable tendencies) for achieving interpersonal motor coordination in time, therefore delineating KinEmp as a measure of interactional synchrony from behavioural mimicry. According to Koehne et al. (2016b), kinesthetic empathy is higher for individuals practising dances requiring high levels of interpersonal coordination and can foster affective and cognitive empathy. Whilst this first study reported an association between kinesthetic and affective empathy, the present results don't replicate the association between kinesthetic and cognitive empathy. Contrary to the present study, the population tested by Koehne et al. (2016b) comprised expert dancers. Furthermore, the authors used the Cognitive and Emotional Empathy Questionnaire, an unpublished measure of empathy to the author's knowledge. Finally, a systematic investigation and validation of the KinEmp's structure is lacking. Complementary analyses revealed that reversed items (2, 7 and 8) were negatively or not correlated with the other items, suggesting a potential lack of understanding of convoluted sentences. Furthermore, items 1 and 4 displayed high correlations underlying possible similar constructs (see **Appendix F**). Consequently, further investigations are required to improve the KinEmp's consistency and differentiate potential multidimensional components such as localised (e.g., item 5) from general body sensations (e.g., item 9) that have already been suggested as relevant inter-individual differences driving variability in susceptibility to body illusion and vicarious pain (i.e., experiencing pain when seeing others in pain), considered as a specific type of affective empathy (Botan et al., 2018).

3.4.2 Association between motor coordination and empathy

In line with the second hypothesis, the cognitive facet *Online Simulation* displayed a trend for a positive association with motor coordination scores - this association was significant but did not hold after correction. Defined as an “effortful attempt” to adopt another’s perspective, *Online Simulation* was associated with tendencies for better motor coordination performances, whilst *Perspective Taking*, conceived as “intuitive” cognitive empathy, did not display a similar pattern (Reniers et al., 2011). This result underlines the role of cognitive control in successful goal-oriented coordination and replicates findings linking motor coordination abilities with the cognitive subscale *Perspective Taking* from the IRI questionnaire (Davis, 1980; Novembre et al., 2019). Notably, QCAE *Online Simulation* items overlap with IRI Perspective Taking items, stressing the “jingle-jangle fallacy” due to the mismatch of IRI and QCAE subscales labels.

The present study also reported a positive association between motor coordination and the QCAE affective subscale *Peripheral Responsivity*. Conceptualised as reflecting affective empathic responses but in a detached context, this subscale is composed of items coming from the IRI Fantasy subscale, associated with the tendency to “transpose oneself into fictional situations” and initially conceptualised as a cognitive facet (Davis, 1980). Echoing this initial conceptualisation, *Peripheral Responsivity* displayed indeed positive correlations with the cognitive facet *Online Simulation* and affective facets but not with *Perspective Taking*, underlining its association with volitional processes of cognitive empathy. Nevertheless, the lower Cronbach’s alpha score displayed by *Peripheral Responsivity* (.52) questioned its reliability and replicated previous findings stressing the need to revise its psychometric properties (Myszkowski et al., 2017).

In contrast, greater KinEmp scores displayed a trend for a negative association with motor coordination scores - this association was significant but did not hold after correction. This finding appears to contradict Koehne et al. (2016b)’s results, reporting higher levels of kinesthetic empathy for dancers, who presumably developed skills in motor coordination. This contradictory outcome calls for future investigations into experts (e.g., dancers, musicians) and novice populations to disentangle potential bias in recruitment and abilities to self-report motor abilities that could explain these mixed findings. The discrepancy observed between self-reports and effective behavioural motor coordination recalls the observations reported by Garfinkel et al. (2015) on interoception and Matthews et al. (2022) on groove, stressing the need for exploring the association between motor coordination impairments and meta-cognitive dysfunction observed in clinical conditions associated with difficulties in social interactions, such as autism or schizophrenia (Cassidy et al., 2016; Hur et al., 2014).

3.4.3 Limitations and Future research

Whilst these results highlight potential inconsistencies within the literature, they also call for cautious interpretations. First, some of the empathy trait measures displayed questionable psychometric properties, replicating previous concerns about their lack of consistency (Myszkowski et al., 2017). Second, the contrasting findings from Koehne et al. (2016b) on the association of kinesthetic empathy with cognitive empathy and motor coordination highlight a potential mismatch between effective behavioural motor coordination and self-reports of behavioural synchrony. This suggests the need to systematically control their associations in future investigations to delineate tendencies for overconfidence bias in self-reports from potential impairments in meta-cognitive processes (Mazor and Fleming, 2021). Third, the association between the QCAE subscale *Online Simulation* and the KinEmp scale with motor coordination scores did not hold significance after corrections for multiple comparisons. This result suggests a possible lack of statistical power and potential experimental artefacts associated with online data collection (Chmielewski and Kucker, 2020) - see further discussion in **Chapter 4**. This discrepancy also highlights the difficulty of conducting exploratory studies delineating sub-components of empathy, that are more sensitive and penalized by multiple comparison corrections (Feise, 2002; Rothman, 1990) - for further discussion, see **Chapter 8**. Consequently, the present results must be interpreted with caution before their replications, and future studies need to consider these limitations.

3.5 Conclusion

To conclude, the present investigation attempted to disentangle the association between affective, cognitive, kinesthetic and somatic empathy with goal-oriented motor coordination. The present findings support the theoretical association between affective, kinesthetic and somatic empathy, yet factorial analyses stress their distinction as latent constructs. Therefore, as Davis (1980) suggested, although it is tempting to merge facets of empathy, psychometric assessments of empathy traits are better understood as "constellations", reflecting the multidimensionality of empathy. Furthermore, this investigation confirmed previous findings reporting an association between cognitive empathy and goal-oriented motor coordination, suggesting a potential overlap of neurocognitive mechanisms. The replication of in-laboratory findings from live social interactions in HCI context suggests that virtual agents are suitable experimental tools for addressing this research question. Yet, this study also revealed tendencies for discrepancies between self-reported inclinations for synchronization (i.e., kinesthetic empathy) and effective motor coordination, calling for further investigations exploring the gap between self-reports and behaviours.

CHAPTER 4

EXPERIMENT II - Virtual Synchrony

"To succeed, planning alone is insufficient. One must improvise as well"
- Isaac Asimov

Chapter 3 presented findings from the online data collection addressing the first research question of this PhD, exploring the association between synchrony and empathy. Confirmatory Factor Analyses (CFA) of self-reports of empathy traits suggested a distinction between affective, cognitive, kinesthetic and somatic empathy. The experimental manipulation of interpersonal motor coordination (IMC) replicated findings from in-laboratory settings and suggested that virtual agents offer appropriate experimental paradigms to replicate and study motor components of social interactions. However, mixed findings are reported (see **Chapter 1**), stressing the difficulties in rendering naturalistic human behaviours in the Human-Computer-Interaction (HCI) context, preventing virtual agents from eliciting prosocial outcomes.

This chapter addresses the second research question of this PhD, namely, whether there are any limitations to using virtual agents for eliciting affiliative and altruistic inclinations in human participants. This experimental chapter is based on the same dataset collected in **Chapter 3** and explores the consequences of IMC with the Virtual Partner of Interaction (VPI). Hypotheses were formulated based on the pre-existing literature that identified affective and cognitive pathways leading to prosocial outcomes of synchrony in human-human interactions. Analyses were first conducted on the dataset collected from the Amazon Mechanical Turk (MTurk) platform. Findings from this first sample were partially replicated with data collected from the Prolific platform. Findings from both samples are summarised in the present chapter. The experimental design of this second study was approved by the NTU Business, Law and Social Sciences Research Ethics Committee and pre-registered in the Open Science Framework (OSF) repository: `https://osf.io/apxch`

4.1 Summary of the theoretical and empirical gaps

Synchrony has attracted attention considering its association with prosocial outcomes. Nevertheless, despite decades of research attempting to decipher this phenomenon, it remains to clarify the mechanisms linking synchrony with affiliative and altruistic tendencies. On the one hand, affective pathways have been identified, linking synchrony with processing fluency, associating synchrony with experiences of "perceptual pleasure" due to the reduction of environmental uncertainty (Hove and Risen, 2009; Zumeta et al., 2016). Consequently, synchrony would activate the opioid system, eliciting a state of euphoria and social bonding (Lang, 2010; Zilcha-Mano et al., 2021). On the other hand, cognitive pathways have also been suggested, linking synchrony with experiences of self-other overlap and a sense of shared goal, driving a shift in self-other boundaries by integrating the other within the self (Cross et al., 2019; Kirschner and Tomasello, 2010). Consequently, synchrony would be associated with an in-group categorisation similar to parochial empathy, driving altruistic tendencies (Bloom, 2017; Levy and Bader, 2020). Although non-exclusive, it is therefore unclear what critical pathways drive the association between synchrony and prosocial outcomes and how these associations are translated in the HCI context.

4.1.1 Synchrony as social glue

Synchrony has been consistently associated with affiliative and prosocial outcomes. Since its first association with social bonding by Durkheim, synchrony, and by extension IMC, has been used to foster a sense of belongingness. Accumulative evidence shows a consistent and robust association between IMC and experiences of self-other overlap (Mogan et al., 2017; Rennung and Göritz, 2016; Vicaria and Dickens, 2016). Yet, multiple hypotheses co-exist in the literature linking IMC with prosocial outcomes.

On the one hand, studies have suggested that this is the affective state elicited by IMC that leads to prosocial outcomes. According to this hypothesis, the matching of observed and executed actions decreases cognitive load, generating a euphoric state associated with the activation of the opioid system involved in affective attachment (Hoehl et al., 2021; Koban et al., 2019; Machin and Dunbar, 2011; Nummenmaa et al., 2015). On the other hand, studies suggest that IMC can blur self-other boundaries. Visuomotor synchronisation can induce body illusions (Botvinick and Cohen, 1998). Similarly, imitation favours the recognition of the similarity between self and others, reducing ingroup bias and parochial empathy (Atherton and Cross, 2018; Hasler et al., 2014; Levy and Bader, 2020). Whilst nonexclusive, these hypotheses underline distinctive pathways, and it remains unclear how affective and cognitive mechanisms influence each other and if they could be translated successfully in the HCI context.

4.1.2 Virtual synchrony

Mixed findings are indeed reported in the literature regarding the consequences of IMC with a virtual agent for affiliative and altruistic tendencies. Similarly to what is observed in human-human interactions, studies showed that being mimicked by a virtual agent increases perceived interpersonal closeness and empathetic concerns toward a computer-generated avatar (Bailenson and Yee, 2005; Hasler et al., 2014). Furthermore, these agents are perceived as more persuasive and likeable than agents who don't mimic, increasing their ability to be perceived as human beings (Bailenson and Yee, 2005; Cacioppo et al., 2014). Nevertheless, other studies failed to replicate these findings, observing that IMC in the HCI context decreases experiences of interpersonal closeness, altruism or trust (Bailenson et al., 2008; Verberne et al., 2013). Worst, detecting excessive spatiotemporal matching of speech and gestures can trigger repulsive reactions, a phenomenon known as the "uncanny valley" in human-robot interactions (Mori, 1970). A tentative explanation suggests that the excess of predictability in implementing IMC in virtual agents could buffer their capacity for eliciting prosocial outcomes. According to some authors, the rewarding experience of IMC comes from a mixture of predictability and uncertainty (Vuoskoski and Reynolds, 2019; Ravreby et al., 2022). Hence, similar to musical experiences, there might be a "sweet spot" between excessive predictability and complete randomness for enjoying interpersonal motor coordination (Stupacher et al., 2022). Consequently, it remains to be demonstrated if the excessive predictability of virtual agents might preclude the fulfilment of social belongingness.

Other studies also have suggested that the perception of joint commitment is important in triggering altruistic outcomes. Studies in human-human interactions stressed that IMC elicits a sense of group entitativity and shared intentionality (Michael et al., 2016; Reddish et al., 2013). Therefore, by eliciting a sense of joint commitment, IMC could also trigger a sense of fairness, leading to prosocial outcomes. Yet, despite attracting considerable attention in human-human interactions, it remains to clarify the necessary components of joint commitment and how they could be translated in HCI contexts. Whilst the perception of joint commitment is directly associated with the level of motor coordination, this association is modulated by the perception of the humanness of the interacting partners (Székely and Michael, 2018). This suggests that virtual agents might fail to elicit a sense of joint commitment, impeding their capacity to fulfil the human need for social relatedness (Fernández Castro and Pacherie, 2021; Fernández-Castro and Pacherie, 2023). Consequently, it remains to delineate whether virtual agents can elicit a sense of joint commitment and influence the association between interpersonal coordination and prosocial outcomes.

4.1.3 Goal and hypotheses

To summarise, synchrony has been systematically associated with prosocial outcomes. Nevertheless, the mechanisms underlying this association remain debated. Some hypotheses underline the association between synchrony and affective state (i.e., processing fluency), while others highlight the association between synchrony and experience of self-other overlap. Whilst non-exclusive, these mechanisms have not been investigated simultaneously because of the difficulties of systematically controlling these factors in real human-human interactions. Virtual agents have therefore been suggested as experimental tools (Dumas, 2011; Pan and Hamilton, 2018). Yet, it remains unclear if the pathways identified in human-human interactions can be translated in HCI, questioning the ability of virtual agents to trigger prosocial outcomes.

To address this research question, a first study was conducted on the population sample collected on the MTurk platform, using self-report measures of affective states, perceived interpersonal closeness (i.e., similarity, closeness, humanness) and joint commitment (i.e., cooperativeness, goal achievement), following the goal-oriented motor coordination task with the VPI. Prosocial tendencies were measured using one-shot economic games measuring altruism (Dictator), interpersonal trust (Trust) and fairness (Ultimatum). Replication of the first study was conducted on the population sample collected on the Prolific platform, using a pictorial assessment of self-other overlap, the Inclusion of the Other in the Self (IOS) developed by Aron et al. (1992). Finally, participants were invited to play six rounds of the Dictator Game. The association between virtual synchrony and its affective and cognitive consequences for prosocial outcomes was investigated with zero-order correlations and logistic regression.

Based on the literature, a first hypothesis postulated an increase of positive affect following synchrony with the VPI (Galbusera et al., 2019; Mogan et al., 2017). A second hypothesis postulated a positive association between synchrony and perceived interpersonal closeness (Atherton et al., 2019; Cross et al., 2019; Reddish et al., 2013). A third hypothesis postulated a positive association of synchrony with prosocial outcomes (Rennung and Göritz, 2016; Vicaria and Dickens, 2016). Finally, exploratory analyses were conducted investigating the role of manipulating the goal of the VPI (i.e., shared or antagonistic goal with participants) on perceived joint commitment and its association with affective, cognitive and prosocial consequences.

4.2 Methods

4.2.1 Participants

A total of 204 participants were recruited through MTurk from October to December 2020 and compensated between \$3 and \$5 for their participation, depending on the completion of additional questionnaires. As a result of technical incompatibility between the VPI implementation and some web browsers, 55 participants were excluded because of missing data. Additionally, one participant was excluded for failure to complete an attentional test and 5 participants for missing values in the Dictator Game. Consequently, the statistical analyses included a final sample size of 143 participants (86 men, 54 women and 3 non-binary US residents, mean age = 36.70, SD =10.58, range 23 to 66 years).

4.2.2 Affective and cognitive consequences of synchrony

Following the goal-oriented coordination task procedure described in **Chapter 3**, participants rated their perception of similarity and closeness with the virtual agent using 4-point Likert scales, humanness of the virtual agent, goal achievement and cooperation using 5-point Likert scales (see Atherton et al. (2019) and **Appendix D**). Participants' emotional state was assessed before (*T0*) and after (*T1*) the synchronisation manipulation using the Positive and Negative Affect Schedule (PANAS; Watson et al. (1988)), where participants indicated to what extent twenty words described how they felt this way "right now [...], at the present moment" on 5-point Likert scales (e.g., very slightly to extremely). Scores were calculated by summing the values of positive items before and after the interaction with the virtual agent.

4.2.3 Prosocial outcomes

After completing these self-reports, participants played one-shot economic games. First, participants played the Dictator Game, assessing fairness and altruism (Bohnet and Frey, 1999). Participants enacted the dictator and decided how to share 50 coins with the VPI. Second, participants played the Trust Game, assessing tendencies for interpersonal trust (Oullier et al., 2010). Participants enacted the truster and decided how to share 50 coins with the VPI, knowing that the sum allocated would be tripled and that the VPI would be free to decide how much to return/send back to the participant. Finally, participants played the Ultimatum Game, assessing tendencies for social punishment (Oullier et al., 2008). Participants enacted the receiver and decided to accept or reject an unfair offer from the VPI (e.g., sending 10 out of the 30 coins offered).

4.2.4 Procedure

The procedure was similar to that described in **Chapter 3**. Participants completed the PANAS (*T0*) before being redirected to the website hosting the VPI. After completing the goal-oriented motor coordination task, participants were redirected to a second Qualtrics survey and completed the PANAS again (*T1*). Then, participants reported their perception of (i) humanness, similarity and closeness with the virtual agent, (ii) goal achievement (e.g., how likely and how frequently the goal of synchronisation was achieved) and cooperativeness. Finally, participants were instructed to play the one-shot economic games. Participants played a practice trial before making their final decision. The total procedure took between 15-20 minutes - see **Figure 4.1** for illustration.

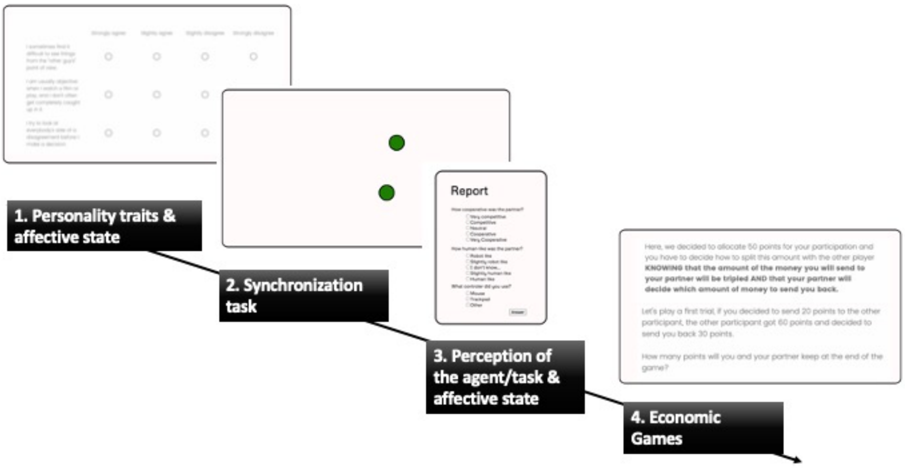

Fig. 4.1 Illustration of the experimental protocol of **EXPERIMENT II**

4.2.5 Data analyses

Scores of motor coordination were extracted using Baillin et al. (2020)'s formula. Self-reports of perceived similarity and closeness ($r = .78$) and goal achievement and frequency scores ($r = .61$) were aggregated by summing respective items. Transformed z-scores of the differences between PANAS scores at *T0* and *T1* measured the effect of synchrony on participants' emotional state. Wilcoxon-Mann-Whitney tests compared the VPI's conditions and Spearman correlations were calculated between motor coordination scores, self-reports of affective states, anthropomorphism and goal achievement, and the economic games' outcomes. Logistic regressions were conducted to assess the associations of the motor coordination scores, self-reports of affective states and VPI's perception with the binary Ultimatum Game outcomes (-1 for rejection and +1 for acceptance). Finally, Holm Bonferroni corrections were applied for multiple comparisons. All R scripts and datasets are available in OSF: `https://osf.io/apxch`

4.3 Results

4.3.1 Comparison of the VPI conditions

Comparison of the VPI conditions did not reveal any significant differences for demographic properties of the population, including age and gender (all $ps > 0.050$). Similarly, there were no significant differences in motor coordination scores, positive affective states before and after the coordination task and no difference for variation in participants' emotional state (all $ps > 0.050$). Additionally, there were no significant differences across the VPI conditions for experiences of self-other overlap, anthropomorphism, goal achievement and cooperativeness (all $ps > 0.050$). Finally, there were also no significant differences in prosocial outcomes for Dictator and Trust Games (all $ps > 0.050$) but a trend for a significant difference across conditions for the Ultimatum Game ($p = 0.050$) - for full statistics, see **Table 4.1**.

	Cooperation ($N = 71$)	Competition ($N = 72$)	Group comparisons
Age	36.56 ± 10.56	36.83 ± 10.67	$t = 0.15, p = .879$
Gender	42 men, 28 women 1 non-binary	44 men, 26 women 2 non-binaries	$p = .873$
Synchrony scores	0.44 ± 0.33	0.43 ± 0.34	$W = 2567, p = .966$
Positive Affect (*T0*)	34.11 ±9.69	33.85 ± 8.20	$t = -0.18, p = .860$
Positive Affect (*T1*)	33.69 ± 10.04	34.42 ± 8.34	$t = 0.47, p = .639$
Difference (*T1* - *T0*)	-0.11 ± 0.90	0.11 ± 1.09	$t = 1.32, p = .188$
Self-Other Overlap	4.51 ± 1.79	4.69 ± 1.63	$t = 0.65, p = .514$
Anthropomorphism	2.23 ± 1.31	2.46 ± 1.44	$t = 1.01, p = .314$
Goal Achievement	6.17 ± 1.85	6.49 ± 1.75	$t = 1.05, p = .295$
Cooperativeness	2.46 ± 1.07	2.75 ± 1.15	$t = 1.54, p = .126$
Dictator Game	19.62 ± 9.89	19.38 ± 9.23	$t = -0.15, p = .879$
Trust Game	27.56 ± 13.26	24.69 ± 11.19	$t = -1.40, p = .165$
Ultimatum Game	0.52 ± 0.86	0.78 ± 0.63	$p = .050$

Table 4.1 Descriptive statistics across VPI conditions for Study 1

4.3.2 Zero-order correlations

Scores of motor coordination were positively correlated with variation in participants' emotional state ($p = .040$) - although this association did not hold significance after corrections ($p = .162$). In contrast, scores of motor coordination were negatively associated with affiliation ($p < .001$), humanness ($p = .006$) and goal achievement ($p < .001$) and these associations remained significant after corrections (all $ps < .050$). Finally, there was no association with cooperativeness, Dictator and Trust Games (all $ps > .050$) - see **Figure 4.2** for a graphical representation, with solid lines representing best fit and transparent grey areas representing 95% confidence interval.

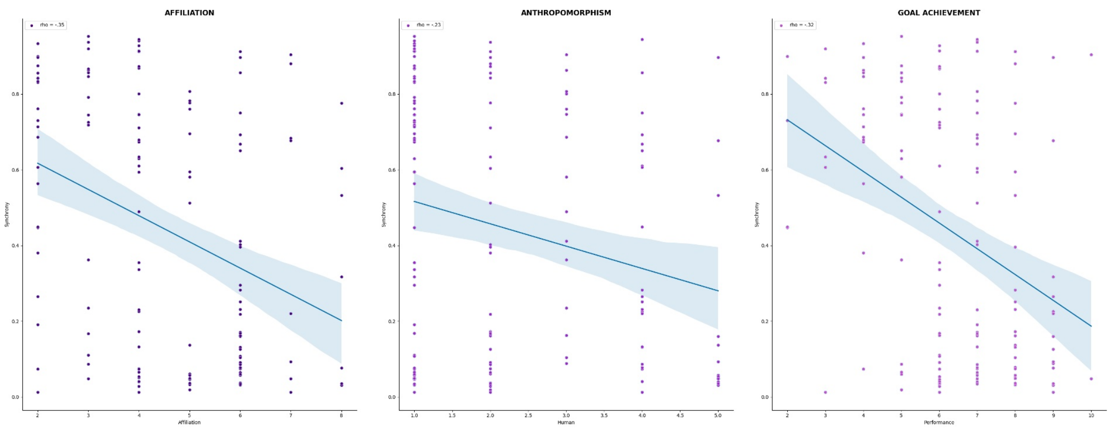

Fig. 4.2 Graphical representation of the associations between synchronisation and self-reports in Study 1

Variations in participants' emotional state were not correlated with affiliation, humanness, cooperativeness, goal achievement, Dictator and Trust Games (all $ps > .050$). Affiliative tendencies were positively correlated with humanness ($p < .001$) and goal achievement ($p < .001$) and these associations remained significant after corrections (all $ps < .050$). However, affiliative tendencies were not associated with cooperativeness, Dictator and Trust Games (all $ps > .050$). Humanness was positively correlated with goal achievement ($p < .001$) and this association remained significant after corrections ($p < .010$). However, humanness was not associated with cooperativeness, Dictator and Trust Games (all $ps > .050$). Goal achievement and cooperativeness were not significantly correlated (all $ps > .050$) and were not associated with Dictator and Trust Games (all $ps > .050$). Finally, Dictator and Trust Games outcomes were positively correlated ($p < .001$) and this association remained significant after corrections ($p < .010$) - for a full summary, see **Table 4.2**.

	SYNC	AFF	SOO	ANT	GOA	COOP	DG
Synchrony scores	-						
Affect (*T1 - T0*)	.17						
Self-Other Overlap	-.35**	.06					
Anthropomorphism	-.23*	-.05	.33**				
Goal Achievement	-.32**	.14	.67***	.29**			
Cooperativeness	.10	.14	$< .01$	.11	.09		
Dictator Game	-.11	-.03	-.02	-.06	-.01	.09	
Trust Game	.08	-.01	.04	-.02	-.04	.09	.32**

Table 4.2 Zero-order correlations for Study 1

Adjusted p-values are reported with $*p < .05$*,* $**p < .01$*,* $***p < .001$

4.3.3 Logistic regressions

The Ultimatum Game outcomes were not significantly predicted by scores of motor coordination ($\chi^2(141) = 136.29, p = .609$), variation in participants' emotional state ($\chi^2(141) = 135.73, p = .354$), affiliation ($\chi^2(141) = 135.94, p = .436$), humanness ($\chi^2(141) = 136.54, p = .928$), goal achievement ($\chi^2(141) = 136.54, p = .924$), cooperativeness ($\chi^2(141) = 136.49, p = .810$), Dictator ($\chi^2(141) = 136.42, p = .718$) and Trust Games ($\chi^2(141) = 136.54, p = .915$).

4.4 Discussion

This first study investigated the affective, cognitive and prosocial consequences of moving in synchrony with a virtual agent. In line with the first hypothesis, behavioural synchrony improved participants' affective state, but this association did not hold significance after corrections. In contrast, the execution of synchronous movements with a virtual agent was associated with decreased self-other overlap experiences but not with prosocial outcomes. Finally, manipulating the VPI's behaviour did not affect participants' sense of joint commitment.

Altogether, these results suggested that the affective consequence of synchrony observed in human-human interactions could be translated in HCI contexts (Hove and Risen, 2009; Zumeta et al., 2016). Yet, this increase in positive affect was weak and not associated with altruistic outcomes. Furthermore, an unexpected negative association was observed between synchrony and affiliative tendencies. Whilst this result contradicts findings from human-human interactions (Atherton et al., 2019; Cross et al., 2019), it echoes previous observations reporting a detrimental effect of IMC in HCI contexts (Bailenson et al., 2008; Verberne et al., 2013).

Importantly, an inspection of the participants' answers during the practice trial suggested that participants may not have fully understood the rules of the economic games. High numbers of participants provided wrong answers for the Dictator ($N = 37$), Trust ($N = 36$), and Ultimatum Games ($N = 66$). These participants were not excluded, considering that these errors occurred during the practice trial. However, these errors could have affected the quality of the data. Consequently, replicating these results was warranted to address the limitations of the experimental design of the first study.

4.5 Replication

To overcome the first study's limitations, a second study was conducted using six rounds of the Dictator Game; this multi-trial design framing was already implemented in studies investigating the role of the affective state on Dictator Game giving (Pérez-Dueñas et al., 2018). Different amounts of coins were presented randomly (60, 25, 40, 35, 50, 15) and transformed into z-scores. Additionally, the measure of perceived similarity/closeness adapted from Atherton et al. (2019) might have captured different constructs than the Inclusion of the Other in the Self (IOS; Aron et al. (1992)), a single-item, pictorial measure of interpersonal closeness used in previous studies (Reddish et al., 2014; Tarr et al., 2018). Consequently, this scale was administered in the second study to capture the individual's sense of social connectedness and check its association with other measures of interpersonal closeness (Gächter et al., 2015). Finally, to rule out potential concerns about data quality, the second study was conducted using Prolific, an online platform advertised as providing better data quality (Peer et al., 2022).

4.5.1 Participants

A total of 180 participants were recruited in July 2021 and compensated using a fixed rate of £5 per hour for completing the survey. As a result of technical incompatibility between the VPI implementation and some web browsers, 48 participants were excluded because of missing data. Additionally, 14 participants were excluded for missing values in the Dictator Game ($N = 11$), failure to understand the Dictator Game instructions ($N = 2$) or failure to pass the attentional test ($N = 1$). Consequently, the statistical analyses included a final sample of 118 participants (59 men and 59 women US residents, mean age = 32.75, SD =10.50, range 18 to 63 years). A population comparison between studies revealed significant differences for age ($p = .003$), motor coordination scores ($p = .001$), and negative affective states ($p < .001$) - for full statistics see **Appendix G**.

4.5.2 Results

Comparison of the VPI conditions did not reveal any significant differences for demographic properties of the population, including age and gender (all $ps > .050$). Similarly, there were no significant differences in motor coordination scores, positive affective state before and after the coordination task and no difference for variation in participants' emotional state (all $ps > .050$). Additionally, there were no significant differences across VPI conditions for affiliative tendencies measured through self-report of similarity/closeness, perceived humanness and cooperativeness (all $ps > .050$) but a trend for significant difference in IOS ($p = .094$) and goal achievement ($p = .090$) with tendencies to report higher scores for IOS and goal achievement in the cooperative compared to the competitive condition. Finally, there were no significant differences for the Dictator Game outcomes ($p = .261$) - for full statistics, see **Table 4.3**.

	Cooperation ($N = 60$)	Competition ($N = 58$)	Group comparisons
Age	32.80 ± 9.90	32.71 ± 11.18	$t = -0.05, p = .962$
Gender	32 men, 28 women	27 men, 31 women	$p = 0.581$
Synchrony scores	0.55 ± 0.31	0.62 ± 0.28	$W = 1950, p = .259$
Positive Affect (*T0*)	33.32 ± 9.10	31.38 ± 10.09	$t = -1.09, p = .276$
Positive Affect (*T1*)	33.60 ± 10.20	32.03 ± 10.41	$t = -0.82, p = .411$
Difference (*T1* - *T0*)	-0.04 ± 1.16	0.04 ± 0.81	$t = 0.41, p = .685$
Self-Other Overlap	3.98 ± 1.55	3.60 ± 1.47	$t = -1.37, p = .175$
Inclusion of the Other	2.65 ± 1.67	2.17 ± 1.40	$t = -1.69, p = .094$
Anthropomorphism	2.03 ± 1.29	1.91 ± 1.22	$t = -0.52, p = .605$
Goal Achievement	5.75 ± 1.79	5.19 ± 1.77	$t = -1.71, p = .090$
Cooperativeness	2.60 ± 0.99	2.33 ± 0.94	$t = -1.53, p = .130$
Dictator Game	0.14 ± 1.04	-0.15 ± 0.95	$t = -1.59, p = .114$

Table 4.3 Descriptive and group comparison statistics for Study 2

Scores of motor coordination were negatively correlated with affiliation ($p = .006$). Similar trends were observed for IOS ($p = .088$) and goal achievement ($p = .059$). Variations in participants' emotional state were not associated with synchrony, affiliation, IOS, humanness, goal achievement, cooperativeness and Dictator Game (all $ps > .050$). Affiliative tendencies were positively correlated with humanness ($p < .001$) and goal achievement ($p < .001$) but not with cooperativeness ($p = .583$) and Dictator Game ($p = .936$) - for a graphical representation see **Figure 4.3**, with solid lines representing line of best fit and transparent grey areas representing 95% confidence interval

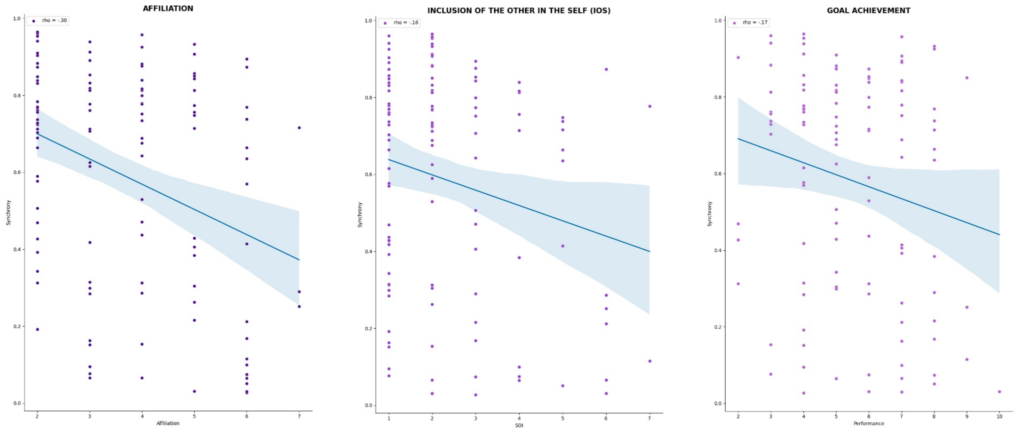

Fig. 4.3 Graphical representation of the correlations between synchronisation and self-reports in Study 2

A similar pattern was observed for IOS scores, displaying a positive correlation with affiliation ($p < .001$), humanness ($p = .001$) and goal achievement ($p < .001$) but not with cooperativeness ($p = .944$) and Dictator Game ($p = .346$). Humanness was positively correlated with goal achievement ($p = .035$) but not with cooperativeness ($p = .513$) and Dictator Game ($p = .724$). Finally, goal achievement and cooperativeness were not correlated with each other ($p = .269$) nor with the Dictator Game ($p = .329$ and $p = .287$ respectively). Significant associations remained below the $p < .050$ threshold after corrections for multiple comparisons - for a full summary, see **Table 4.4**.

	SYNC	AFF	SOO	IOS	ANT	GOA	COOP
Synchrony scores	-						
Affect (*T1* - *T0*)	.02						
Self-Other Overlap	-.30**	.02					
Inclusion of the Other	-.16	.13	.67***				
Anthropomorphism	-.14	.03	.38***	.30**			
Goal Achievement	-.17	-.05	.60***	.51***	.25*		
Cooperativeness	.11	-.01	.05	.01	.06	.10	
Dictator Game	-.14	-.02	.01	-.09	.03	.09	.10

Table 4.4 Zero-order correlations for Study 2

Adjusted p-values are reported with $*p < .05$, $**p < .01$, $***p < .001$

4.6 General Discussion

This second study partially replicated the findings from study 1. The positive association observed in Study 1 between synchrony and positive affect was not replicated in Study 2. However, the negative and unexpected association between synchrony and affiliative tendencies was replicated in Study 2. Finally, synchrony did not elicit prosocial outcomes. However, study 2 replicated the positive association between goal achievement, anthropomorphism and affiliation.

4.6.1 Affective and cognitive consequences

The positive association between synchrony and positive affective state was not replicated across studies. The association observed in Study 1 did not hold after corrections and complementary analyses revealed significant differences in affective states across studies (see **Appendix G**). Whilst previous studies already underlined that affective states are simultaneously predictors and outcomes of synchrony (Smykovskyi et al., 2022; Tschacher et al., 2014), the discrepancy in affective states measurements challenges their comparisons. The present investigation questions the "processing fluency" hypothesis, associating synchrony with uncertainty reduction leading to positive affective states (Hoehl et al., 2021; Hove and Risen, 2009). Although unexpected, these findings are aligned with the systematic review conducted during this PhD highlighting potential confounds in the associations between synchrony and affective states. Beyond the scope of the thesis, exploratory analyses investigated the role of emotion dysregulation - see **Appendix C**.

In contrast to pre-existing studies reporting a positive association between synchrony and affiliation, both studies revealed a reversed pattern, with a negative association between synchrony and self-reports of similarity and closeness. This pattern contradicts previous studies observing a positive association between synchrony and affiliative tendencies in human-human interaction but echoes previous reports of detrimental or null effects of synchrony in HCI context. Bailenson et al. (2008) and Verberne et al. (2013) suggested that the excess of predictability and the lack of flexibility of virtual agents parroting participants' movement can lead to uncanny feelings, increasing self-other distinction rather than promoting affiliation. Importantly, despite strong correlations between perceived similarity/closeness and IOS scores, the negative association of synchrony on affiliative tendencies was not significant for IOS, suggesting that lexical self-reports based on Likert scales and pictorial assessment of interpersonal closeness may capture different aspects of togetherness. Therefore, a careful assessment of the methods used for investigating interpersonal closeness is warranted for delineating possible multiple facets of togetherness.

The negative association of synchrony with experiences of self-other overlap was associated with decreased anthropomorphic tendencies. Importantly, self-reports of perceived similarity and closeness were associated with anthropomorphism and tendencies for perceiving the VPI as human in both studies. Based on the pre-existing literature, two hypotheses are suggested for explaining these patterns. On the one hand, complexity rather than synchrony has been recently emphasised for eliciting social bonding in human-human interactions (Dahan et al., 2016; Ravreby et al., 2022)[1]. Therefore, the rewarding experience of IMC could be similar to the experience of the musical groove, where the mixture of predictability and uncertainty challenges predictions to avoid boredom recalling the concept of "flow" state (Csíkszentmihályi and Larson, 2014; Stupacher et al., 2022; Vuoskoski and Reynolds, 2019). Applied to the HCI context, these findings align with the 3-Factor model of anthropomorphism stressing the role of uncertainty in attributing human-like behaviours (Epley et al., 2007). Therefore, these findings pave the way for designing human-agent interactions that mimic human-human interactions more efficiently through layers of complexity and unpredictability. On the other hand, the lack of social identity or "credibility" of the VPI may have failed to trigger a need for belongingness and social connection (Fernández Castro and Pacherie, 2021). These results call for a more careful assessment of the association between synchrony and affiliative tendencies in HCI contexts, paving the way for future investigations exploring the role of predictability in attributing human features to virtual agents.

4.6.2 Prosocial outcomes and joint commitment

Synchrony was unassociated with altruistic outcomes in both studies. Whilst this finding contradicts previous studies reporting a positive association between synchrony and prosocial outcomes, it highlights potential confounding variables. Previous studies have indeed used experimental designs involving enjoyable activities, such as simple movements choreography (Reddish et al., 2014; Tarr et al., 2018), walking (Atherton et al., 2019; Wiltermuth and Heath, 2009), or tapping (Tunçgenç and Cohen, 2016). Other investigations stressed the impact of contextual factors, mediating the impact of synchrony on feelings of connectedness and prosocial outcomes, such as music (Demos et al., 2012; Tarr et al., 2014), collective sports (Davis et al., 2015; Zumeta et al., 2016), religion (Cohen et al., 2014; Fischer et al., 2013) and cultural contexts (Gelfand et al., 2020). Importantly, the association between synchrony and prosocial outcomes disappears when controlling for confounding variables, suggesting that synchrony is not directly associated with altruism but mediated by the experience of social bonding (Mogan et al., 2017; Rennung and Göritz, 2016; Tarr and Dunbar, 2023).

[1]Complexity can be measured by the "Wundt curve", predicting a U-inverted relationship between exposure and complexity in aesthetics judgments - see Berlyne (1970) and Madison and Schiölde (2017)

The positive correlations observed in the first study between Dictator and Trust Games outcomes suggest that these two measures are not independent, questioning the relevance of economic games for assessing the association between synchrony and prosocial outcomes. Previous studies already stressed the role of social norms in economic games outcomes (Bolton and Ockenfels, 2000; Burton-Chellew and West, 2013; Fehr and Schmidt, 1999) and it is unclear if these norms can be translated in HCI context. Although previous studies reported similar findings in human-human and human-computer economic games (Nouri and Traum, 2013), others suggest a more complex interplay between altruism and anthropomorphism in HCI context (Melo et al., 2016; De Kleijn et al., 2019). Altogether, these findings suggest that synchrony might not be sufficient for eliciting prosocial outcomes but that the associated context seems more important, especially in HCI context. This statement aligns with the systematic review conducted during this PhD, stressing the contrasting outcomes of synchrony reported in the literature (Ayache et al., 2021). Consequently, future investigations need to identify these potential confounding factors.

Exploratory analyses on the role of goal achievement revealed that perceived goal achievement was positively associated with tendencies for affiliation and anthropomorphism but not with prosocial outcomes. Interestingly, perceived goal achievement was also negatively associated with scores of coordination, revealing a discrepancy between perceived and effective behavioural synchrony. These findings echo recent observations reporting that perception of synchrony rather than motor synchrony is associated with the perception of musical groove (Matthews et al., 2022). Moreover, studies have already reported potential difficulties and bias for participants in assessing their performance, underlying the role of motivational bias (Logg et al., 2018). Finally, previous studies already reported an association between motor coordination impairment and meta-cognition dysfunction in pathological conditions such as Parkinson's or Huntington's diseases (Leritz et al., 2004; Sitek et al., 2011), schizophrenia (Hur et al., 2014; Poletti et al., 2012), and atypical neurodevelopment (Lou, 2012).

This discrepancy between self-reports of affiliative tendencies, goal achievement and effective coordination echoes findings from **Chapter 3** reporting a negative association between self-reports of spontaneous synchrony (i.e., KinEmp) and behavioural motor coordination. Altogether these findings call for a cautious examination of the association between the subjective perception of synchrony and the objective execution of temporally aligned motor behaviours (i.e., real synchrony). Therefore, future investigations are required to explore the potential gap between actual behavioural motor coordination, perceived goal achievement and affiliative outcomes of synchrony.

Importantly, the manipulation of the joint commitment did not lead to any significant changes in agent and task perception, suggesting that the manipulation of the VPI's condition was too subtle to be detected despite a trend for a significant difference in study 2. Additionally, the duration of the trial may have been too short, with previous studies using longer interaction duration (e.g., 2 to 6 minutes - see Hove and Risen (2009) and Reddish et al. (2014)), or repetition of several short trials (Cacioppo et al., 2014; Cross et al., 2019). Nevertheless, the duration of synchrony in moderating its prosocial outcomes remains unclear, and the literature does not provide any specific guidance on the impact of synchrony duration. Whilst the meta-analysis from Vicaria and Dickens (2016) did not report any moderating role of synchrony durations, Chen et al. (2021) and Tschacher et al. (2018) used synchrony duration for assessing social presence and feelings of "nowness" in social interactions. Consequently, a systematic investigation of the role of synchrony duration is warranted.

4.6.3 Limitations and Future research

Considering the context in which these data collections occurred, these results must be taken cautiously. First, the inconsistencies observed in the association between synchrony and affective state across the two samples highlighted the role of potential inter-individual differences (i.e., emotion dysregulation) across samples. The first data collection occurred during the COVID-19 pandemic when social interactions drastically changed and might have affected participants' behaviours (Teater et al., 2021). Second, the use of a completely online setting might have interfered with participants' behaviours by promoting social desirability (Antin and Shaw, 2012; Gamblin et al., 2017) and by disrupting the completion of the experimental task in the absence of a laboratory-controlled environment. Third, despite a trend for a significant difference across VPI's conditions on goal achievement, the too-subtle manipulation of the VPI's behaviours might have failed to induce the usual outcomes of synchrony. Previous studies already stressed that "size matters", suggesting that synchrony's outcomes are particularly salient in large groups and for activities requiring greater muscle exertion (Mogan et al., 2017; Tarr et al., 2015). Therefore, these results need to be replicated using a laboratory-controlled environment and movements with greater muscular effort. Despite these limitations, this online data collection questions the systematic association of synchrony with positive outcomes. This online data collection paves the way for investigations exploring (i) the causality between synchrony and affective state[2], (ii) togetherness measurements, and (iii) the role of predictability in anthropomorphism.

[2]The "enslavement" principle highlights the influence of top-down and bottom-up processes, rendering difficult to tease apart causal mechanisms across various scales - see Haken (1987)

4.7 Conclusion

To summarise, this second experiment investigated the limitations of virtual agents in triggering affiliative and altruistic tendencies in HCI contexts. Despite inconsistencies across studies on the role of affective states and null findings for prosocial outcomes, synchrony was consistently negatively associated with affiliative tendencies, stressing that virtual synchrony can be detrimental in HCI context. The excessive predictability of the VPI might have led participants to judge the VPI as "robot-like", resulting in its failure to trigger affiliative and prosocial tendencies. Although speculative, this hypothesis aligns with the "credibility problem", and the next chapters will investigate the role of predictability in anthropomorphism. Additionally, whilst the results from **Chapter 3** highlighted the association between empathy and goal-oriented motor coordination, it remains to clarify the association between empathy and spontaneous motor coordination. Consequently, the research questions guiding this PhD will be expanded in the next chapters, investigating (i) the association between IMC and empathy and (ii) the appropriate use of virtual agents for modelling social interactions.

CHAPTER 5

METHODS - PART II

"Everywhere where there is an interaction between a place, a time and an expenditure of energy, there is rhythm"
- Henri Lefebvre

The online study reported in **Chapter 3** explored the association between Interpersonal Motor Coordination (IMC) and self-reported empathy using the Haken Kelso Bunz model (HKB) (Dumas et al., 2014a). This study revealed that self-reports of spontaneous tendencies for entrainment (i.e., kinesthetic empathy), although strongly associated with affective empathy, is a distinct facet of empathy associated with impaired goal-oriented IMC. On the other hand, the capacity for predicting other behaviours (i.e., cognitive empathy) was associated with better goal-oriented IMC performances, replicating results from laboratory settings (Koehne et al., 2016b; Novembre et al., 2019). Although theoretical models suggest a strong entanglement between neurocognitive mechanisms sustaining empathy and IMC, experimental findings remain scarce (Decety and Meltzoff, 2011; Gallese, 2001; Preston and De Waal, 2002). Additionally, the online study reported in **Chapter 4** showed that contrary to human-human interactions, goal-oriented IMC in Human-Computer Interactions (HCI) reduced tendencies for affiliation, revealing a potentially detrimental impact of predictability on perceived virtual agents as social entities (Bailenson et al., 2008; Epley et al., 2007). Consequently, further clarifications are required on the association between the ability to predict others' mental states, spontaneous tendencies for IMC and anthropomorphism.

The second part of this thesis expanded the two research questions introduced in **Chapter 1**, namely (i) the association between affective, cognitive, motor, and kinesthetic facets of empathy with automatic imitation and (ii) their association with anthropomorphic tendencies. The present chapter introduces the methods implemented in the experiments reported in **Chapters 6** and **7**, starting with the behavioural assessment of spontaneous tendencies for imitation, then describing the behavioural assessment of the capacity to predict others' behaviours and finally presenting methods for investigating the underlying neurophysiological correlates of these processes.

5.1 Synchrony and imitation: distinct or overlapping concepts?

As detailed in **Chapter 1**, synchrony comes in different flavours in the literature, overlapping with concepts borrowed from joint action, encompassing goal-oriented motor coordination, expanding to spontaneous tendencies for synchrony, mimicry, and imitation. Imitation can be considered a spontaneous tendency to reproduce gestures with several conceptualisations and methods measuring this behavioural pattern. Echoing the first observations of synchrony in collective gatherings, studies of synchrony are often associated with rhythmic activities, ranging from ecological tasks (e.g., paired walking; Cheng et al. (2020)) to more controlled settings (e.g., finger tapping; Heggli et al. (2019)) - see **Chapter 2, section 2.1.3** for an overview.

In contrast, imitation is characterised by the execution of spatially congruent movements (Bernieri and Rosenthal, 1991). Methods used in assessing imitation often require the involvement of at least two or more participants to study the dynamics of their interaction. However, this entangles imitation with social norms, whereby social identity influences imitation. That is, individuals tend to mimic more often those who are similar or from desirable social groups (Dalton et al., 2010; Levy and Bader, 2020). Moreover, excessive imitation or the lack of imitation is experienced as socially awkward, hampering the implementation of control conditions (Bailenson et al., 2008). Alternatively, methods to study imitation can also involve the observation of facial mimicry using pre-recorded material or the tendency of contagious yawning (Platek et al., 2003). Automatic imitation can also be observed by modulating participants' reaction times while presenting stimuli depicting congruent (or incongruent) movements (Brass et al., 2001). Consequently, there is a range of assessments of spontaneous tendencies for imitation, and there are difficulties in clarifying if these various measurements map onto similar or distinctive concepts.

According to Heyes (2011), automatic imitation must be distinguished from mimicry, assessed by action frequency rather than behavioural performances. Automatic imitation can indeed be conceptualised as a specific stimulus-response compatibility effect, where "the speed or accuracy of behavioural performance is modulated by the relationship between the topographic features of task-irrelevant action stimuli and the participant's responses" (Heyes, 2011, p. 464). A study from Genschow et al. (2017) reported a lack of convergence between behavioural measures of automatic imitation and mimicry, stressing their problematic conflation in the literature. Consequently, automatic imitation and mimicry need to be considered as distinct constructs.

5.1.1 The Automatic Imitation Task (AIT)

The Automatic Imitation Task (AIT) developed by Brass et al. (2001) is one of the most widespread measures of automatic imitation, conceptualised as stimulus-response compatibility effect, where participants are instructed to execute specific movements (i.e., (e.g. lifting a finger or pressing specific keystrokes) while watching pictures of neutral, congruent or incongruent movements. Speed (i.e., reaction time) and accuracy (i.e., errors) are the two behavioural metrics extracted from the AIT used for measuring (i) the *congruency* effect, comparing congruent versus incongruent trials, (ii) the *facilitation* effect, comparing congruent versus neutral trials, and (iii) the *interference* effect, comparing incongruent versus neutral trials. Studies usually report a tendency for faster responses and greater accuracy for congruent compared to incongruent (i.e., *congruent* effect) and neutral trials (i.e., *facilitation* effect) and slower responses with more errors for incongruent compared to neutral trials (i.e., *interference* effect) (Cracco et al., 2018). The AIT is suggested to be a robust and reliable assessment of automatic imitation that can be implemented in online and in-laboratory settings(Galang and Obhi, 2023).

Nevertheless, it remains to clarify whether the AIT measures automatic imitation or reflects a spatial compatibility fluency effect (Heyes, 2011). A meta-analysis from Cracco et al. (2018) revealed a reduced effect of the AIT when controlling for spatial compatibility - that is when the movements that need to be executed are anatomically compatible with the stimulation cues but not spatially congruent. This suggests that automatic imitation could be associated with a domain-general system associated with processing fluency rather than specific to social interactions (Ramsey, 2018). Supporting this, another meta-analysis suggested that automatic inhibition is not associated with the neural network dedicated to social cognition (Darda and Ramsey, 2019). Nevertheless, Cracco and Brass (2019) maintain that the AIT measures overt tendencies for imitation and relies on other brain areas dedicated to social cognition, such as neural networks involved in Theory of Mind (ToM) and self-other distinction (i.e., the right temporal junction, rTPJ). Furthermore, whilst Ramsey (2018) criticised the lack of construct validity of the AIT, Cracco and Brass (2019) stressed that the AIT is designed for minimising inter-individual differences and identifying universal mechanisms, recalling the opposition of nomothetic and idiographic approaches exposed in **Chapter 2**. Thus, despite some debates in the scientific community on the nature of the process measured, extensive experimental investigations are using the AIT as an index of automatic imitation. Consequently, this thesis used the AIT as an operationalisation of automatic imitation in the investigation reported in **Chapter 6**.

5.1.2 Disentangling space and time in imitation

Importantly, none of the AIT studies have considered the dynamics of participants' responses in imitation processes, that is, the role of temporal sequences - except in learning processes and stimulus-onset (Cracco et al., 2018; Heyes et al., 2005). Despite the importance of rhythms in social interactions (Cirelli et al., 2018; Malloch and Trevarthen, 2018), the role of the temporal sequences in the AIT has been neglected. Rhythmicity is a core feature of human cognition, as illustrated by the intrinsic rhythmicity of human languages and the capacity to create musical pieces (Jones, 1987; Kotz et al., 2018). Experimental studies showed that the temporal sequences of stimulation matter, with tendencies for faster reaction times when repeated responses occurred with short inter-trial intervals (ITI) (< 500ms) but faster for alternated responses with increased ITI (Kirby, 1976). This pattern was initially interpreted as automatic facilitation and tendencies for alternation expectation in random series for longer ITI, a tendency observed in the gambler fallacy (Ayton and Fischer, 2004).

More recently, Annand et al. (2021) suggested that this pattern matches predictions from the Haken-Kelso-Bunz model (HKB). Indeed the HKB predicts that alternation cannot be maintained when frequency increases (Kelso, 1984). Previous implementations of the AIT used variable ITI, ranging from 300 ms up to 2400 ms (Butler et al., 2015; Cross et al., 2021; Hogeveen and Obhi, 2013; Obhi et al., 2014). However, most studies implemented an ITI of 500 ms (Galang and Obhi, 2023; Genschow et al., 2017,0; Newey et al., 2019). Interestingly, this frequency corresponds to the critical frequency of 2 Hz identified by the HKB for phase transition, a switch from an anti-phase to an in-phase pattern of motor coordination. Thus, it is unclear if this modulation can be attributed to the coordination pattern's intrinsic rhythmicity or if it results from higher hierarchical cognitive functions associated with conscious prediction. Consequently, in addition to averaging speed and accuracy across congruent, incongruent and neutral trials, the experimental investigation presented in **Chapter 6** explores the role of temporal sequences in the AIT and its association with empathy.

5.1.3 Automatic imitation and empathy

Accumulative evidence suggests potential shared mechanisms between automatic imitation, synchrony, and empathy - see **Chapter 1, section 1.4.1** for an overview. Nevertheless, theoretical debates remain on the neurocognitive mechanisms underlying imitation. Although the Perception-Action model of empathy and imitation suggested the Mirror Neuron System (MNS), as a common hard-wired neurocognitive architecture of imitation and empathy (Ramachandran and Oberman, 2006), this view is strongly criticised among the scientific community (Heyes, 2010; Southgate and Hamilton, 2008).

Recent empirical evidence underlines the role of learning mechanisms in developing automatic imitation. According to the Associative Sequence Learning model, the binding of action/observation and action/execution occurs through repetitive exposure (Brass and Heyes, 2005). This model contradicts the nativist view on imitation and, by extension, on empathy and postulates that automatic imitation is not innate but learned through environmental exposure and by building internal models predicting self and other-initiated actions. Furthermore, other studies suggest that brain areas involved in self-other distinction, such as the rTPJ, are also activated during automatic imitation (Quesque and Brass, 2019; Hamilton, 2015). Consequently, there is a strong case for an association between imitation and empathy, considering their reliance on a common neurocognitive architecture involving the Action-Perception matching system (i.e., the MNS) and the conflict monitoring system (i.e., self-other overlap/distinction).

However, despite a substantial number of studies investigating the association between empathy and imitation, there is a lack of empirical evidence supporting this hypothesis. The meta-analysis conducted by Cracco et al. (2018) concluded that the link between empathy and AIT is spurious, considering that most studies report mixed findings with null or weak associations between the two variables[1]. For example, Butler et al. (2015) reported a lack of association between the AIT and empathy measured using the Empathy Assessment Index (Lietz et al., 2011); however, they did not delineate affective and cognitive facets. In contrast, Genschow et al. (2017) reported a modulation of the congruency effect (i.e., contrasting reaction time between congruent and incongruent trials) and the Interpersonal Reactivity Index (IRI) subscale *Personal Distress*. However, they suggested that this effect could be driven by statistical artefacts and gender differences rather than empathy traits. Finally, Cracco et al. (2018) analysed the IRI subscales *Empathic Concern* and *Personal Distress* as affective facets without considering their possible conflation with sympathy and emotional distress (see **Chapter 2, section 2.2.3**). This gap between theoretical models and empirical evidence can partially be attributed to the current "jingle-jangle" fallacy occurring in empathy measurements, conflating its components. Therefore, the third study conducted during this thesis explored the association between imitation and empathy by considering distinct empathy facets, namely, cognitive, affective, kinesthetic and somatic empathy. Additionally, the role of temporal sequences in automatic imitation and its association with empathy will be explored. Further details on the electrophysiological correlates of imitation and empathy will be provided in **section 5.3**.

[1]Similarly, inconsistent findings are also reported regarding the association between mimicry and empathy - see Chartrand and Bargh (1999) and Sonnby-Borgström et al. (2003)

5.2 Role of predictability in human-computer-interaction

As discussed in **Chapter 1**, **section 1.4.1**, the capacity to coordinate movement with others is associated with neurocognitive mechanisms involved in mirroring gestures through the integration of the other in the self but also requires the capacity for distinguishing self from other through segregation mechanisms (Sebanz and Knoblich, 2009; Shamay-Tsoory et al., 2019). The same applies to empathic abilities that require sharing similar affective states and distinguishing self from other viewpoints (Decety and Jackson, 2006). How these human-human processes can be translated into the Human-Computer Interaction (HCI) context needs to be clarified. The results reported in **Chapter 3** revealed that the ability to predict others' mental states is crucial for the achievement of motor coordination with a virtual agent, reproducing similar results from in-laboratory studies (Koehne et al., 2016b; Novembre et al., 2019).

However, contrary to human-human interactions, results from **Chapter 4** suggested that Interpersonal Motor Coordination (IMC) in HCI decreases affiliation and anthropomorphism. Theoretical models of anthropomorphism suggest that perceived randomness in human behaviour is a characteristic feature of human behaviour, a consequence of the need of humans to reduce environmental uncertainty (Epley et al., 2007). This suggests that the excessive predictability of a virtual agent could be perceived as stereotypical or robot-like behaviour and be detrimental to fostering a sense of togetherness in HCI (Bailenson et al., 2008; Verberne et al., 2013). Recent studies have suggested that movement complexity (i.e., characterised by a certain amount of randomness), rather than zero-lag synchrony (i.e., sequences with higher predictability) might be a better marker of the rewarding experience of rhythmic interactions (Dahan et al., 2016; Stupacher et al., 2022; Vuoskoski and Reynolds, 2019).

This section will discuss to what extent predictability is a core feature in HCI design, emphasising its role from an engineering point of view and stressing that predicting others' behaviours overlaps with empathy's conceptualisation and varies from one individual to another. Consequently, this section will review the current challenges in HCI, focusing on the Out-Of-The-Loop (OOTL) problem and anthropomorphism. Then, this section will briefly summarise ToM ability assessments and their possible translation in the HCI context. By considering both agents' predictability and inter-individual differences in capacities for predicting others' behaviours (i.e., empathy), this section calls for including empathy theories in designing virtual agents capable of nurturing the feeling of togetherness. Finally, this section suggests methodological advancement for designing and evaluating virtual agents capable of sustaining human operators' attentional processes.

5.2.1 The Out-of-the-Loop problem

Fueled by the development of artificial intelligence, modern societies are developing towards and are increasingly dependent on automation - that is, the substitution of a function initially performed by humans to automated algorithms (Klien et al., 2004). Consequently, the capacity of humans interacting with automated algorithms (also called "operators") to understand the system's state is crucial to avoid detrimental consequences. For example, Gouraud et al. (2017) reported that most aircraft crashes can be attributed to problems of miscommunication between humans and automated algorithms, linked to a loss of "situational awareness", characterised by a lack of understanding of the situation. Labelled as the OOTL problem, this research area has attracted considerable interest in improving human capacity to operate in an automated environment (Berberian et al., 2017). On the one hand, predictions of the system's state can be understood as a technical problem, where features need to be implemented to improve the readability of the system for the human operators. For example, De Greef et al. (2007) and Di Flumeri et al. (2019) suggested that adaptive automation systems that support continuous exchanges between operators and automated algorithms should be implemented to maintain the operators in the interaction loop. On the other hand, a loss of situational awareness can be understood as an attentional drop, where systems need to be implemented to monitor the operators' vigilance levels. For example, Gouraud et al. (2017) suggested that monitoring levels of vigilance through electrophysiological markers could detect operators' disengagement from the task. Altogether, both approaches assume that automated algorithms and human operators must maintain mutual awareness of their respective states.

As seen in **Chapter 1**, mutual awareness falls into the umbrella term of togetherness. Therefore, recent approaches in HCI suggest that the interaction between automated agents and human operators should be considered a collaborative task, where operators and automated agents are team partners that must understand each other (Klien et al., 2004). These approaches suggest a switch from the perspective of seeing "computers as tools" to seeing "computers as collaborators", where operators need to recognize and grant automated algorithms as having a mind and avoid their objectification (Vispoel et al., 2018). Recognizing others as having a mind and acting as such is a fundamental aspect of empathy, and failure to acknowledge this shared humanity can buffer empathetic processes and its prosocial outcomes (Fiske, 2009; Bloom, 2017). Consequently, the ability to understand automated algorithms (i.e., ToM abilities) and their capacity to be perceived as human (i.e., anthropomorphic) are core components of empathetic processes that need to be considered for designing successful HCI.

5.2.2 Anthropomorphism and the uncanny valley

Inspired by the "uncanny valley" phenomenon in robotics (Mori, 1970), anthropomorphism is a vast topic of research in HCI, measuring the tendencies for attributing human characteristics to nonhuman things (Bartneck et al., 2009). According to Mori (1970)[2], a shift occurred in HCI design where automated agents needed to be considered as social agents rather than tools. Therefore, designers were tempted to increase the humanoid features of automated agents but risked falling into the "uncanny valley", an area where automated agents are more prone to elicit fear-evoked responses as a result of their failure to replicate human characteristics accurately. As discussed in **Chapter 1**, several models of anthropomorphism co-exist in the literature, challenging the understanding of tendencies to ascribe machines' human-like features.

According to the Computer-As-Social-Actor (CASA) model, humans tend to perceive computers as social agents (Nass et al., 1994) and empirical evidence suggests that we apply "mindlessly" social norms toward machines (Grynszpan et al., 2017; Hasler et al., 2014). However, as Iachini et al. (2014) noted, the elusive social identity of virtual agents can also be disturbing, and participants tend to increase interpersonal distance in such circumstances. Bailenson et al. (2008) and Verberne et al. (2013) reported similar findings, highlighting that the replication of stereotypical human behaviours can also trigger feelings of "eeriness". According to the 3-factor model of anthropomorphism, human agentivity is attributed when randomness is perceived to reduce environmental uncertainty (Epley et al., 2007). Unpredictability and propensity for mistakes are attributed to human behaviour rather than machines, which are judged more reliable and trustworthy (Dzindolet et al., 2003). This complacency toward machines is, in turn, part of the OOTL problem, as humans place excessive trust in agents, leading to a loss of situational awareness (Endsley and Kiris, 1995). Consequently, it is unclear when automated agents should display human-like features and how these features might change how they are perceived as social entities.

Importantly, there is no consensus on anthropomorphism measurements and empirical evidence for the "uncanny valley" effect has been mixed. Some studies reported that non-human agents were perceived as more human than humans, stressing the difficulties in delineating characteristics associated with humanness. For example, Bartneck et al. (2007) suggested distinguishing between perceived humanness and likeability, leading to the development of the Godspeed scale, a multidimensional assessment of the uncanny valley encompassing several facets associated with anthropomorphism such as

[2] Interestingly, Mori emphasised that movements executed by a machine were particularly prone to be detected as eerie considering their mechanical nature - see Mori (1970)

perceived animacy, intelligence and safety (Bartneck et al., 2009). However, the psychometric properties of the Godspeed scale are questioned, particularly because of the lack of discrimination between facets associated with anthropomorphism (Ho and MacDorman, 2010). For instance, perceived warmth and competence are often conflated, entangling affective and cognitive mechanisms.

Furthermore, definitions of the “uncanny effect” change from one study to another. The Japanese terminology “shinwakan” used by Mori was first translated as “familiarity” and later changed to “affinity”, capturing the idea of having a similar mind (Wang et al., 2015). According to evolutionary and psychoanalytic theories, the uncanny valley is a fear-evoked response where eerie robot features evoke perceptions of death and sickness (Moosa and Ud-Dean, 2010). Alternatively, cognitive theories suggest that this effect is the ambiguity or cognitive dissonance arising from the difficulties in categorising human-like robots that trigger the uncanny effect (Carpenter et al., 2006; Yamada et al., 2013). Importantly, these hypotheses have assessed mostly the categorisation of physical features of automated agents. The uncanny valley is often conceptualised in terms of aesthetics and framed as an emotional response to the graphical representation of virtual agents (Geller, 2008; Hanson et al., 2005). Therefore, the role of the behavioural patterns expressed by virtual agents and the associations with the perception of having a mind remains understudied.

According to the mind perception and the dehumanisation hypotheses, the uncanny valley is an unnerving experience resulting from the failure to recognize humanness in an anthropomorphized agent, where humanness is conceived as (i) capacity for agentivity (i.e., acting and thinking independently) and (ii) capacity for sentience (i.e., experiencing emotions) echoing empathy conceptualisations (Gray and Wegner, 2012; Wang et al., 2015). Therefore, anthropomorphism tendencies are entangled with empathic abilities and can be conceptualised as a dynamic exchange between an automated agent displaying human-like behaviours and the capacity of a human operator to interpret these behaviours as such. Consequently, the design of automated agents with anthropomorphic features doesn’t rely only on the sole agents’ characteristics but must consider inter-individual differences in the abilities to understand others (i.e., empathy) and tolerance of ambiguity and uncertainty.

5.2.3 Behavioural assessments of empathy

As discussed in **Chapter 1, section 1.3.1**, empathy is an umbrella term encompassing a constellation of components associated with affective (i.e., capacity to share emotions) and cognitive (i.e., capacity to infer mental states of others) processes. Several theories of empathy co-exist, but it remains unclear if experiencing similar affective states is a prerequisite for cognitive empathy or if understanding others' mental states is independent of affective components. Clinical conditions such as autism or psychopathy provide some insights into separate cognitive and affective empathy deficits, respectively. Yet, mixed findings are reported in the literature, stressing the difficulties in delineating affective from cognitive components and assessing these empathy facets independently.

Empathy measures followed the ebb and flow of the development of psychology as a scientific discipline and remained crippled by important limitations (Hall and Schwartz, 2019). Starting with introspective methods that were discarded in favour of systematic assessments, empathy can be measured with self-reports (as presented and reviewed in **Chapter 2**, **section 2.2.3**) or by behavioural assessments combined with electrophysiological recordings and, more recently, with neuroimaging methods (Eisenberg and Miller, 1987; Eisenberg and Fabes, 1990). On the one hand, affective empathy is often assessed by measuring the vicarious responses to emotional simulations such as others' pain (Lamm et al., 2011; Lockwood, 2016), pleasant and unpleasant touch (Lamm et al., 2015), facial expressions (Besel and Yuille, 2010; Jospe et al., 2018) and more recently, the sharing of emotional autobiographical memories, providing a new measure of empathy accuracy (Jospe et al., 2020). On the other hand, cognitive empathy is typically assessed by measuring the ability to read others' minds without considering affective sharing (Leudar et al., 2004). Also labelled as Theory of Mind (ToM), this is a core feature of human cognition supporting capacities to deal with complex social environments (de Waal, 2008; Dunbar, 1998; Moore, 2021).

Beyond social cognition, ToM abilities are associated with self-awareness and adopting a decentring point of view, and therefore, reflect on one's thoughts, considered a marker of meta-cognitive processes (Proust, 2007; Sodian and Frith, 2008). The assessments of ToM abilities were initially conducted using false belief tasks (e.g., Sally-Anne test), testing the ability to distinguish self and others' perspectives (Wimmer and Perner, 1983) and later expanded to subdomains such as perspective-taking (Baker et al., 2017), recognition of "faux-pas" in social interactions or emotional facial expressions (e.g., the Reading the Mind in the Eyes, Baron-Cohen et al. (1997)) rendering it unclear to understand what is exactly measured.

The various behavioural assessments associated with different conceptualisations of cognitive empathy led to a lack of consistency across measurements (Beaudoin et al., 2020). For example, Melchers et al. (2015) reported a lack of correlation between the Reading the Mind in the Eyes (Baron-Cohen et al., 1997) and the Cambridge Face-Voice Battery (Golan et al., 2006) - two tasks assessing emotion recognition from facial expressions or voice recordings, designed for detecting empathy deficits in autism. Importantly, it remains unclear whether these tasks measure cognitive or affective components of empathy considering their emotional content (Oakley et al., 2016; Zahavi, 2008). Furthermore, ToM assessments are typically not interactive, as they rely on linguistic features, perspective-taking tasks or recognition of facial expressions, lacking contextual cues. Consequently, it is difficult to ascertain if ToM abilities measured in the laboratory can be translated to real-life scenarios.

To address these limitations, new experimental paradigms are being developed involving video recording of interpersonal interactions, allowing one to understand the capacity to infer others' mental state, such as the empathy accuracy task (Jospe et al., 2020). However, this task contains emotional material, entangling affective and cognitive components. Furthermore, the facial expression of emotions can differ from one individual to another and across cultures, rendering it difficult to generalise this measurement (Ekman, 1993). Considering that the purpose of the present investigation was to assess the effects of the predictability of an automated agent and inter-individual empathy variabilities on perceived humanness, the following section will discuss new assessments of ToM abilities that are particularly interesting in the context of HCI, as they capture the tendencies to attribute mental states to others, namely the recursive or second-order theory of mind assessments.

5.2.4 Second-other theory of mind

Inspired by evolutionary game theory, new ToM assessments are developed, offering new ways of assessing perceived humanness in HCI contexts (Yoshida et al., 2008). Characterised by the recursive thinking of "I think that you think that I think", second-order ToM reflects tendencies to infer mental states of the other about one's mental states. These economic games offer new paradigms for ToM assessments by manipulating the uncertainty and interactivity of automated agents (Rusch et al., 2020). The analysis of game strategies captures the tendencies of participants to consider others' mental states (de Weerd et al., 2018) and how individuals tend to adjust their behaviour according to the outcomes of their actions (Mookherjee and Sopher, 1994).

According to the Nash equilibrium, the best game strategy in zero-sum games with asymmetric pay-off (i.e., one player wins, the other loses) is to play randomly (Veltman et al., 2019). However, humans perform poorly in generating random sequences because of cognitive limitations (Bar-Hillel and Wagenaar, 1991; Rapoport and Budescu, 1992; Warren et al., 2018). Consequently, players tend to rely on strategies that can be biased (i.e., choice based on probability distribution), self-oriented (i.e., choice based on previous action) or other-oriented (i.e., choice based on other's actions). In this latter case, participants rely on recursive ToM abilities (e.g., I think that you think) or a more elaborated ToM model (e.g., I think that you know that I think).

Applied to the Matching Pennies Game (MPG)[3], the analysis of behavioural patterns and game strategies can offer new insights into tendencies to apply ToM abilities. The MPG can be framed as a social or non-social interaction by guessing the probability distribution between two alternative options (e.g., red and blue cards). For example, Forgeot d'Arc et al. (2020) compared the performances of autistic and neurotypical participants in hide-and-seek (social framing) and gambling games (non-social framing) using intelligent automated agents that were able to adjust their behaviour according to the human participant by implementing recursive functions (k-ToM). However, as de Weerd et al. (2018) noted, it remains unclear if individuals rely on game strategies or ToM abilities to perform during the MPG. Indeed, recursive ToM abilities are cognitively costly and may not always be the best cognitive strategy for performing in cooperative or competitive contexts (Devaine et al., 2014). Further investigations are required to understand how individuals adjust their behaviours and adopt specific game strategies when interacting with an automated agent.

In short, predictability is a crucial element in HCI for preventing the OOTL problems. Yet, excessive predictability can lead automated agents to be perceived as machine-like rather than having a mind. Abilities for reading others' minds fall under the umbrella term of cognitive empathy, calling for a consideration of empathic abilities for designing efficient HCI. Expanding results from **Chapter 4**, the fourth study of this thesis used the MPG for assessing ToM abilities in association with empathy questionnaires and self-reports of anthropomorphism and predictability. The MPG allows the analysis of (i) the association between predictability and perceived humanness, (ii) the association between self-reports of empathy and participants' ability to predict agents' behaviour, and (iii) the interaction between predictability and self-reports of empathy on participants' performances and perceived humanness of the agent.

[3] The MPG can also be used for studying tendencies for automatic imitation - see Belot et al. (2013)

5.3 Electrophysiological markers of mirroring and predicting

Chapter 1 reviewed the shared neurocognitive mechanisms of IMC and empathy. On the one hand, accumulative evidence suggests that imitation and motor coordination involve the sensorimotor cortex and the Mirror Neuron System (MNS), which fires when observing and executing similar actions, explaining the spontaneous tendency for imitation and synchronisation. Nevertheless, the MNS appears insufficient for explaining modulations in imitation and capacities for joint motor coordination that require anticipation, involving a frontoparietal network supporting capacities for self-regulation and self-other distinction. On the other hand, theoretical models of empathy suggested the involvement of sensorimotor areas and MNS in the shared experience of others' mental and emotional states. Yet, similarly to motor coordination, the MNS appears insufficient in explaining empathy as a multidimensional concept and the prefrontal and temporoparietal areas are also involved in predicting others' actions. Consequently, IMC and empathy are entangled and share neurocognitive mechanisms.

This section will briefly introduce neuroimaging methods that allow the recordings of neural activations associated with motor coordination and empathy, focusing on electroencephalography (EEG), used the in-laboratory experiments presented in **Chapters 6 and 7**. Hence, an overview of signal processing methods used for EEG pre-processing for removing artefacts with filtering methods and Independent component analyses (ICA) will be provided.

Methods for computing spectral analyses, such as the Fast Fourier Transform (FFT), will be introduced. The EEG frequency bands associated with mirroring will be reviewed to identify neurophysiological markers suggested as a marker of the MNS activation, such as the modulation of the alpha-mu and beta bands and its current limitations (Hobson and Bishop, 2016,0; Dumas et al., 2014b).

Finally, methods for extracting the Event-Related Potential (ERP) will be introduced alongside a brief overview of the ERP associated with conflict monitoring, such as the N2 and P3 (Rauchbauer et al., 2021) and the Feedback-Related-Negativity (FRN) observed in experimental paradigms investigating decision-making processes (Hauser et al., 2014; Nieuwenhuis et al., 2001; Walsh and Anderson, 2012).

5.3.1 Introduction to electroencephalography

As discussed in **Chapter 2**, classical scientific approaches in psychology are challenged by the difficulties of measuring "private" mental states and rely mostly on indirect observations of psychological phenomena. Neuroimaging methods allow mapping neural activity to mental operations by recording neural activity while participants are exposed to stimuli or during resting states. The methods currently available for recording neural activity rely on various approaches. Functional magnetic resonance imaging (fMRI) and functional near-infrared spectroscopy (fNIRS) allow the identification of regional brain activation associated with task-induced or spontaneous modulation of neural metabolism by capturing and contrasting the hemodynamic variations of blood oxygen levels (i.e., BOLD response, Ogawa et al. (1990)). Whilst fMRI and fNIRS methods offer high spatial resolution, allowing more accurate identification of specific activated brain areas, these neuroimaging techniques suffer other limitations. For example, temporal resolution in fMRI is lower than that of the EEG as a result of the time course of the hemodynamic response (3 to 6 seconds after a stimulation), limiting the capture of temporal dynamics of evoked responses (Glover, 2011). EEG and magnetoencephalogram (MEG) provide alternative methods to investigate neural dynamics by recording the temporal fluctuation of the electrical activity and magnetic fields (i.e., field potentials) of the brain coming from the post-synaptic activity of the external cortical layer of pyramidal neurons (Teplan et al., 2002)[4]. Compared to fMRI and fNRIS, EEG offers lower spatial resolution, though it is possible to estimate neural sources using inversion algorithms (Michel et al., 2004). EEG captures the synchronisation of neurons and can be studied using similar mathematical formulations as for motor synchronisation (Jirsa et al., 1994; Strogatz, 1994).

The term "elektrocerebrogramm" initially coined by Wladimir Práwdicz-Neminski was later changed to "elektroenkephalogramm" by Hans Berger, who performed the first EEG recordings on humans (Coenen and Zayachkivska, 2013). Berger developed an apparatus combining electrodes placed on the scalp coupled with an amplifier for recording characteristic brain waves, such as the alpha waves, also known as Berger's waves (Kaplan, 2011). Nowadays, EEG recordings are performed using monopolar or bipolar systems, where the former captures the voltage difference between an active electrode on the scalp and a reference electrode on the earlobe. In contrast, bipolar electrodes give the difference in voltage between two scalp electrodes (Osselton, 1965). The localisation of the electrodes on the scalp is usually determined by international standards, such as the 10–20 system, based on the distance of adjacent electrodes from nasion to inion (Jasper, 1958) - see **Figure 5.1** for a graphical representation.

[4]The EEG captures the electric activity coming from extracellular potentials - see Speckmann (1993).

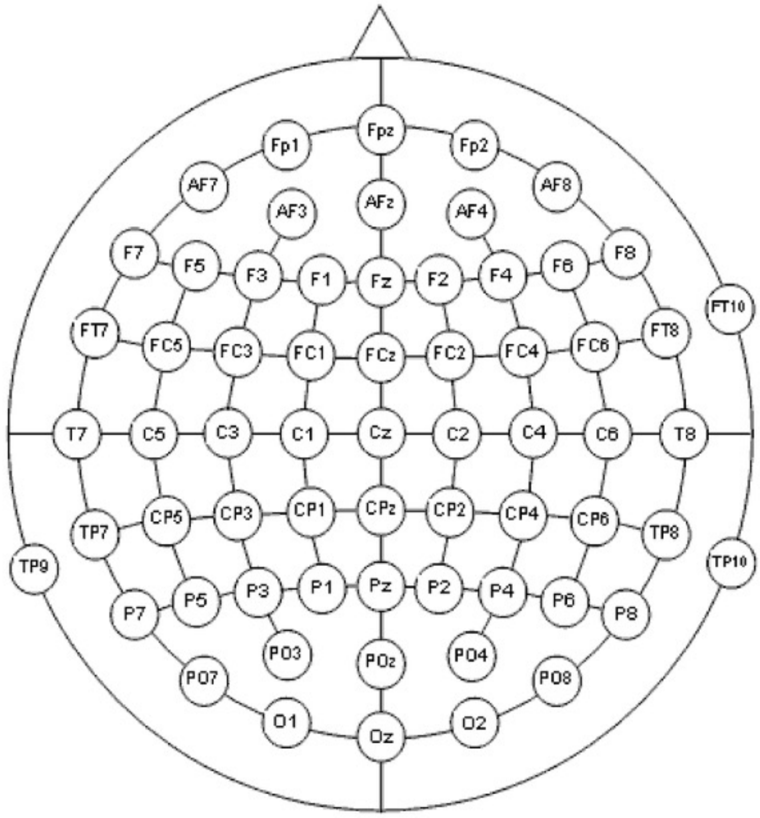

Fig. 5.1 Graphical representation of a 64-channels EEG BioSemi system, following the International 10–20 system

5.3.2 EEG pre-processing

The EEG signal is composed of a mixture of electrical activity coming from neuron synchronisation and noise coming from environmental sources such as electric devices or physiological sources such as eye movements and muscular and/or cardiac activity. Therefore, EEG recordings require pre-processing to improve the signal-to-noise ratio[5]. Whilst traditionally, there is inconsistency across studies, standardised procedures are emerging, such as the PREP pipeline, which suggests the following steps: (i) removing line noise, (ii) detecting and interpolating bad channels, (iii) re-referencing of the signal (Bigdely-Shamlo et al., 2015) - for a graphical summary, see **Figure 5.2**.

Removing line noise from the signal can be performed with filtering algorithms, such as a notch or Finite Impulse Response (FIR) filter, that attenuate the power over a narrow region of the frequency spectrum (e.g., 50 or 60Hz; Widmann et al. (2015)). However, filtering can generate signal distortions and should be guided by the EEG components of interest (de Cheveigné and Nelken, 2019).

[5]In a recent article, Delorme (2023) questions the relevance of EEG pre-processing methods.

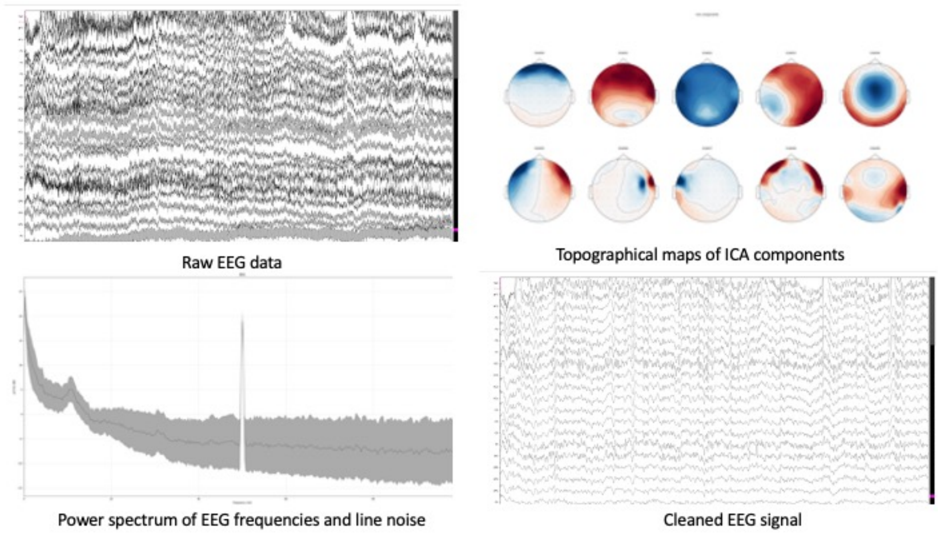

Fig. 5.2 Illustration of the EEG pre-processing steps

Identification of “bad” channels characterised by poor signal-to-noise ratio can be performed by detecting extreme amplitudes or high-frequency noise, computing z-scores, and looking at correlations with or predictability of other channels (Bigdely-Shamlo et al., 2015). Once detected, bad channels can be removed (resulting in data loss) or interpolated (data estimation). Interpolation methods can include neighbour interpolation (NI), averaging adjacent “good” channels, or spherical spline interpolation (SSI), projecting channels onto a unit sphere and calculating mapping matrices to reconstruct bad channels’ signals (Perrin et al., 1989). However, interpolation methods can lead to artefacts when excessive bad channels are reconstructed or when appropriate referencing methods are not conducted (Dong et al., 2021).

Given that EEG data are based on the difference in potential between two electrodes, choosing an appropriate referencing system is important for approximating a minimal potential to reduce artefact contaminations of the signal. Some methods include vertex reference (Cz), linked mastoids or ear lobes and averaging techniques (Dong et al., 2019). However, these referencing methods are not neutral as they capture electrical activity coming from the body that can contaminate the spatial and temporal features of the signal. Consequently, new methods have been developed to overcome this limitation, such as the Reference Electrode Standardisation Technique (REST) that reconstructs the potential with a reference at infinity from scalp electrodes or averages using source reconstruction (Zhai and Yao, 2004).

Additionally to the PREP pipeline, artefacts from eye movements can be removed by recording electrooculogram (EOG) signals, using additional external channels, and subtracting them from the EEG signals (Croft and Barry, 2000; Gratton et al., 1983). Alternative techniques, such as Independent Component Analysis (ICA), can also decompose the signal into separated components, allowing artefacts' identification and their subtraction from the signal[6]. Finally, the EEG signal can be downsampled to hasten its processing. However, downsampling procedures need to follow the Nyquist–Shannon sampling rule, a mathematical theorem demonstrating that frequency reconstruction above half of the nominal sampling rate is invalid and can introduce distortion (i.e., aliasing). Consequently, the sampling frequency must be at least twice the highest frequency of interest[7]. To summarise, pre-processing EEG recordings is not trivial and should be guided by the research questions addressed and the EEG analyses associated.

5.3.3 Frequency Bands

Beyond the alpha band that was first observed by Hans Berger, a large spectrum of frequency bands can be extracted from the EEG signal by decomposing the signal into frequency bands using the Fast Fourier Transform (FFT) algorithm. Developed by Cooley and Tukey (1965), the FFT has a long history in mathematics, and the Fourier Transform methods are part of a branch of mathematics focused on harmonic analyses, developing algorithms for decomposing a function into oscillatory components (Heideman et al., 1985). Consequently, FFT is applied in various fields beyond signal processing and EEG analyses.

The Fourier Transform (F) equation can be written as follows – see Equation 5.1:

$$X(\omega) = \int_{-\infty}^{+\infty} x(t)e^{-i\omega t}dt \tag{5.1}$$

Where ω is a specific frequency or pulsation, $X(t)$ is the temporal series representing the signal, multiplied by $e^{-i\omega t}dt$, representing the mathematical formulations of the function associated with the frequency ω based on Euler's formula.

[6] Visual identification of ICA components is often fastidious and lacks reliable classification methods. Consequently, machine learning techniques are developed to label ICA components automatically - see ALICE from Soghoyan et al. (2021)

[7] New techniques are developed for sample signals at frequencies below the Nyquist–Shannon sampling limit - see the Compressing Sensing method from de Oliveira et al. (2020)

Considering that EEG signals are composed of discrete values, a Discrete Fourier Transform (DFT) is usually performed using the following formula – see Equation 5.2

$$X(k) = \sum_{n=0}^{N-1} x(n)e^{-i\omega k \frac{n}{N}} \tag{5.2}$$

With k representing the signal's length and n the signal's sampling that complies with the Nyquist–Shannon sampling theorem. The output, $X(\omega)$ or $X(k)$, is a complex number called the dot or scalar product. The projection of its imaginary and real parts on an orthogonal axis is used to extract the signal's amplitude and phase - for a graphical illustration, see **Figure 5.3**.

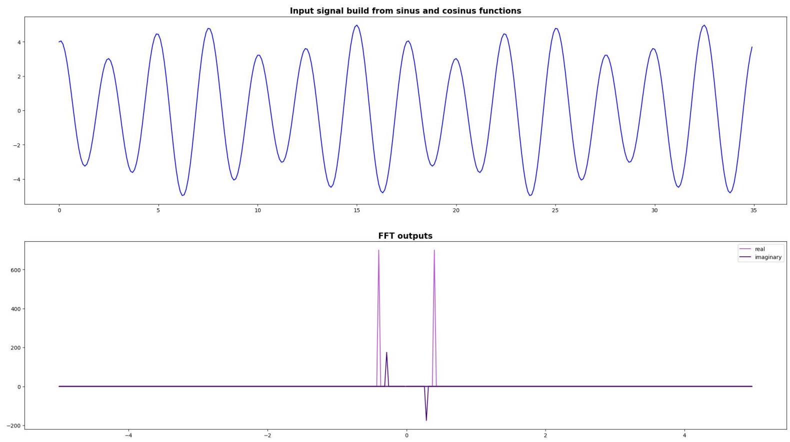

Fig. 5.3 Illustration of the Fast Fourier Transform outputs

However, the DFT requires high computational costs that prevent its direct use for signal processing. Therefore, the Fast Fourier Transform (FFT) was developed based on the signal's harmonics - that is, the recurrence of information between frequencies through the factorisation of the DFT matrix (Cochran et al., 1967). Whilst the FFT can decompose the spectral properties of the EEG signal in the frequency domain, the FFT does not provide information about the temporal resolution. Furthermore, EEG signals violate the assumption of signal stationarity, characterised by the stability of spectral features over time. Consequently, the Short-time Fourier Transform (STFT) can also be performed using a window function, computing the FFT on local chunks of the data. Still, its bandwidth modulates the frequency and temporal resolutions - see **Chapter 6** and **7** for further discussions on the limitations of the FFT.

The frequencies extracted from the EEG signal by the FFT have been classified according to their ranges, partially overlapping with specific functional stages characterising consciousness states. Indeed, as underlined by Buzsaki (2006), the classification of frequency bands in EEG reflects the adoption of international conventions rather than mapping specific cognitive functions. For example, the slow frequency delta band (δ, 0.5 - 4 Hz) that is usually observed during deep sleep (Amzica and Steriade, 1998; Walter, 1936) can also be observed in the waking state and is associated with novelty detection (Harper et al., 2017), motivational processes (Knyazev, 2012) or brain damage (Spironelli and Angrilli, 2009). Similarly, the high-frequency epsilon or high-gamma band (ϵ, above 80 Hz), characterised by high-frequency oscillations, traditionally considered a marker of epileptic seizures, has been recently investigated in clinical conditions such as schizophrenia (Buzsáki and da Silva, 2012; Uhlhaas and Singer, 2022; Zijlmans et al., 2012). Regarding the aim of this thesis, the frequency bands ranging from 4 up to 80 Hz characterising waking states are of particular interest for mapping cognitive functions associated with imitation (i.e., mirroring) and conflict monitoring processes.

Regarding imitation, the mu band (μ, 8 - 14 Hz) or rolandic rhythm has been associated with mirroring and in clinical conditions associated with empathy deficits, such as psychopathy (Decety et al., 2015; Hobson and Bishop, 2017). The mu band is an event-related desynchronization (ERD) of the EEG, observed when motor actions are executed and when observing or imagining an action being performed, resulting in the desynchronisation of the neurons located in brain areas previously identified as the mirror neuron network (Perry et al., 2010). Consequently, it has been suggested that the mu band is the EEG signature of the mirror neuron system activation.

However, there is a lack of consensus about the robustness of this measure given the frequency overlap with the EEG alpha band (Fox et al., 2016; Hobson and Bishop, 2016). First described by Berger, who noticed a variation of this frequency band in some individuals, the mu band is usually recorded in centroparietal areas of the scalp at a frequency range that overlaps the alpha band (8 - 14 Hz). Therefore, some authors suggested that the mu band reflects travelling alpha waves from occipital areas to the sensorimotor cortex and prefrontal areas involved in attentional processes (Dumas et al., 2014b). Consequently, by restricting EEG analyses to the fluctuation of the mu band in centroparietal locations as a marker of inhibition of automatic imitation, previous studies may have neglected important components also involved in imitation, such as attentional processes that are also involved in the OOTL problem.

Attentional processes can be decomposed into sub-components associated with specific EEG frequency bands: (i) the alert network, maintaining attentional focus is reflected by a decrease in the theta band (θ, 4 - 8 Hz); and the (ii) orienting and executive control, allowing one to switch from one task to another and to monitor and resolve conflicts in the presence of competing information; are associated with regionally specific increases in the gamma band (γ, 30 - 80 Hz). This is followed by a decrease in all frequency bands (i.e., theta, gamma, alpha) and beta (β, 14–30 Hz) before responding to incongruent stimulation, followed by an increase after responding to the stimulation. (Fan et al., 2007; Posner and Boies, 1971). Consequently, the analyses of EEG frequency bands have revealed the complex interplay between brain rhythms and attention components, and the present thesis will focus on the conflict monitoring processes.

In automatic imitation, conflict monitoring processes can be understood as a mismatch between observed and executed movements (i.e., self-other distinction), and the right temporoparietal junction (rTPJ) has been identified as a hub of the default mode network, involved in self-other distinction (Decety and Lamm, 2007; Saxe, 2010; Sperduti et al., 2011). Stimulation of the rTPJ is associated with reduced tendencies for automatic imitation (Sowden and Catmur, 2015). In the EEG frequency domain, studies reported modulation of the beta band recorded in somatosensory areas near the rTPJ during rhythmic activities involving self-other distinction (Large and Snyder, 2009; Park et al., 2018). Additionally, other studies reported modulation of the alpha/mu band in centroparietal areas as a marker of self-other integration (Novembre et al., 2016; Tognoli et al., 2007). Consequently, modulations of the alpha and beta bands will be investigated as markers of mirroring and self/other distinction processes in imitation.

In OOTL, conflict monitoring processes can be understood as the ability to discriminate the incongruence between internal and external representations, overlapping with self-other distinction processes (Knyazev, 2013). The incongruence between internal and external representations engages brain areas associated with conflict monitoring, such as the anterior cingulate cortex (Botvinick et al., 2004; Bush et al., 2000). Translated into EEG frequency bands, conflict monitoring can be inferred from alpha and beta frequency as a marker of attentional components (Fan et al., 2007), extraction of musical rhythms (Gordon et al., 2011; Large et al., 2015) and expectancy violations (Öniz and Başar, 2009)[8]. Consequently, modulations of the alpha and beta bands will be investigated as markers of conflict monitoring in the Matching Pennies Game (MPG).

[8] In fact, brain rhythms affect the way we extract patterns in the external world and, in return, environmental rhythms can influence brain oscillations. This phenomenon of "neural entrainment" is different from the bi-directional coupling occurring in synchrony but results from the unidirectional influence of an external periodic force - see Jones (1976); Lakatos et al. (2019); Large and Snyder (2009)

5.3.4 Event-Related-Potential

Another method for analysing the EEG signal can be done by extracting the event-related-potentials (ERP), a time-locked (or phase-locked) EEG response “evoked” by triggers: external stimulation, behaviour or a cognitive process (Picton et al., 1995). The ERP can be “exogenous” - associated with the physical properties of the stimulation (e.g., auditory or visual modality), or “endogenous” – associated with the psychological consequences of the stimulation (e.g., decision-making or feedback processes). The ERPs are detected by increasing the signal-to-noise ratio by averaging the signal over trials across specific time windows, labelled epochs (Michalopoulos et al., 2011) - for a graphical illustration, see **Figure 5.4**.

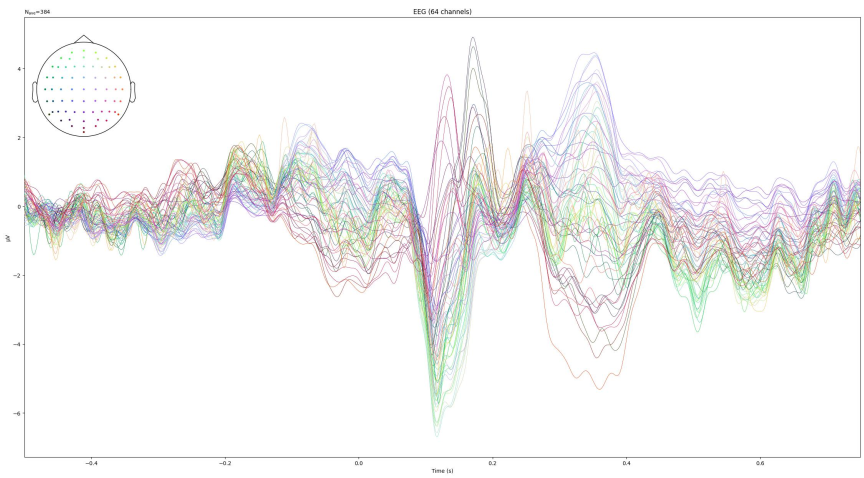

Fig. 5.4 Illustration of an ”evoked” response across 64 channels

The “evoked” responses only preserve the activity that is phase-locked in time and needs to be distinguished from “induced” responses obtained by applying time-frequency decomposition to each trial before averaging across trials. The time-frequency decomposition obtained from each trial is then subtracted from the averaged power, revealing the “induced” responses (Mazaheri, 2022; Tallon-Baudry and Bertrand, 1999). Therefore, “evoked” responses refer to the neural synchronisation elicited by the trigger that becomes apparent by averaging the signal, whilst induced responses are the synchronisation or desynchronisation of the signal, that cannot be explained by the power of the average (David et al., 2006). Whilst ERP and induced EEG responses are considered as separate measures, they likely share common mechanisms of emergent neural coupling or “resonance” triggered by environmental changes (David et al., 2006; Varela, 1995)[9].

[9]Resonance refers to the alignment of oscillations to a system’s natural frequency (i.e., eigenfrequency), resulting in its amplification - see Hutcheon and Yarom (2000); Lomas et al. (2022).

The ERP components are characterised by positive and negative deflections, from which amplitude (expressed in microvolts, µV) and latency (i.e., temporal assessment point, typically time between trigger and peak, expressed in ms) can be measured across scalp regions/electrode sites. The comparison of experimental conditions can be conducted by contrasting ERPs' peak amplitude and latency. However, this approach is sensitive to high-frequency noise. To overcome this limitation, the mean amplitude can be calculated within a specified time window[10]. Traditionally, ERPs have been named after the polarization of their amplitude (**N** for negative and **P** for positive) and latency (e.g., time elapsed after the triggered stimulation). Alternatively, some ERPs are named according to their functionality (e.g., Feedback-Related-Negativity, FRN). However, amplitude and latency show inter-individual variability and can be affected by cross-study differences in sampling rate, stimuli and experimental protocols. This complicates cross-study comparisons and the development of precise theories regarding functionality and underpinning brain mechanisms (Walsh and Anderson, 2012).

Several ERP components associated with conflict monitoring have been identified in the literature in the context of experimental paradigms requiring decision-making processes, similar to the AIT and MPG (Dyson et al., 2020; Hu et al., 2010; Rauchbauer et al., 2021). The next section will briefly review the ERPs identified as markers of conflict monitoring processes, such as the N2, P3, FRN and FB-P3 (or P300).

The N2 component is considered a marker of conflict monitoring, recorded in frontocentral electrodes around 250 ms after the stimulation's onset. The N2 is larger during incongruent compared to congruent trials, with anterior and posterior subcomponents, reflecting mismatch detection and motor control (Folstein and Van Petten, 2008; Grützmann et al., 2022; Mathalon et al., 2003; Yeung et al., 2004). The N2 is followed by a positive peak labelled as P3 (or Cue-P3 when triggered by a warning stimulus), composed of a mixture of a frontoparietal component (P3f or P3a) and a longer-latency large component (P3b), located over the parietal cortex, followed by a post-motor potential component (PMP), reflecting attentional orienting and motor preparation/execution (Jang et al., 2016; Jonkman, 2006; Makeig et al., 1999). The N2 and P3 components are sensitive to social cues. For example, the presentation of in-group stimuli increases the N2 and P3 amplitude compared to responses to out-group stimuli (Luo et al., 2018). Similarly, Fukushima et al. (2004) reported increased N2 amplitude when imitating a finger's motion compared to reacting to a flashing light. Previous studies using the AIT showed that the ERPs components' amplitude were sensitive to the congruence of AIT cues (Rauchbauer et al., 2021). Consequently, this thesis investigated the modulation of the N2 and P3 components by stimulation cues associated with automatic imitation.

[10]However this approach is more prone to false positive - see Luck and Gaspelin (2017)

The Error-Related-Negativity (ERN), sometimes labelled as Ne, is another ERP component of interest, recorded in frontocentral electrodes and characterised by a negative peak, occurring around 50 to 100ms after an error is committed. This negative peak is also observed for correct responses (i.e., Correct-Response-Negativity, CRN), but with lower amplitude, and is proposed to reflect performance monitoring (Grützmann et al., 2022). Anatomically, the ERN arises from the activation of the anterior cingulate cortex (ACC), a key node of the salience network, involved in switching from default to executive network and, therefore, overlapping with self-awareness processes (Knyazev, 2013; Lenzoni et al., 2022; Uddin, 2015). Therefore, the ERN would have been an interesting candidate for investigating conflict-monitoring processes in automatic imitation. However, the ERN requires a certain number of errors to be considered a reliable measure, with a lack of consensus on the number of trials required (Larson et al., 2010; Olvet and Hajcak, 2009). Considering the small number of errors usually observed in the AIT (Cracco et al., 2018), this ERP was not included in the subsequent analyses.

The Feedback-Related-Negativity (FRN) is a component observed in frontocentral electrodes, characterised by a negative peak arising between 200 to 400ms after a feedback stimulus. The FRN is elicited when a mismatch occurs between observed and expected outcomes and could reflect interindividual differences in tolerance to uncertainty (Hirsh and Inzlicht, 2008). However, inconsistencies across studies render it unclear if the FRN is sensitive to favourable or unfavourable outcomes (Cohen et al., 2007; Hajcak et al., 2006; Nieuwenhuis et al., 2005). The FRN is suggested to arise from the activation of the ACC, though there are inconsistencies in the literature on the FRN neural localisation (Nieuwenhuis et al., 2005). The FRN is considered a marker of the activation of the reward system but also arises with expectancy violations (Balconi and Canavesio, 2015; Schaefer et al., 2016; Zhou et al., 2010).

Although the FRN shared similar scalp locations with the ERN, it remains to be clarified if they reflect similar neurocognitive components. Several studies suggested a potential overlap between the neurocognitive processes underlying ERN and FRN (Hauser et al., 2014). However, whilst the ERN is observed following response errors, the FRN is observed following performance feedback. Therefore, the ERN could reflect endogenous processes while the FRN reflects exogenous processes (Bernat et al., 2008; Walsh and Anderson, 2012). Previous studies investigated the modulation of the FRN in the context of the MPG and showed the influence of subjective beliefs in successful performances and its association with reinforcement learning processes (Dyson et al., 2020; Hu et al., 2010). Consequently, this ERP was investigated to explore the role of the agent's predictability during the MPG.

A positive peak usually follows the FRN, sometimes referred to as the FB-P3 or P300 and is observed around 200 to 600 ms in temporoparietal areas following feedback. Amplitudes of the FB-P3 increase for unexpected outcomes, suggesting its involvement in updating internal models (Balconi and Canavesio, 2015). However, it remains to clarify if the FB-P3 is a distinctive marker from the FRN and is sensitive to the valence (i.e., positive or negative feedback) or magnitude (i.e., better or worse than expected) of the outcomes (Bernat et al., 2008; Wang et al., 2017; Zhou et al., 2010). Studies suggest similar mechanisms underlying the Pe, a positive component following the ERN and FB-P3, both reflecting affective and motivational processes, yet inconsistencies in experimental protocols challenge their comparison (Nieuwenhuis et al., 2001; van Veen and Carter, 2006; Wu and Zhou, 2009). Furthermore, it remains to be clarified if the FB-P3 reflects reward-based decision-making or metacognitive processes (Boldt and Yeung, 2015; Herrmann et al., 2004). Consequently, the modulation of this component was also investigated during the MPG.

5.3.5 Sampled population

Participants were recruited from October to December 2021 within a student population from Nottingham Trent University (NTU) and completed empathy questionnaires before coming to the laboratory to complete the AIT and MPG tasks. Participants were pre-screened for handedness using the revised version of the Edinburgh Handedness Inventory Short Form (Veale, 2014) and for neuropsychological diagnosis (i.e. diagnosis of neurological or psychiatric conditions), considering their impact on EEG signals (Slezicki et al., 2009; Zapała et al., 2021).

Based on the pre-existing literature, a sensitivity power analysis suggested a sample size of 193 participants for detecting the small effect size of $r = .20$ reported on the association between empathy and automatic imitation (Cracco et al., 2018). However, none of the previous studies reached this sample size, except Butler et al. (2015) with $N = 230$, while most reported a sample size ranging around $N = 25$. Regarding the MPG tasks, the current literature is scarce considering its novelty with reported sample size ranging from $N = 34$ to 48 (Dyson et al., 2020; Forgeot d'Arc et al., 2020). Consequently, a minimal sample size of 30 participants was initially targeted, allowing the detection of a medium effect size of .5, with an $\alpha = .05$ and power of the test $(1 - \beta)$ = 0.8. However, considering the risk of data loss due to artefacts, the data collection was carried out beyond this initial threshold. The procedure received a positive opinion from the NTU Schools of Business, Law and Social Sciences ethics committee (n°2021/174)[11].

[11] In addition to the AIT and MPG task, participants completed the HeartBeatCounting Task (Schandry, 1981), a measure of interoception not reported in the present manuscript.

CHAPTER 6

EXPERIMENT III - AIT and EEG

"Let there be spaces in your togetherness, and let the winds of the heavens dance between you"

- Kahlil Gibran

Although theoretical accounts of Interpersonal Motor Coordination (IMC) and empathy suggest shared neurocognitive mechanisms, empirical evidence remains scarce.

Theoretical accounts of IMC and empathy stress common reliance on shared neurocognitive mechanisms (Shamay-Tsoory, 2011; Shamay-Tsoory et al., 2019). Of particular interest is the action observation/execution matching system, which relies on the Mirror Neuron System (MNS) and is suggested as a core component of empathy and imitation (Decety and Meltzoff, 2011; Gallese et al., 1996; Preston and De Waal, 2002). Yet, this sole mechanism is insufficient in accounting for the full spectrum of IMC and empathy (see **Chapter 1** for a detailed overview).

The results presented in **Chapter 3** replicated associations between the ability to predict others' mental state (i.e., cognitive empathy) and goal-oriented motor coordination (Koehne et al., 2016b; Novembre et al., 2019). Additionally, self-reported spontaneous tendencies for synchrony (i.e., kinesthetic empathy) were associated with reduced goal-oriented motor coordination, delineating an important discrepancy between self-reports and effective behavioural coordination. Consequently, these findings required further investigations to clarify whether these patterns can be reproduced in spontaneous motor entrainment behavioural assessments.

The present chapter reports an in-laboratory data collection investigating this research question with self-reports of empathy and behavioural assessment of spontaneous imitation, combined with electroencephalography (EEG) recordings, exploring the role of spatiotemporal matching and conflict monitoring processes.

6.1 Summary of the theoretical and empirical gap

Synchrony and imitation are considered to fall into the overarching umbrella term of IMC, yet these concepts nurtured different streams of research. On the one hand, synchrony can be elicited through rhythmic activities such as music, dance, or turn-taking in conversations, leading to planned or spontaneous temporal alignment (Demos et al., 2012; Hale et al., 2020; Tarr et al., 2015). On the other hand, imitation is often observed as spontaneous or goal-oriented tendencies for reproducing gestures or facial expressions that are spatially or anatomically congruent (Heyes, 2011; Platek et al., 2003). Their respective or overlapping associations with empathy remain unclear. Theoretical accounts of IMC and empathy postulate their reliance on action/perception matching (i.e., the MNS), suggesting a shared neurocognitive mechanism for empathy and imitation (Decety and Meltzoff, 2011; Gallese et al., 1996; Preston and De Waal, 2002; Prinz, 1990). Yet, empirical evidence remains scarce.

Chapter 3 replicated previous findings reporting an association between cognitive empathy and behavioural synchrony (Koehne et al., 2016b; Novembre et al., 2019). These results were in line with recent models of IMC and empathy suggesting a complex interplay of several neurocognitive mechanisms, composed of (i) mirroring (i.e., the MNS), (ii) self-other distinction (i.e., conflict monitoring processes) and (iii) self-regulation processes (Decety and Jackson, 2006; Levy and Bader, 2020; Shamay-Tsoory, 2011; Shamay-Tsoory et al., 2019). However, it remains to be clarified if imitation relies on similar mechanisms as synchrony or should be considered a distinctive component of IMC and empathy.

The present study investigates this research question using the Automatic Imitation Task (AIT) developed by Brass et al. (2001) discussed in **Chapter 5, section 5.1.1**, alongside psychometric assessments of affective, cognitive, somatic, and kinesthetic empathy questionnaires discussed in **Chapter 2, section 2.2.3**. Behavioural automatic imitation indices were extracted to investigate the moderating role of the AIT cues and their interactions with empathy facets. The role of temporal sequences was considered by computing the contiguity of participants' responses and AIT trials. EEG recordings were performed to investigate the association between behavioural and neural patterns and their association with empathy traits. The EEG frequencies associated with the MNS activation and attentional processes (i.e., alpha/mu and beta bands) and the event-related-potential (ERP) associated with conflict monitoring processes (i.e., the N2 and P3 components) were extracted (Hobson and Bishop, 2016; Rauchbauer et al., 2021).

6.1.1 Imitation and synchrony, distinct or overlapping concepts?

In **Chapter 1**, the concept of IMC was introduced, delineating synchrony from imitation, where the former is associated with coordination in time while the latter is associated with coordination of shape (Bernieri and Rosenthal, 1991). According to this segmentation, imitation is a distinct concept from synchrony. However, synchrony and imitation have nurtured different streams of research, and the taxonomy of IMC has not reached a consensus yet in the scientific communities, resulting in the proliferation of IMC measurements.

In **Chapter 2**, methods and indices associated with synchrony were reviewed. Synchrony can be measured during rhythmic activities such as finger-tapping tasks, walking, singing, talking, or playing musical instruments (Demos et al., 2012; Cheng et al., 2017; Hale et al., 2020; Heggli et al., 2021). Additionally, synchrony can be induced through goal-oriented task activity or spontaneously as an emergent phenomenon (Athreya et al., 2014; Varlet et al., 2011). Finally, several synchrony indices co-exist in the literature, such as cross-correlations, relative phase or coherence based on time series or extracted frequencies. These measures rely on the methods used for motion tracking and are task-dependent, making comparing results across studies challenging. As suggested by Delaherche et al. (2012) and Schoenherr et al. (2019), these synchrony indices are not converging, suggesting multiple components of synchrony.

In **Chapter 5**, methods and indices associated with imitation were reviewed. Imitation can be measured by counting imitative gestures and tendencies for facial mimicry through video recordings or by measuring muscle activity through electromyogram recordings (Blair, 2005; Platek et al., 2003). Alternatively, imitation can be investigated by measuring stimulus-response compatibility effects such as interference or facilitation when presenting congruent or incongruent movements (Brass et al., 2001; Heyes, 2011). Finally, imitation can be studied as a form of vicarious learning, that is, through the repetitive exposure of observing others executing movement or as a spontaneous phenomenon (Heyes et al., 2005). Consequently, several measures labelled as imitation are used in the literature, and it is challenging to understand if they are overlapping or distinct constructs.

Whilst the thesis has already revealed distinctive associations between self-reports of spontaneous tendencies for synchrony and goal-oriented behavioural synchrony (see **Chapter 3**), how these measurements of synchrony map with imitation and their distinctive relationship with empathy facets remain unclear and need to be disentangled.

6.1.2 Imitation and empathy, shared or distinct mechanisms?

In **Chapter 1**, the possible overlap between IMC and empathy was introduced. Whilst theoretical models suggest an overlap between neurocognitive mechanisms underlying IMC and empathy, empirical evidence remains scarce. This gap between theories and experimental evidence suggests that the proliferation of indexes and conceptualisations of IMC and empathy challenges establishing a comprehensive and unified theoretical framework.

On the one hand, theories of imitation and empathy suggest their reliance on the action/perception matching system associated with the MNS (Gallese et al., 1996; Preston and De Waal, 2002; Prinz, 1990). However, other neural networks are also involved in monitoring self and other representations associated with IMC and empathy, such as the default mode and the salience networks, including the right temporoparietal junction (rTPJ), involved in self-other overlap/distinction and the anterior cingulate cortex (ACC), involved in conflict monitoring (Decety and Jackson, 2006; Shamay-Tsoory et al., 2019). Consequently, neuroimaging studies suggest an overlap between neurocognitive mechanisms involved in IMC and empathy.

In contrast, **Chapter 5** summarised studies investigating behavioural imitation and provided a more nuanced account. Whilst several studies reported an association between behavioural or facial mimicry with cognitive and affective empathy (Chartrand and Bargh, 1999; Sonnby-Borgström et al., 2003), the meta-analysis conducted by Cracco et al. (2018) concluded on a weak or null association between empathy and imitation measured using the AIT. In parallel, another stream of research scrutinized the role of self-other overlap/distinction in imitation, suggesting a potential "aberrant control" in autism and psychopathy. Whilst tendencies for hyper-imitation were initially reported in autism, suggesting a potential failure of self-other distinction (Spengler et al., 2010), these findings were not replicated, and recent studies suggest more generalised difficulties in visuo-motor integration or circumscribed attention (Gordon et al., 2020a; Gowen et al., 2008). In contrast, studies reported an initial tendency for hypo-imitation in narcissism (Obhi et al., 2014). However, this effect might be restricted to individuals displaying tendencies for egocentric perspective-taking (Bukowski and Samson, 2021). Finally, a recent study from Galang and Obhi (2023) failed to observe an association between empathy, vicarious pain and increased automatic imitation, casting doubt on the "aberrant control" hypothesis and the role of self-other overlap/distinction mechanisms. Altogether, these findings highlight the current gap between neuroimaging and behavioural studies of imitation, stressing the need to clarify their associations.

6.1.3 Goal and hypotheses

To summarise, the association between imitation and empathy appears spurious, although theoretical models of empathy suggest a strong association between the two concepts. On the one hand, the multiple definitions and measurements associated with imitation and empathy could explain these mixed findings, widening the gap between potential overlapping motor components of empathy, such as kinesthetic/motor empathy and synchrony. On the other hand, neuroimaging studies supporting a link between imitation and empathy have seldom accounted for the role of self-other distinction/overlap (i.e., conflict monitoring) in automatic imitation and their influence on imitation tendencies. Consequently, the association between imitation and empathy remains unclear, and the role of conflict monitoring needs to be considered and clarified.

An in-laboratory data collection was conducted using the AIT combined with EEG recordings to address this research question, providing temporal resolution of brain activity. Additionally, participants completed affective, cognitive, somatic, and kinesthetic empathy questionnaires presented in **Chapter 2**. Behavioural patterns associated with indices of automatic imitation were computed (i.e., reaction times and scores). The role of temporal sequences of the AIT task was investigated by computing sequences of the participants' responses and AIT cues. Finally, EEG recordings were pre-processed for extracting the alpha/mu and beta frequency band associated with mirroring and attentional processes and the ERPs associated with conflict monitoring such as the N2 and P3 components measured in the centroparietal electrodes and contrasted between AIT cues and temporal sequences (Hobson and Bishop, 2016; Rauchbauer et al., 2021).

Based on theoretical models of empathy, a first hypothesis postulated a positive association of automatic imitation with affective and motor-related facets of empathy, linked with greater tendencies for self-other overlap (Decety and Jackson, 2006; Spengler et al., 2010). A second hypothesis postulated an association of the magnitude of alpha/mu and beta bands by AIT cues. Specifically, a decrease in the magnitude of the alpha/mu and beta bands was expected for congruent cues (Davis et al., 2012; Dumas et al., 2014a; Khanna and Carmena, 2017; Perry et al., 2010). A third hypothesis predicted an association between the amplitude of the ERP components N2 and P3, associated with task-monitoring processes, by the AIT cues. In particular, higher amplitudes of these ERP components were expected for incongruent cues (Rauchbauer et al., 2021). Finally, exploratory analyses investigated the role of temporal sequences, their association with empathy, and their modulations of behavioural and EEG markers.

6.2 Methods

6.2.1 Participants

A total of 46 participants were recruited from a population of students at NTU. Participants were excluded for missing data (N = 3), scores of Edinburgh Handedness Index below the cut-off ($< 10, N = 5$), and neuropsychological diagnosis ($N = 4$), resulting in a remaining sample of 34 participants (12 men, 20 women and 2 non-binary, mean age = 21.35, SD = 3.31, range 18 to 32 years). Additionally, 4 participants were excluded for missing EEG recordings ($N = 2$) and excessive artefacts ($N = 2$), and a reduced sample of 30 participants (11 men, 18 women and 1 non-binary, mean age = 21.43, SD = 3.44, range 18 to 32 years) was included in the EEG analyses.

6.2.2 Empathy questionnaires

Considering the lack of reliability of QCAE subscales reported in **Chapter 3**, participants also completed the Index of Interpersonal Reactivity (IRI) developed by Davis (1980), constituted of 28 items divided into two cognitive subscales: (i) *Perspective Taking* and (ii) *Fantasy* ; and two affective subscales: (i) *Empathic Concern* and (ii) *Personal Distress*. Participants also completed the somatic subscale of the Cognitive, Affective and Somatic Empathy Scale (CASES) from Raine and Chen (2018) and the Kinesthetic Empathy Scale (KinEmp) developed by Koehne et al. (2016b)[1]. Items were scored on a 4-point Likert scale, and scores were calculated by summing the items (see **Chapter 2**, **section 2.2.3** for further details on their psychometrics properties).

6.2.3 Automatic Imitation Task

The Automatic Imitation Task (AIT) was adapted from Brass et al. (2001) and implemented in PsychoPy (Peirce et al., 2019). Participants were instructed to respond as quickly as possible to pictures by pressing the left arrow of the keyboard with their index finger for red pictures and the right arrow with their middle finger for blue pictures. A fixation cross followed by a baseline picture showing a hand in a neutral position was presented for a fixed duration of 700 ms. Using a within-subject design, the imitation cue was presented either as (i) neutral (i.e., coloured red or blue pictures), (ii) congruent (i.e., index pressing the left arrow for red) or (iii) incongruent (i.e., index pressing the left arrow for blue). Pictures ($N = 180$) were randomly presented (60 per condition) with 2 self-paced pauses after 60 trials, resulting in 3 experimental blocs - see **Figure 6.1** for a representation of experimental blocs.

[1]Participants also completed the Short Dark Triad (Jones and Paulhus, 2014) and the Multidimensional Assessment of Interoceptive Awareness (Mehling et al., 2012) questionnaires, but these measures are not included in the present manuscript.

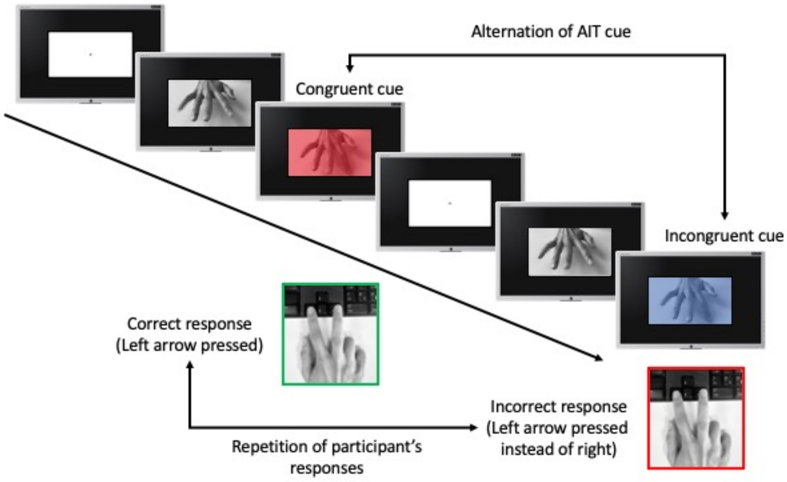

Fig. 6.1 Graphical representation of the adapted Automatic Imitation Task

6.2.4 Electroencephalography recordings

The EEG recordings were performed using a BioSemi Active2 EEG system composed of 64 active electrodes positioned according to the International 10–20 system (see previous Chapter for a graphical representation). An additional external channel recorded participants' cardiac activity[2]. Data acquisition was performed using a DC amplifier at a nominal sampling rate of 2048 Hz, and the electrodes' impedance was maintained below 10 μV.

6.2.5 Procedure

Participants were recruited from a student population through the SONA platform and invited to the laboratory. Participants completed a Qualtrics survey recording their informed consent, unique participant code, demographics (i.e., age, gender), pre-screening information (i.e., handedness, neuropsychiatric diagnosis), followed by the empathy questionnaires (IRI, QCAE, KinEmp, CASES) and the additional scales (MAIA and SD3, see previous footnote). While participants completed the Qualtrics survey, the EEG cap was set up and checked before starting the experiment. Then, participants were instructed to complete the HeartBeat Counting Task developed by Schandry (1981), not included in the present manuscript, followed by the AIT and by the Matching Pennies Game (MPG) tasks (see **Chapter 7**). Each task started with a practice session to ensure participants understood the instructions. After the practice trial, participants were left alone in the room to complete the experiment. The procedure took 45 to 75 minutes, depending on the setup of the EEG.

[2]Two linked-mastoid were initially suggested as referencing methods but unused in favour of the offline algebraic method REST (see section 5.3.2

6.2.6 EEG pre-processing

EEG recordings were pre-processed using the MNE Python toolbox (Gramfort et al., 2014) and the PyPREP Python package (Appelhoff et al., 2022). The EEG signal was downsampled to 512 Hz before applying a 40Hz low-pass and a 1-Hz high-pass Finite Impulse Response filter for removing high-frequency artefacts and slow drifts (Winkler et al., 2015). Bad channels were detected through visual inspection and PREP pipeline methods (i.e., high-frequency, NaN, z-score, drop-out) before being interpolated by spherical spline interpolation (Bigdely-Shamlo et al., 2015; Perrin et al., 1989). The Reference Electrode Standardisation Technique (REST) method was applied for re-referencing electrodes before computing the Independent Component Analysis (ICA) for removing ocular artefacts - see **Chapter 5** and Zhai and Yao (2004). EEG recordings were sliced in windowed epochs before (-500 ms) and after (1500 ms) AIT cues onset. Epochs were visually inspected and rejected using a maximum peak-to-peak signal amplitude (i.e., the absolute difference between the lowest and highest signal value).

For frequency analyses, a set of central electrodes was selected (i.e., C3, C1, Cz, C2, C4) based on previous studies (Dumas et al., 2014b; Hobson and Bishop, 2016). The alpha/mu and beta frequency bands (8–30 Hz) were extracted using Welch's method (Welch, 1967) before averaging by AIT conditions and temporal sequences. For ERP analyses, a set of midline electrodes were selected (i.e., Fz, FCz, Cz, CPz, Pz) and the signal was averaged for AIT conditions and temporal sequences. Mean amplitudes were extracted from averaged epochs using time windows ranging from 0 to 250, 250 to 500 and 500 to 750 ms after the AIT cue's onset. These parameters were chosen based on previous studies (Lenzoni et al., 2022; Yeung et al., 2004).

6.2.7 Data analyses

Data analyses were performed with R Studio (RStudio Team, 2020). Manipulation checks controlled the psychometric properties of the empathy subscales using Cronbach's alpha. Spearman's correlations computed their association with AIT indices (i.e., reaction times and scores) averaged per AIT conditions (i.e., congruent, incongruent, neutral) and temporal sequences of participants' response and AIT cues (i.e., repetition, alternance). Mixed models were performed with AIT indices and EEG markers (i.e., power spectral density of alpha/mu and beta frequency bands and ERP mean amplitudes) as outcome variables and with AIT conditions and temporal sequences constituted the fixed predictors. Participants were added as random effects. Empathy subscales were added as fixed predictors, testing their possible interaction with AIT conditions and temporal sequences. Holm Bonferroni corrections were applied for multiple comparisons.

6.3 Results

6.3.1 Zero-order correlations

Consistencies of the scales and subscales were all above .60, apart from the QCAE subscales *Peripheral Responsivity* (.53) and *Proximal Responsivity* (.58), and KinEmp (.59). Therefore, only the IRI subscales were considered for the subsequent analyses. The IRI subscale *Empathic Concern* was positively associated with *Perspective Taking*, *Personal Distress* and somatic empathy (CASES). However, only the association with *Personal Distress* remains significant after corrections for multiple comparisons. In addition, KinEmp displayed a positive association with IRI *Fantasy* but this association did not hold significance after corrections. Finally, there was a negative association between somatic empathy (CASES) and accuracy scores ($p = .001$) but this correlation did not hold significance after corrections. A similar trend was observed for KinEmp with speed - for descriptive statistics and correlations, see **Table 6.1**.

	Mean	PT	FS	EC	PD	CASES	KinEmp
Perspective Taking	25.32 ± 5.20	-	-.08	.43	-.03	.07	.07
Fantasy	25.38 ± 5.08	-	-	.23	.17	.24	.39
Empathic Concern	26.97 ± 4.96	-	-	-	.46*	.38	.26
Personal Distress	19.21 ± 5.06	-	-	-	-	.19	.17
Somatic (CASES)	32.62 ± 4.98	-	-	-	-	-	.28
Kinesthetic (KinEmp)	24.44 ± 3.56	-	-	-	-	-	-
Speed	444.10 ± 9.69	.01	-.19	-.09	0.10	-0.07	-.32
Accuracy	94.90 ± 3.45	.04	.14	-.05	-.05	-.44	-.20

Table 6.1 Descriptive statistics and correlations between empathy and AIT indices

Adjusted p-values are reported with $*p < .05$, $**p < .01$, $***p < .001$

6.3.2 AIT indices

There were no significant differences across experimental conditions for reaction times ($F(2,66) = 0.977, p = .382$) but for accuracy ($F(2,66) = 5.606, p = .006$). Post-hoc comparisons revealed that this effect was driven by a significant difference between congruent and incongruent conditions (i.e., congruency effect, $beta = 2.11, t = 2.87, p = .007$) and this difference remains significant after corrections ($p = .037$). There was also a significant difference between congruent and neutral conditions ($beta = -1.86, t = -3.26, p = .003$). However, this difference didn't hold after correction ($p = .094$) - for descriptive statistics, see **Table 6.2** and for graphical representation, see **Figure 6.2**, with bold lines represent the median; upper and lower bound of the boxes the 1st and 3rd quartiles.

	Speed *Reaction-time in milliseconds*	Accuracy *Percentage of correct responses*
Neutral	441.66 ± 76.24	95.44 ± 4.31
Congruent	448.71 ± 78.42	93.58 ± 4.72
Incongruent	441.92 ± 74.42	95.69 ± 3.31

Table 6.2 Descriptive statistics for speed and accuracy for AIT cues

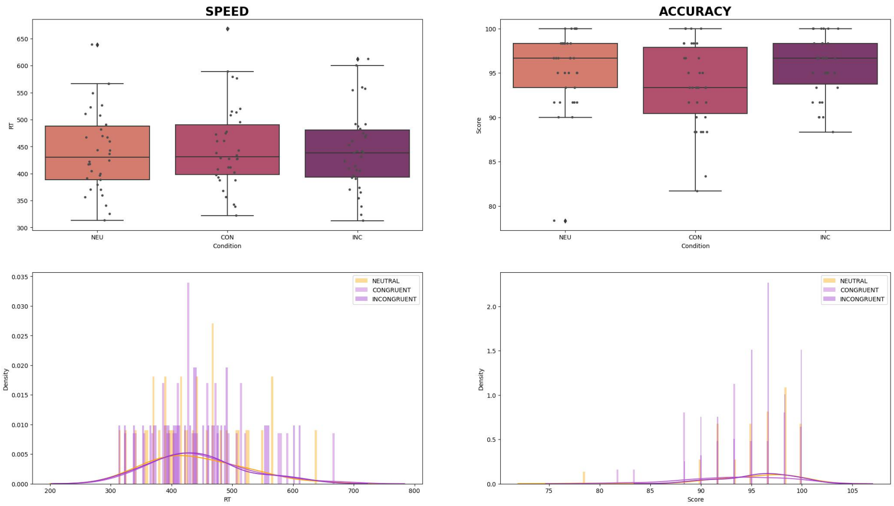

Fig. 6.2 Graphical representation of speed (reaction time) and accuracy (correct responses) for AIT cues (neutral, congruent, incongruent)

The repetition of participants' responses and AIT cues modulated reaction times. Participants' reaction times increased when similar motor responses (e.g., pressing the left arrow) were repeated ($beta = 24.36, t = 3.86, p < .001$). In contrast, participants' reaction times decreased when similar AIT cues were repeated ($beta = -14.03, t = -2.67, p = .012$). However, these differences did not reach the significance threshold after corrections ($p = .20$ and $p = .43$). Whilst the repetition of participants' responses was not associated with accuracy ($beta = 0.18, t = 0.23, p = .819$), the accuracy increased for repeated AIT cues ($beta = 1.58, t = 3.12, p = .004$), but this difference did not reach the significant threshold after corrections ($p = .082$) - for descriptive statistics, see **Table 6.3** and for graphical representation, see **Figure 6.3** with bold lines represent the median; upper and lower bound of the boxes the 1st and 3rd quartiles.

	Speed *Reaction-time in milliseconds*	Accuracy *Percentage of correct responses*
Participant - Repetition	458.59 ± 82.29	95.02 ± 2.97
Participant - Alternation	434.22 ± 71.15	94.86 ± 4.56
AIT cues - Repetition	433.42 ± 71.35	96.13 ± 3.71
AIT cues - Alternation	447.45 ± 75.85	94.55 ± 3.67

Table 6.3 Descriptive statistics for speed and accuracy across AIT cues

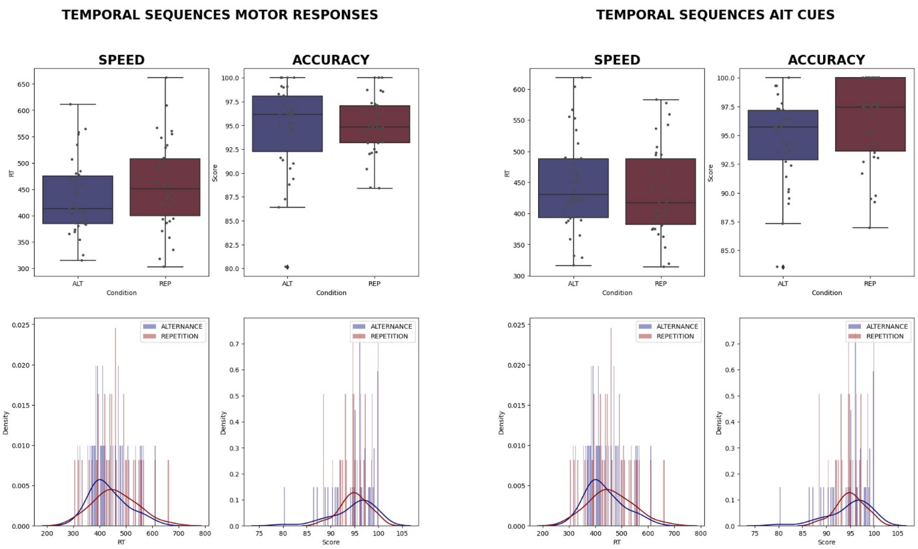

Fig. 6.3 Graphical representation of speed and accuracy for temporal sequences (alternation versus repetition) of motor responses (left) and AIT cues (right)

6.3.3 EEG analyses

There was no modulation of alpha/mu and beta bands for AIT conditions, alternation/repetition of participant's responses and AIT cues (all $ps > .050$). The N2 and P3a amplitudes were not modulated by the AIT cues (all $ps > .050$). In contrast, the Fz, FCz, Cz and CPz electrodes displayed lower amplitude for the P3b for neutral cues ($beta = -0.87, t = -5.26$, $beta = -0.81, t = -4.26$, $beta = -0.70, t = -4.66$ and $beta = -0.40, t = -3.26$, all $ps < .010$) while CPz and Pz electrodes displayed lower amplitude for the incongruent cues ($beta = -0.36, t = -2.97$ and $beta = -0.42, t = -2.73$, both $p < .010$). However, these differences did not reach the significance threshold after corrections (all $ps > .050$) - see **Figure 6.4** for graphical representation.

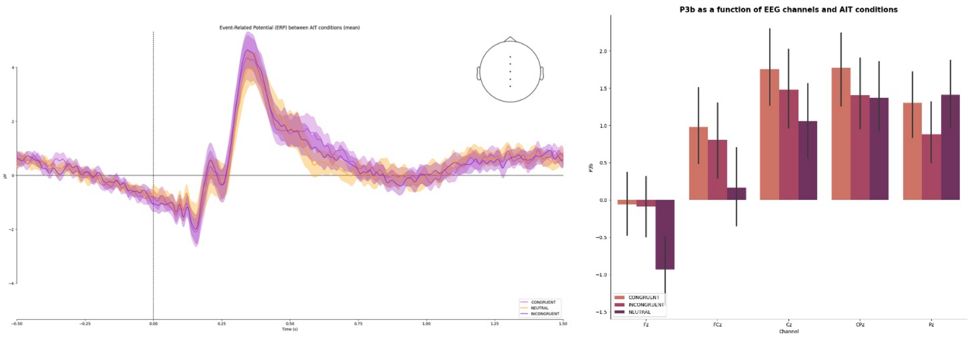

Fig. 6.4 Graphical plots of the evoked responses for the AIT conditions with grand average ($N = 30$) for midline electrodes (left) and barplot for P3b component (right)

The alternation/repetition of participants' responses influenced the P3a amplitude for frontal and parietal electrodes. Whilst the responses' repetition increased the amplitude of frontal electrodes Fz and FCz ($beta = 0.55, t = 3.77$, $p = .001$ and $beta = 0.46, t = 3.11$, $p = .004$), the amplitude decreased for the parietal electrode Pz ($beta = -0.31, t = -2.46, p = .020$) - see **Figure 6.5** for graphical representations.

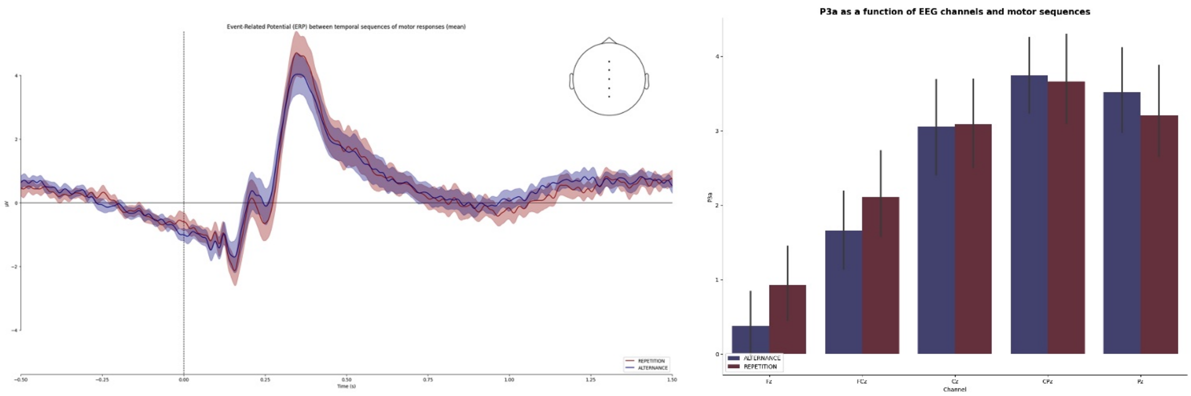

Fig. 6.5 Graphical plots of the evoked responses for temporal sequences of motor responses with grand average ($N = 30$) for midline electrodes (left) and barplot for P3a component (right)

In contrast, the alternation/repetition of AIT cues influenced the P3a and P3b. The amplitude of P3a of frontal and central electrodes was lower for the repetition of AIT cues at the Fz, FCz and CPz locations ($beta = -0.39, t = -2.16$, $beta = -0.47, t = -2.48$ and $beta = -0.40, t = -2.14$, all $p < .050$). The same pattern was observed for P3b at the central and parietal electrodes FCz, CPz and Pz ($beta = -0.32, t = -2.70$, $beta = -0.44, t = -4.07$ and $beta = -0.36, t = -2.81$, all $p < .050$). However, these differences did not reach the significant threshold after correction (all $ps > .050$) - see **Figure 6.6** for graphical representations.

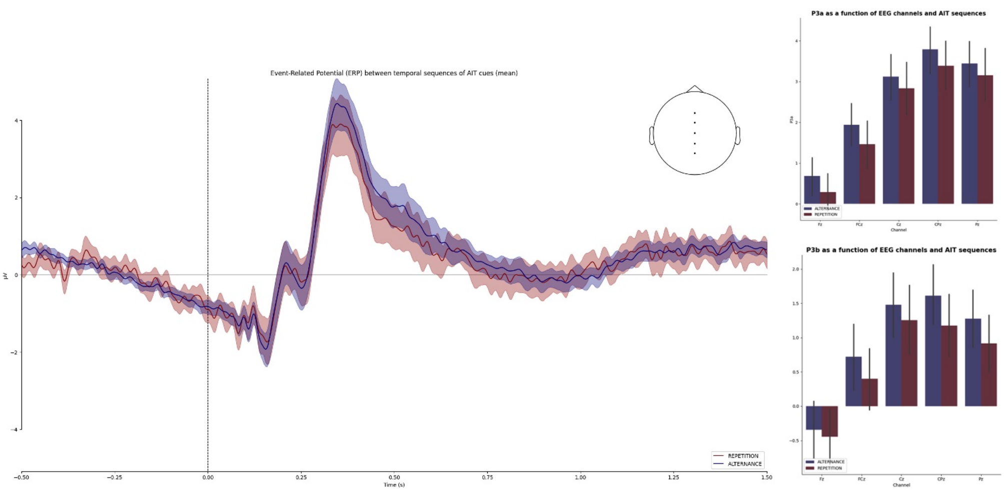

Fig. 6.6 Graphical plots of the evoked responses for temporal sequences of AIT cues with grand average ($N = 30$) for midline electrodes (left) and barplot for P3a (top right) and P3b component (bottom right)

6.3.4 Interaction with empathy scores

There was no significant association nor interaction of AIT cues with empathy scores for reaction times (all $ps > .050$) but for accuracy scores.

The IRI subscale *Perspective Taking* displayed an interaction with AIT conditions when comparing congruent and neutral cues ($beta = 0.23, t = 2.17, p = .037$). This subscale also displayed an interaction with the repetition of AIT cues for reaction times ($beta = -2.39, t = -2.51, p = .017$). In contrast, the IRI subscale *Personal Distress* displayed an interaction with the repetition of participants' responses on reaction times ($beta = -2.65, t = -2.22, p = .034$); however, these associations did not hold after corrections for multiple comparisons. For graphical representations, see **Figure 6.7** with solid lines representing regression lines and transparent grey areas representing 95% confidence interval.

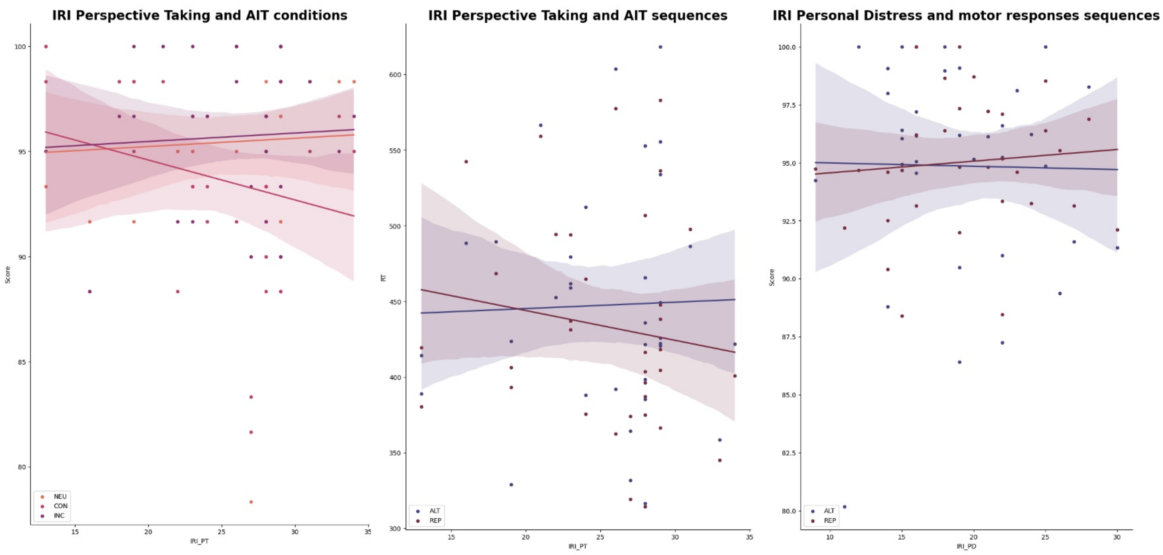

Fig. 6.7 Graphical representation of the interactions of IRI *Perspective Taking* with AIT cues (left), AIT sequences (middle) and IRI *Personal Distress* with participants' responses sequences

Empathy scores were not associated with a modulation of the EEG frequency bands alpha and beta (all $ps > .050$) but with ERP.

The CASES displayed an interaction with the neutral cues for the N2 component ($beta = -0.06, t = -3.00, p = .003$). This interaction was driven by frontal electrode Fz and remains significant after corrections ($p = .040$). - see **Figure 6.8** for graphical representations, with solid lines representing regression lines and transparent grey areas representing 95% confidence interval.

The IRI *Fantasy* showed a similar interaction with the neutral cues for the N2 component, driven by the CPz electrode ($beta = -0.07, t = -2.33, p = .023$). This subscale displayed also an interaction with the neutral cues for the P3b component driven by the Pz electrode ($beta = 0.06, t = 2.08, p = .042$). However, these associations did not hold after corrections for multiple comparisons.

The IRI *Personal Distress* displayed an interaction with temporal sequences of AIT cues for P3a and P3b ($beta = -0.11, t = -3.40$, $p = .002$ and $beta = -0.05, t = -2.31, p = .028$). These interactions were driven by the frontocentral electrode FCz and remain significant after corrections only for P3a ($p = .010$). Similar interactions were observed for IRI *Empathic Concern* with AIT temporal sequences for P3a at FCz ($beta = -0.10, t = -2.61, p = .014$) but did not hold significance after corrections for multiple comparisons.

Finally, the KinEmp displayed an interaction with temporal sequences of AIT cues for P3a and P3b ($beta = -0.11, t = -2.21, p = .036$ and $beta = -0.08, t = -2.76, p = .010$). These interactions were driven by the frontal electrode Fz and remained significant after corrections only for P3b ($p = .041$) - for graphical representations, see **Figure 6.8**, with solid lines representing regression lines and transparent grey areas representing 95% confidence interval.

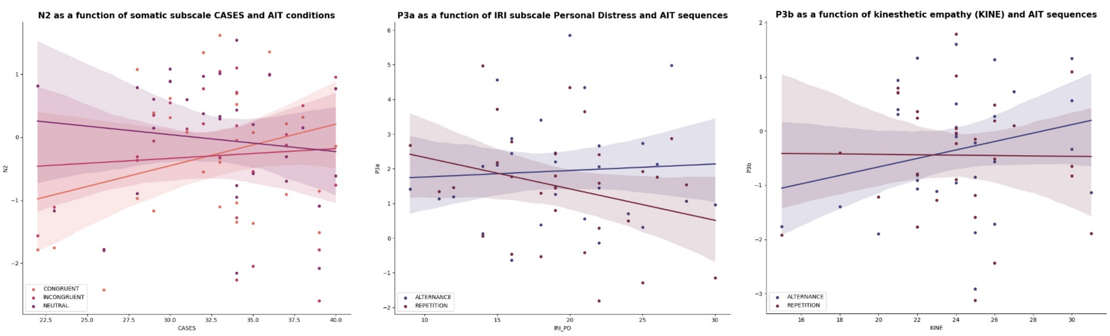

Fig. 6.8 Graphical plots of ERP mean amplitudes of N2 and CASES (left), P3a and IRI *Personal Distress* (middle), and P3b and KinEmp (right)

6.4 Discussion

The present study investigated the association between automatic imitation and empathy by combining the AIT paradigm with EEG recordings and by considering the temporal sequences of participants' responses and AIT cues. Overall, results from this study provide new insights into the relationship between imitation and empathy by revealing an association between self-report and behavioural measures of motor empathy and by considering the role of rhythm and its association with empathy facets.

6.4.1 Motor components of empathy

In line with the first hypothesis postulating an association between imitation and affective and motor empathy, an association was observed between accuracy and somatic empathy (CASES) and a similar trend was observed for kinesthetic empathy (KinEmp) and reaction times. Although these associations did not reach and did not hold significance after corrections, these results suggest specific associations between automatic imitation and motor-related empathy facets. Despite a positive but non-significant association between the somatic subscale of CASES and affective-related subscales from the IRI (i.e., *Empathic Concern* and *Personal Distress*), the motor-related empathy subscales were the only facets negatively associated with AIT accuracy and reaction times.

Conceptualised as a self-report measure of a motor-related component of empathy, the somatic empathy subscale from the CASES questionnaire was developed by Raine and Chen (2018) based on the definition of motor empathy provided by Blair (2005), encompassing emotional contagion and mimicry. Echoing results from **Chapter 3**, this finding suggests that motor-related components of empathy must be distinguished from affective empathy, stressing the need to consider empathy subscales separately and their respective contribution to the empathy "constellations" (Davis, 1980). Importantly, this study replicated results from **Chapter 3**, showing a lack of internal consistency of the QCAE affective subscale *Peripheral Responsivity* and the KinEmp, calling for a careful investigation of their psychometric properties.

The negative association between CASES and accuracy was not moderated by the congruence or incongruence of AIT cues, suggesting possible global motor impairments or attention deficits. This finding aligns with the negative association observed between KinEmp and behavioural synchronisation in **Chapter 3**. Importantly, the KinEmp was also negatively associated with reaction times in this study but did not reach the significance threshold. Similarly to the notion of interoception (Garfinkel et al., 2015), these results call for exploring the discrepancy between self-reports of motor empathy and effective motor behaviours, paving the way for new insights into empathy deficits (Cassidy et al., 2016; Hur et al., 2014).

6.4.2 Imitation or spatial compatibility?

Although non-significant for reaction times, the adapted version of the AIT conditions implemented in this study modulated the accuracy of participants' responses. Notably, the effect of the AIT cues was reversed with a congruency effect for incongruent instead of congruent cues. This pattern highlights the role of spatial compatibility (i.e., movements that are spatially congruent but not anatomically congruent), already identified in reducing the impact of anatomical compatibility on automatic imitation (Cracco et al., 2018). Interestingly, the IRI subscale *Perspective Taking*, associated with tendencies to adopt others' viewpoints, displayed an interference effect for congruent cues, though this association did not hold after correction. Nevertheless, this association stresses the intertwining between capacities for perspective-taking and anatomical compatibility and highlights the possible conflation between spatial and anatomical congruence due to the symmetrical nature of human anatomy and questions the phenomenon measured by the AIT task (Ramsey, 2018). The present findings suggest a possible role of inter-individual differences in empathy in modulating the influence of spatial and anatomical AIT cues that future investigations must take into account.

6.4.3 Temporal sequences

The exploratory analyses conducted on the temporal sequences revealed that the repetition of participants' responses decreased task performances (i.e., slower responses). In contrast, their alternation improved task performances (i.e., faster responses). Although these associations do not reach the significance threshold after corrections, they are in line with Kirby (1976), suggesting that repetition is associated with greater cognitive costs for longer inter-trial intervals (> 500 ms), leading to lower performances. This pattern was reversed for the AIT cues (i.e., repetition increased and alteration decreased task performances). This result echoes previous findings from synchrony, showing that repetition (i.e., lack of new information) increases processing fluency due to reduced uncertainty (Hove and Risen, 2009). Importantly, processing fluency is a subjective experience of ease associated with cognitive operations, resulting from the interaction between individual cognitive abilities and environmental uncertainty that has already been explored in aesthetic experiences (McGlone and Tofighbakhsh, 2000; Nunes et al., 2015; Oppenheimer, 2008; Reber et al., 2004). These findings suggested an interaction between participants' and task rhythms and complementary analyses showed antagonist dynamics between their temporal sequences - see **Appendix H**. Altogether these results highlight a potential association between empathy and rhythmic processing that echoes the initial overlap of empathy with aesthetic experiences.

Although exploratory, the present study showed that empathy scores modulate the influence of temporal sequences on participants' responses. On the one hand, participants scoring higher on the IRI subscale *Perspective Taking* displayed quicker responses when AIT cues were repeated. On the other hand, participants scoring higher on the IRI subscale *Personal Distress*, associated with the tendency to experience anxiety and discomfort in interpersonal settings, displayed similar behavioural performances when similar or different responses were executed. These patterns suggest that the repetition of AIT cues was associated with processing fluency, especially for those building expectations about patterns in random series (Ayton and Fischer, 2004). In contrast, participants who tend to display an attentional bias toward their own emotional state and body awareness were more influenced by the temporal sequences of their movements. Whilst these analyses were exploratory and did not reach the significance threshold after corrections, they suggest that the temporal sequences associated with motor responses could provide interesting insights into rhythm processing. Therefore, following the suggestions made by Annand et al. (2021), taking into account temporal sequences offers a novel approach for analysing experimental tasks involving the repetitive execution of motor responses, widely employed in experimental psychology.

6.4.4 EEG components of AIT and empathy

EEG analyses were consistent with patterns observed in behavioural data analyses.

Whilst the AIT conditions did not modulate the alpha/mu and beta bands, ruling out the second hypothesis, there were significant differences in the P3b component. Neutral cues were associated with lower amplitude for the P3b than incongruent cues. Although this association did not reach significance after correction, this finding is partially consistent with behavioural patterns. While neutral cues did not provide additional information, incongruent cues provided additional information, increasing the P3b amplitude, suggesting an increase of the cognitive load (Volpe et al., 2007). Importantly, this pattern differs from behavioural results, revealing the possible conflation of spatial and anatomical congruence of the AIT cues. Previous studies have already stressed the role of self-other distinction in imitation (Bukowski and Samson, 2021) and its association with the right temporoparietal junction (rTPJ), a brain area that has been previously linked to P3b modulation (Polich, 2007; Verleger et al., 1994). Consequently, future studies need to investigate the role of perspective-taking in automatic imitation and its association with P3b modulation and the rTPJ activation using source reconstruction methods such as LORETA (Pascual-Marqui et al., 1994).

The exploratory analyses revealed the influence of the temporal sequences on the P3 component. Whilst the amplitude of P3b increased with repetition of participants' responses, the reversed pattern was observed for AIT cues. This pattern aligns with Annand et al. (2021) and Kirby (1976) stressing the role of temporal sequences in motor responses. Importantly, whilst Annand et al. (2021) postulated an association with HKB predictions, Kirby (1976) stressed the role of participants' expectations for randomness. Although the current study does not allow to tease apart these two hypotheses and the lack of statistical significance after corrections suggests possible lack of statistical power, the present findings echo pre-existing studies associating the P3 component with expectancy violation. The P3 component is indeed an ERP component usually observed during the oddball paradigm, an experimental task measuring brain responses to expectancy violation (Friedman et al., 2001; Goldstein et al., 2002). Consequently, the present study provides consistent evidence for an association between temporal sequences and participants' expectations.

The influence of empathy facets in modulating EEG signatures of imitation echoes behavioural patterns, showing distinctive associations between somatic, cognitive and affective-related empathy facets with AIT cues and temporal sequences.

The association of the somatic subscale from the CASES with the N2 component suggested a possible link with attentional processes considering its modulation of frontocentral activity (Yeung et al., 2004). Therefore, this association suggest that this motor-related empathy subscale is associated with attentional processes and future studies could investigate this pathway as a mechanism linking this empathy subscale with deficits in motor accuracy. Whilst the cognitive IRI subscale *Fantasy* displayed a similar pattern for N2 and also P3b amplitudes, these associations did not reach the significance threshold after corrections. Although the present data prevent any firm conclusions and the questionable reliability of this subscale casts doubt on a robust association, this pattern suggests that capacities for empathy toward fictional characters could modulate cognitive processes associated with perspective-taking and self-other distinction, already identified in imitation (Bukowski and Samson, 2021; Ramsey, 2018; Shaw et al., 2017). Alternatively, these P3b modulations could also reflect expectancy violation and further investigations would be required to disentangle potential overlapping P3 components (Friedman et al., 2001; Goldstein et al., 2002).

Finally, exploratory analyses of the EEG signature of participants' and AIT sequences provided further information on the distinctive role of empathy facets in processing rhythm. Analyses revealed indeed that IRI affective-related facets (*Personal Distress* and *Empathic Concern*) and kinesthetic empathy were associated with lower P3a for AIT cues repetition, suggesting a facilitation effect for affective empathy and a possible association with processing fluency (Hove and Risen, 2009). However, after corrections, these associations remain significant only for the IRI subscale *Personal Distress* and KinEmp. Nevertheless, these patterns reveal possible sensitivity of affective and motor-related facets of empathy to temporal sequences. Although the current experimental design prevents any firm conclusions, these results pave the way for future studies disentangling the respective role of empathy facets in automatic imitation and their association with self-other distinction and temporal predictions.

6.4.5 Limitations and Future research

This study has several limitations that must be addressed in future investigations. The internal consistency of the QCAE and KinEmp questionnaires questioned their reliability. Whilst these results reproduced findings from **Chapter 3** and previous studies (Graf et al., 2019; Myszkowski et al., 2017), they call for cautionary interpretations of the present findings. As pointed out in **Chapter 2** (see also Reniers et al. (2011)), it is unclear whether the IRI subscales are measuring affective empathy or its consequences. Therefore, findings associated with these subscales must be interpreted with caution.

Implementing the AIT cues with static pictures rather than short videos might have reduced the occurrence of automatic imitation and its neural correlates (Cracco et al., 2018). Additionally, reaction-time measurements can be prone to speed-accuracy trade-offs, and although the inverse-efficiency score could have also been computed, this measure can also be prone to bias (Bruyer and Brysbaert, 2011; Gordon et al., 2020a; Liesefeld and Janczyk, 2019). Consequently, other methods for modelling behaviours could be implemented, such as drift-diffusion models that could provide additional insights into the neurocognitive mechanisms underlying behavioural patterns in automatic imitation (Wagenmakers et al., 2007). Furthermore, the present implementation of the AIT was not initially designed to manipulate imitation cues contiguity, and the role of temporal sequences was considered for exploratory analyses after the beginning of the data collection. To the author's knowledge, only Gordon et al. (2020a) manipulated the ratio of congruent-to-incongruent trials, reporting that motor impairments usually associated with autism were not observed. Therefore, manipulating cues' occurrence and temporal sequences appears promising for investigating automatic imitation and its modulation by temporal expectations.

The lack of modulation of the EEG frequency bands across AIT conditions could be interpreted as an insufficient contrast between experimental conditions as mentioned above. Moreover, there is also the possibility that variations within trials were not captured by the FFT. Alternatively, the EEG analyses may have failed to capture variations across the whole scalp and within single trials (Chavan and Kolte, 2011; Cohen, 2019; Dumas et al., 2014b; Fan et al., 2007; Tallon-Baudry et al., 1996). Consequently, more fine-grained EEG frequency band analyses, such as time-frequency analyses (e.g., Morlet Wavelet), could offer more insight into the modulation of alpha/mu and beta bands by AIT conditions, considering spatiotemporal variations generated by travelling brain waves (Hughes, 1995; Muller et al., 2018; Nunez and Srinivasan, 2006).

Finally, several statistical associations did not hold significance after corrections for multiple comparisons, suggesting a possible lack of statistical power due to the small sample size. Initial power calculations suggested a sample size of more than 100 participants for detecting a small effect size. Unfortunately, the restricted time frame and use of EEG for this data collection prevented reaching this sample size. Furthermore, the multiplication of statistical tests for investigating the role of empathy facets may have led to the inflation of risk for false significance (but see Feise (2002) and Rothman (1990) for a more nuanced view on corrections for multiple comparisons). Therefore, although the investigation of the empathy "constellation" is promising, it also requires bigger sample sizes.

Notwithstanding these important limitations, the present investigation provided new insights into the association between empathy and imitation. Expanding findings from Chapter 3, this study delineates important distinctions between empathy facets (i.e., motor and affective) and imitation components (i.e., anatomical and spatial). These results suggest overlapping mechanisms (i.e., predictions and self-other distinction) between empathy, imitation and synchrony, paving the way for future investigations bringing together the temporal and spatial matching of motor components in social interactions.

6.4.6 Conclusions

To summarise, the present investigation explored the role of empathy facets in modulating automatic imitation, providing new insights into their respective association. The association between somatic empathy (i.e., CASES) and global motor impairments suggests that motor-related components of empathy must be considered distinct from affective-related components. This important distinction echoes findings from **Chapter 3** and paves the way for future investigations in populations displaying difficulties in social interactions (Baillin et al., 2020; Cassidy et al., 2016; Hur et al., 2014). Additionally, this study stresses the risk of conflation between spatial and anatomical compatibility, pointing out the role of perspective-taking and self-other distinction in disentangling imitation from spatial congruence and their association with cognitive empathy facets (Bukowski and Samson, 2021; Ramsey, 2018; Shaw et al., 2017). In line with behavioural patterns, EEG analyses highlighted the role of attentional processes and self-other distinction in automatic imitation. Finally, exploring temporal sequences provided new insights for analysing the influence of empathy on automatic imitation by considering the role of rhythms, suggesting an overlap with empathy mechanisms.

CHAPTER 7

EXPERIMENT IV - MPG and EEG

"What we don't know is vastly greater than what we know. But we are learning."
- Carlo Rovelli

The increasing reliance on algorithms and automation has led human operators to rely more and more on computers to perform joint action, yet how the mechanisms usually observed in Human-Human Interactions are translated in Human-Computer Interaction (HCI) context remains to be clarified.

As seen in **Chapters 1** and **2**, the feeling of togetherness can be conceptualised through joint action (i.e., interpersonal motor coordination, IMC), and mutual understanding (i.e., empathy). In **Chapters 3** and **6**, the association between IMC components (i.e., synchrony and imitation) and empathy facets were investigated, revealing a complex interplay between these multidimensional constructs. Whilst **Chapter 3** replicated findings from in-laboratory settings (Koehne et al., 2016b; Novembre et al., 2019), suggesting that virtual agents can provide computational models of human-human social interactions, **Chapter 4** revealed a detrimental effect of synchrony in HCI context. It was suggested that the excessive predictability of virtual agents buffers the effect of synchrony on social bonding by reducing anthropomorphic tendencies (Bailenson et al., 2008; Verberne et al., 2013). Yet, the ability to predict others' behaviours (i.e., cognitive empathy) varies from one individual to another, and its impact on the association between predictability and anthropomorphism needs to be clarified.

This research question was investigated in an in-laboratory data collection combining self-reports of empathy and anthropomorphism, behavioural assessments of Theory of Mind (ToM), and electroencephalography (EEG).

Part of this chapter has been published as a poster presentation titled **Humanness lies in unpredictability: Role of Theory of Mind on anthropomorphism in human-computer interactions** in the *Proceedings of the 10th International Conference on Human-Agent Interaction (HAI '22)*.

7.1 Summary of the theoretical and empirical gap

The capacity to predict virtual agents' behaviour is a fundamental aspect of HCI. Nevertheless, predictability can be both beneficial and detrimental in designing virtual agents. On the one hand, predictability can prevent the Out-Of-The-Loop (OOTL) problem by allowing operators to monitor and predict the activity of autonomous agents (Berberian et al., 2017). On the other hand, predictability can decrease the perceived agentivity of autonomous agents, disrupting their capacity for eliciting social connectedness because of the lack of human-like features such as randomness (Fernández Castro and Pacherie, 2021; Fernández-Castro and Pacherie, 2023; Epley et al., 2007). Previous studies already demonstrated that complexity (i.e., variability) is an important feature of human behaviours, and the inflexible implementation of motor behaviours in virtual agents could elicit "phoney" interactions (Bailenson et al., 2008; Verberne et al., 2013). The experimental investigation reported in **Chapter 4** supported these notions, showing that moving in synchrony with a virtual agent was associated with decreased experiences of self-other overlap and anthropomorphism tendencies. Nonetheless, the role of inter-individual variability in predicting others' behaviours, that is, individual differences in capacity for empathy, was not considered. Consequently, there was a need to clarify how predictability can affect anthropomorphic tendencies and how inter-individual differences in empathy influence this association.

The present experimental investigation used the Matching Pennies Game (MPG), assessing the impact of agents' predictability on anthropomorphism and their potential interactions with self-reported affective, cognitive, somatic, and kinesthetic empathy. Behavioural indexes of participants' performances (i.e., accuracy) and game strategy (i.e., Win-Stay and Lose-Shift) were extracted, investigating the role of agent's predictability on anthropomorphism tendencies and their potential interactions with empathy facets. Additionally, EEG recordings were performed to investigate the association between behavioural and neural patterns and their potential association with empathy questionnaires. Similarly to **Chapter 6**, indices of neural activity were extracted from the EEG recordings, such as the alpha and beta bands associated with attentional processes and the Event-Related Potential (ERP) associated with task monitoring (i.e., Feedback-Related Negativity (FRN and P300), investigating their modulation by the agents' predictability and empathy scores. Mixed models were performed with behavioural and neural indices as outcome variables and MPG conditions and empathy as predictors.

7.1.1 Machines as collaborators

Since the Industrial Revolution and the development of computers, modern societies increasingly rely on automation, replacing humans with machines. This intensive use of automated algorithms raises societal and ethical issues, echoing the Luddism movement and questioning the capacity of machines to replace human beings (Hobsbawm, 1952; Roszak, 1994)[1]. Beyond these important issues, it remains to clarify how humans interact with machines. As seen in **Chapter 1**, social interactions are complex, encompassing layers of sensorimotor (i.e., interpersonal coordination) and social components (i.e., joint commitment), and it is unclear how the mechanisms identified in human-human interactions are translated into HCI. Of particular interest is the research conducted on the OOTL problem, stressing the detrimental outcomes associated with the difficulties for humans in understanding machines.

The OOTL problem can be considered as a "miscommunication" between the human operators and the automated systems, characterised by a loss of "situational awareness", leading to "confusion" and the inability to understand the state of the system (Gouraud et al., 2017). Considering the increasing reliance on automation, mitigating the OOTL problem is essential. Several factors have already been suggested in the literature, targeting neurocognitive components for preventing the OOTL occurrences. On the one hand, Gouraud et al. (2017) suggested monitoring operators' vigilance state through monitoring EEG frequency bands associated with attentional processes (i.e., alpha and beta bands). On the other hand, other studies suggested that the complacency toward automated systems, that is, the excessive trust placed in machines, is an important factor of the OOTL, leading to a decrease in task monitoring and could be investigated through EEG markers of conflict monitoring processes (i.e., FRN, P300) (Dzindolet et al., 2003; Gouraud et al., 2017). Therefore, the human operator's attribution and perception of the automated agent's competence appear crucial in preventing the attention drop associated with the OOTL problem.

Framing the OOTL in those terms echoes the definition of cognitive empathy, that is, the ability to attribute mental states to predict and explain behaviour (Frith and Happé, 1999). Consequently, a paradigmatic shift is encouraged in HCI, moving from "computers as tools" to "computers as collaborators" and encouraging operators to recognize computers as having a mind (De Visser et al., 2018). However, this approach questions the capacity of virtual agents to be "credible" enough to trigger empathic processes (Fernández Castro and Pacherie, 2021; Fernández-Castro and Pacherie, 2023).

[1]For a more in-depth discussion on the problematic anthropomorphisation of automated algorithms, see **Chapter 8**, but also Mitchell and Krakauer (2023) and Shiffrin and Mitchell (2023)

7.1.2 Anthropomorphism and Theory of Mind

How humans perceive machines is a fruitful research field in industrial design, postulating that increasing machines' humanness could improve the fluency of HCI. However, as discussed in **Chapters 1** and **5**, several models of anthropomorphism coexist in the literature, and it remains to delineate the distinctive features of humanness.

On the one hand, the Computer-As-Social-Actor model (CASA, Nass et al. (1994)) postulated that humans tend to apply similar social heuristics when interacting with agents and humans. On the other hand, the three-factor model of anthropomorphism (Epley et al., 2007) suggested that the way humans perceive machines is contextual and modulated by (i) perceived agentivity, (ii) motivation to reduce uncertainty, and (iii) the need for social connection. Therefore, whilst the CASA assumes that the mechanisms underlying human-human social interactions can be translated to HCI, the three-factor model suggests the influence of (i) the agent's behaviour and (ii) the inter-individual differences in detecting and interpreting this behaviour. Importantly, failure to recognize humanness can lead to the "uncanny valley" (Mori, 1970), where agents that are perceived as lacking the capacity for acting and thinking independently can generate an unnerving experience (Gray and Wegner, 2012; Wang et al., 2015). Consequently, the recognition of "another mind" is crucial in generating anthropomorphic tendencies and resembles the concept of the Theory of Mind.

Often considered overlapping with the conceptualisation of cognitive empathy, Theory of Mind (ToM) can be considered beyond social interactions as the capacities for self-other distinction, reflecting meta-cognitive abilities (Proust, 2007; Sodian and Frith, 2008). Whilst the first assessments of ToM were restricted to measuring the capacity to distinguish self from other, the proliferation of measurements lacks consistency (Beaudoin et al., 2020). Alternative ToM tasks are suggested to address these limitations, such as the Matching Pennies Game (MPG, Forgeot d'Arc et al. (2020); Devaine et al. (2014)). Consisting of guessing the probability distribution between two alternative options (e.g., red and blue cards), the MPG is testing the recursive thinking, "I think that you think that I think", and can be classified as a second-order ToM task, reflecting tendencies to infer mental states of the other about one's mental states (Yoshida et al., 2008). However, it remains to clarify if individuals rely on cognitively costly recursive ToM abilities or simpler game strategies when playing the MPG (Devaine et al., 2014; de Weerd et al., 2018). Consequently, the MPG offers a novel way of measuring tendencies to attribute a mind to an automated agent.

7.1.3 Goal and hypotheses

To summarise, the increasing reliance on automation requires a shift in designing HCI, where human operators are encouraged to perceive automated agents as collaborators. Although this approach can be considered a threat in considering the role of human beings in the workplace, it also questions the ability of virtual agents to be perceived as humans. Despite intensive research in designing HCI, it remains unclear what features make humans perceive machines as human-like. Previous research highlights the role of predictability, stressing its benefits in inferring the agent's state and its detriment in impeding agents to display agentivity (i.e., acting and thinking independently). The capacity to attribute independent mental states to self and others is a core aspect of ToM abilities, overlapping with cognitive empathy. Consequently, the association between ToM abilities and anthropomorphic tendencies must be clarified.

An in-laboratory data collection was conducted to address this research question, using self-reports of empathy and anthropomorphism, combined with the MPG task and EEG recordings. This study aimed to explore the role of virtual agents' predictability and its interaction with inter-individual differences in empathy on behavioural patterns (i.e., ability to predict virtual agent's choices and game strategies), anthropomorphism and EEG markers of attention processes (i.e., alpha and beta frequency bands) and ERP associated with conflict-monitoring processes (i.e., FRN, P300).

Based on the pre-existing literature and following the results reported in **Chapters 3** and **4**, a first hypothesis postulated a positive association between cognitive empathy scores and abilities in predicting virtual agent's choices (Koehne et al., 2016b; Novembre et al., 2019). A second hypothesis predicted a negative association between virtual agents' predictability and anthropomorphic tendencies (Dzindolet et al., 2003; Epley et al., 2007). Additionally, a third hypothesis postulated an association between the agent's predictability and EEG markers associated with attentional processes (i.e., alpha and beta bands) and a negative association with ERPs (i.e., FRN, P300) associated with conflict-monitoring processes (Dzindolet et al., 2003; Gouraud et al., 2017). An increase in the agent's predictability was expected to be associated with a decrease in attention (i.e., an increase of alpha but a decrease of beta) and conflict monitoring processes (i.e., lower FRN and P300 amplitudes). Alternatively, excessive unpredictability could also lead to the same outcomes considering the lack of capacity to build predictions about the agent's behaviour. Finally, exploratory analyses were conducted investigating the association of empathy facets with anthropomorphic tendencies and the modulation of behavioural and neural markers of attentional and task-monitoring processes.

7.2 Methods

7.2.1 Participants

Participants were as described in **Chapter 6**. After exclusion criteria (i.e., Handedness Score, neuropsychological diagnosis) were applied to the initial sample ($N = 43$), the resulting sample consisted of 34 participants (12 men, 20 women and 2 non-binary, mean age = 21.35, SD = 3.3, range 18 to 32 years) for psychometrics and behavioural performances. Additionally, 3 participants were excluded for missing EEG recordings ($N = 1$) and excessive artefacts ($N = 2$). Therefore, a subsample of 31 participants (11 men, 20 women, mean age = 21.42, SD = 3.42, range 18 to 32 years) was included in the subsequent EEG analyses[2].

7.2.2 Empathy questionnaires

Psychometrics for empathy were completed as described in **Chapter 6**.

7.2.3 Matching Pennies Game

Participants played a version of the Matching Pennies Game (MPG) adapted from Waade et al. (2022) by guessing the agent's choice (i.e., picking a blue or red card). The agent's choices were manipulated using a within-subjects experimental design across four conditions by increasing the tendency of the agent to choose a specific card colour from 50% to 80% by increments of 10%. The presentation order of the conditions was randomised between subjects. A fixation cross was presented for a fixed duration of 350 ms, followed by the presentation of the blue and red cards. The feedback on the participant's performance was provided after each trial and presented for 750 ms. Participants scored 1 point when they accurately predicted the card the agent would pick up. After each condition ($N = 30$ trials), participants rated their perception of humanness and predictability of the agent using visual analogue scales ranging from 0 to 100 - for a graphical representation, see **Figure 7.1**.

7.2.4 EEG pre-processing

The administration of the task and EEG recordings were conducted following the procedure and pipeline described in **Chapter 6**. EEG epochs were created for each MPG trial ($N = 120$), before (-400 ms) and after (600 ms) feedback's onset. However, for parsimony, only the most random (i.e., 50% bias) and most biased (i.e., 80% bias) MPG conditions were retained for the subsequent EEG analyses.

[2]Sample size differs from the associated publication due to EEG recordings - see Ayache et al. (2022)

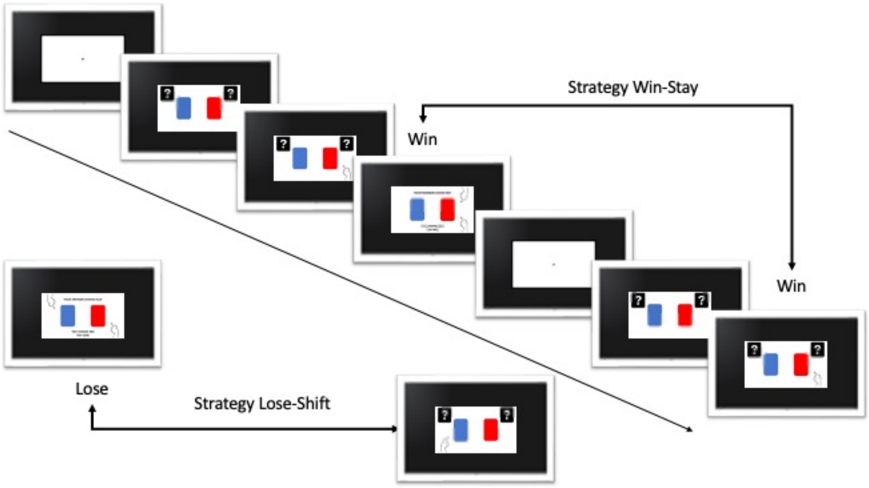

Fig. 7.1 Graphical representation of the Matching Pennies Game

The same set of electrodes from **Chapter 6** was selected for analyses, including frontal central and parietal midline electrodes (i.e., Fz, FCz, Cz, CPz, Pz). The alpha and beta frequency bands (8–30 Hz) were extracted following the procedure described in **Chapters 6** and **7**. Mean amplitudes were extracted using time windows ranging from 0 to 200 and from 200 to 400 after the feedback's onset, corresponding to the onset of the FRN and P300 (Nieuwenhuis et al., 2005; Zhou et al., 2010).

7.2.5 Data analyses

Behavioural data consisting of accuracy (i.e., the proportion of correct responses) and game strategies (i.e., Win-Stay and Lose-Shift) were averaged for each MPG condition. Spearman's correlations were computed between empathy subscales, anthropomorphism, perceived predictability, MPG scores and game strategies (i.e., Win-Stay and Lose-Shift). Mixed models were computed using standardized participant-wise MPG scores, anthropomorphism and perceived predictability scores and brain activity (i.e., alpha frequency band and ERP mean amplitudes) as outcome variables with MPG conditions and empathy scores as fixed predictors; testing their interaction. Participants were added as random effects, and Holm Bonferroni corrections were applied for multiple comparisons. Scripts and dataset associated with the published manuscript are available online on OSF: `https://osf.io/wvs9p/`

7.3 Results

7.3.1 Zero-order correlations

Accuracy scores displayed a positive correlation with predictability ($p < .001$). The game strategy Win-Stay displayed a positive correlation with accuracy and predictability, whilst the Lose-Shift strategy displayed a negative and reversed pattern (all $ps < .010$). Perceived humanness and predictability displayed a trend for a positive correlation near the significant threshold ($p = .045$). For empathy, all subscales displayed good reliability (Cronbach's alphas $> .70$).

Empathy subscales were not associated with MPG scores and game strategies (all $ps > .050$) but with perceived humanness and predictability. Perceived humanness was negatively correlated with the IRI subscale *Fantasy*, somatic empathy (CASES) and KinEmp scores ($p = .005$, $p = .043$ and $p = .040$ respectively). Perceived predictability was positively correlated with *Perspective Taking* ($p = .025$). However, none of these associations held significance after corrections for multiple comparisons. Finally, perceived predictability was also negatively correlated with CASES scores ($p = .004$) and this association remained significant after corrections ($p = .025$) - for descriptive statistics and correlations, see **Table 7.1**[3].

	Mean	Score	WS	LS	ANT	PRED
Score	52.16 ± 9.69	-				
Win-Stay	28.77 ± 11.37)	.40***				
Lose-Shift	24.80 ± 9.62	-.66***	-.07			
Anthropomorphism	42.07 ± 26.19	.06	-.11	-.12		
Predictability	42.91 ± 21.46	.51***	.37***	-.26*	.17	
Perspective Taking	25.32 ± 5.20	.04	.06	-.02	.15	.19
Fantasy	25.38 ± 5.08	-.14	.01	.12	-.24	-.08
Empathic Concern	26.97 ± 4.96	-.04	-.02	.07	-.16	-.09
Personal Distress	19.21 ± 5.06	-.12	-.1	.06	-.13	-.16
CASES	32.62 ± 4.98	-.01	.02	.04	-.17	-.25*
KinEmp	24.44 ± 3.56	-.06	.02	.09	-.18	-.08

Table 7.1 Descriptive statistics and correlations between empathy, anthropomorphism, predictability and MPG indices

Adjusted p-values are reported with $*p < .05$, $**p < .01$, $***p < .001$.

[3]**WS** stands for Win-Stay; **LS** for Lose-Shift; **ANT** for anthropomorphism; **PRED** for predictability.

7.3.2 MPG indices

The MPG conditions did not influence scores (all $ps > .050$) but game strategies.

Participants displayed greater tendencies for the Win-Stay strategy in the 70 and 80% bias conditions ($beta = 6.67, t = 3.01, p = .003$ and $beta = 14.61, t = 6.59, p < .001$). Post hoc analyses with Holm Bonferroni corrections revealed significant differences between the 50% and the 70% and 80% bias conditions (all $ps < .050$). Additionally, there was a significant difference between the 70% and 80% bias conditions ($p = .005$). However, no significant differences were observed between the 50% and 60% conditions ($p = .597$). Finally, despite a trend, there were no significant differences between the 60% and the 70% conditions ($p = .053$).

In contrast, participants displayed lower tendencies for the Lose-Shift strategy in the 80% bias condition ($beta = -5.29, t = -2.54, p = .013$). However, post hoc analyses revealed only a significant difference between the 60% and the 80% condition ($p = .032$) - for descriptive statistics, see **Table 7.2** and for graphical representation, see **Figure 7.2**, with bold lines representing the median; upper and lower bound of the boxes the 1st and 3rd quartiles.

	Bias 50%	Bias 60%	Bias 70%	Bias 80%
Scores	53.04 ± 11.29	49.90 ± 9.04	52.35 ± 8.38	53.33 ± 9.85
Win-Stay Strategy	23.14 ± 10.31	24.41 ± 9.09	29.80 ± 10.38	37.75 ± 9.80
Lose-Shift Strategy	26.18 ± 11.70	27.35 ± 10.34	24.80 ± 8.61	20.88 ± 5.99

Table 7.2 Descriptive statistics for scores and game strategies for MPG conditions

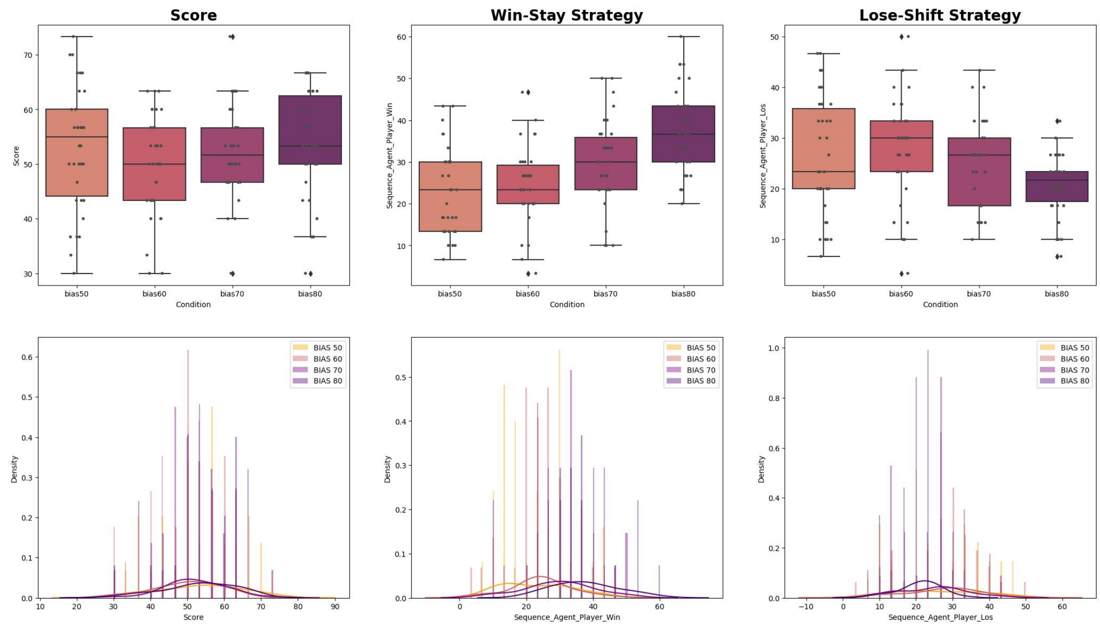

Fig. 7.2 Graphical plots of MPG conditions for scores (left), win-stay strategy (middle) and lose-shift strategy (right)

7.3.3 Anthropomorphism and perceived predictability

The MPG conditions influenced perceived humanness, with participants reporting a lower perception of humanness in the 80% bias condition ($beta = -0.63, t = -2.85, p = .005$). However, this effect disappeared after corrections for multiple comparisons (all $ps > .050$)[4]. Finally, there was a trend for associations between perceived predictability and the 60% and 80% bias condition ($beta = -0.37, t = -1.85, p = .067$ and $beta = 0.35, t = 1.72, p = .089$, respectively) but these associations did not reach the significant threshold - for descriptive statistics, see **Table 7.3** and see **Figure 7.3**, with bold lines representing the median; upper and lower bound of the boxes the 1st and 3rd quartiles.

	Bias 50%	Bias 60%	Bias 70%	Bias 80%
Anthropomorphism	44.91 ± 25.86	45.50 ± 29.42	42.94 ± 25.53	34.91 ± 23.37
Predictability	42.62 ± 21.15	39.09 ± 20.65	41.12 ± 21.86	48.82 ± 21.87

Table 7.3 Descriptive statistics for anthropomorphism and perceived predictability for MPG conditions

[4]This result differs from the published results because of sample size difference - see Ayache et al. (2022)

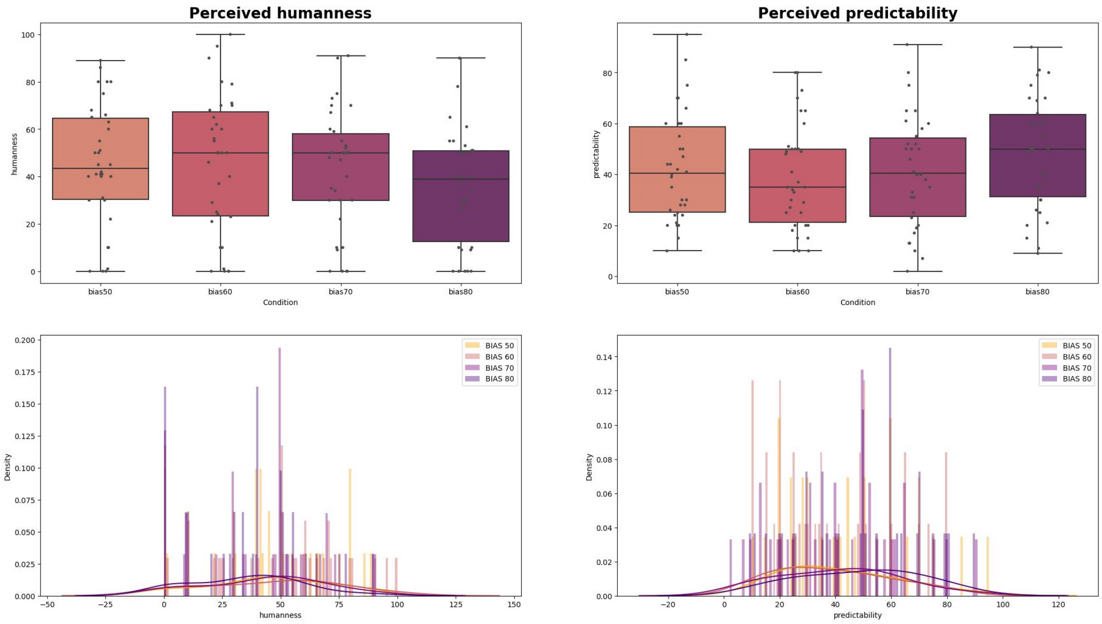

Fig. 7.3 Graphical plots of MPG conditions for perceived humanness (left) and predictability (right)

7.3.4 EEG analyses

The MPG conditions and correct/error trials were not associated with the alpha band (all $ps > .050$), but with the beta band. The MPG conditions were associated with the beta band ($beta = -0.51, t = -3.97, p < .001$). This association remained significant after correction ($p < .001$) and complementary analyses revealed that the 80% condition was associated with a decrease of the beta band upper range (20-30 Hz) at the Fz, FCz and Cz electrodes ($beta = -0.51, t = -3.05, p = .002$, $beta = -0.45, t = -2.67, p = .008$ and $beta = -0.3, t = -2.01, p = .044$) - see **Figure 7.4** for a graphical representation, with bold lines representing the median; upper and lower bound of the boxes the 1st and 3rd quartiles.

An association was also observed between the beta band, anthropomorphism and perceived predictability. On the one hand, anthropomorphism was associated with an overall increase of beta band ($beta = 0.20, t = 4.51, p < .001$), driven by frontocentral electrodes Fz, FCz and Cz ($beta = 0.26, t = 3.10, p = .002$, $beta = 0.22, t = 2.67, p = .008$ and $beta = 0.26, t = 3.11, p = .002$). On the other hand, perceived predictability was associated with a decrease in the beta band ($beta = -0.11, t = -2.82, p = .005$), driven by the frontal electrode Fz ($beta = -0.19, t = -2.57, p = .010$) - see **Figure 7.4** for a graphical representation, with solid lines representing regression lines and transparent grey areas representing 95% confidence interval.

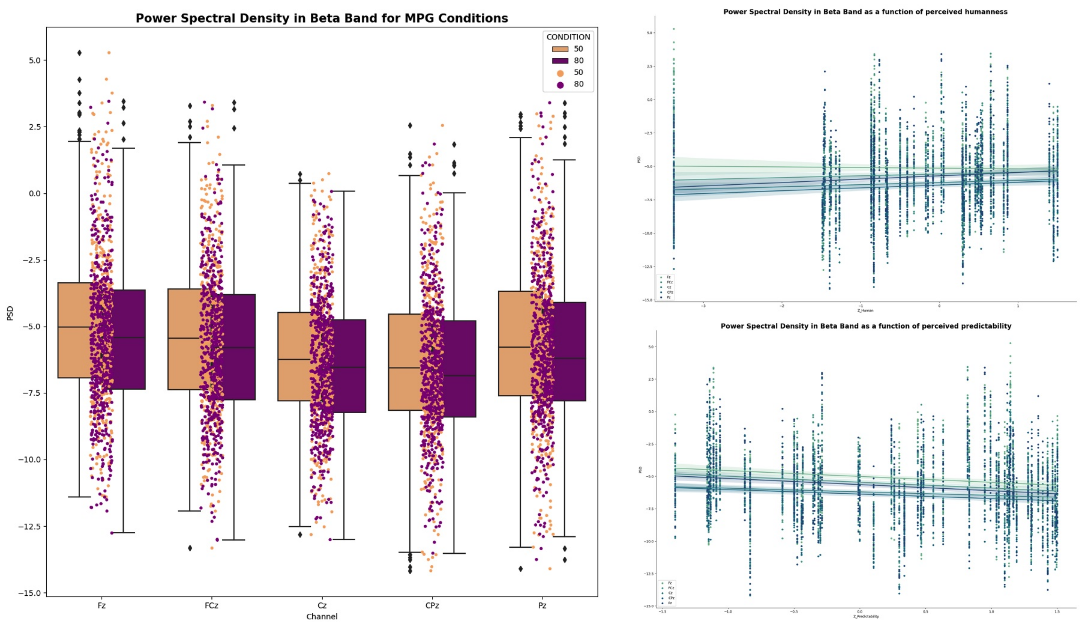

Fig. 7.4 Graphical plots of the power spectral density of the beta band for MPG conditions (left) and for perceived humanness (top right) and predictability (bottom right)

The ERP components were not modulated by self-reports of anthropomorphism and perceived predictability (all $ps > .050$), but by MPG conditions and correct/error trials. On the one hand, the 80% condition was associated with a significant increase of the FRN amplitude at the frontocentral electrodes Fz and FCz ($beta = 0.82, t = 2.23, p = .028$ and $beta = 0.94, t = 2.23, p = .028$). On the other hand, the error trials were associated with an increase of the P300 at the centroparietal electrodes CPz and Pz ($beta = 1.17, t = 3.06, p = .003$ and $beta = 1.24, t = 2.71, p = .008$) - see **Figure 7.5** for graphical representations.

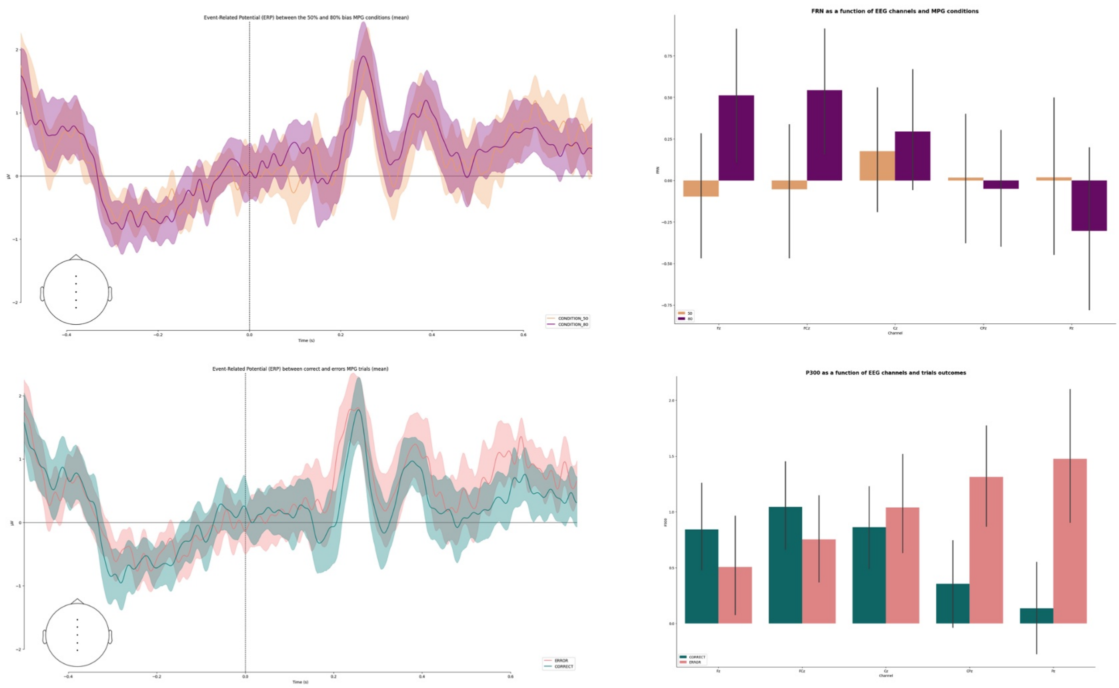

Fig. 7.5 Graphical plots of the evoked responses for the 50 and 80% bias conditions (top) and for correct/error trials (bottom) with grand average ($N = 31$) for midline electrodes (left) and barplots for FRN (top right) and P300 components (bottom right)

7.3.5 Interaction with empathy scores

Empathy scores were not associated and did not moderate the association of conditions with MPG scores and the Win-Stay strategy (all $ps > .050$). However, there was an interaction between IRI *Perspective Taking* and the 80% bias condition for the Lose-Shift strategy ($beta = -0.88, t = -2.19, p = .031$), but this association did not hold after corrections for multiple comparisons - see **Figure 7.6** for graphical representations, with solid lines representing regression lines and transparent grey areas representing 95% confidence interval.

Empathy scores were not associated and did not moderate the association of conditions with anthropomorphism (all $ps > .050$) but there was an interaction of the IRI subscales *Fantasy* and *Personal Distress* with MPG conditions for perceived predictability. Participants scoring higher on these subscales perceived the agent as more predictable in the 80% bias condition ($beta = 0.08, t = 2.05, p = .043$ and $beta = 0.09, t = 2.34, p = .021$ respectively). However, these associations did not hold after corrections for multiple comparisons - see **Figure 7.6** for graphical representations, with solid lines representing regression lines and transparent grey areas representing 95% confidence interval.

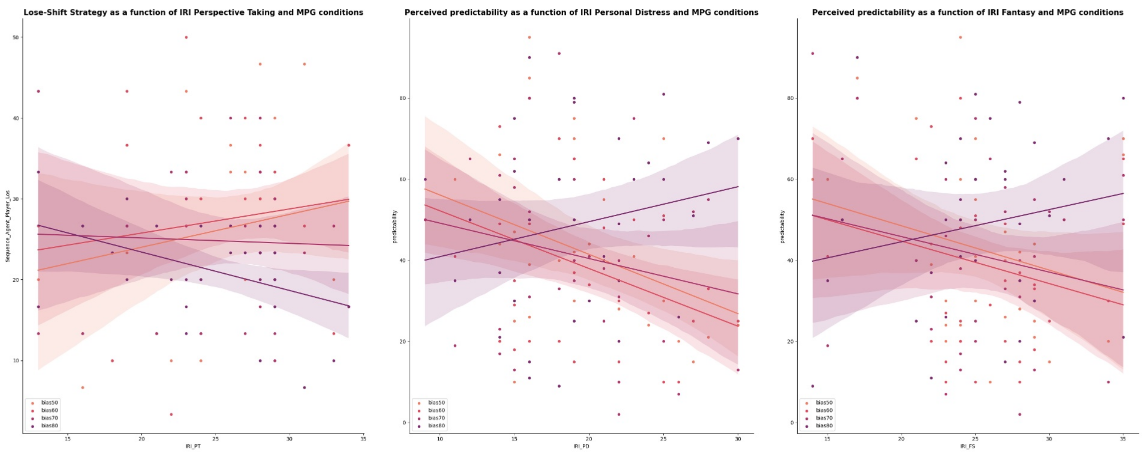

Fig. 7.6 Graphical plots of lose-Shift strategy for MPG conditions and IRI *Perspective Taking* (left), and perceived predictability and *Personal Distress* (middle) and *Fantasy* (right)

Empathy scores were not associated with alpha (all $ps > .050$) but with beta band.

The IRI subscale *Perspective Taking* scores displayed an interaction with the MPG conditions for the beta band ($beta = 0.04, t = 3.17, p = .002$). This association remains significant after corrections ($p = .003$) and was driven by FCz, Cz and CPz electrodes ($beta = -0.07, t = -2.18, p = .030$, $beta = -0.07, t = -2.16, p = .031$ and $beta = -0.08, t = -2.22, p = .027$). This subscale displayed also an interaction with error/correct trials ($beta = -0.04, t = -3.30, p = .001$). This association remains significant after corrections ($p = .003$) and this interaction was driven by the central electrode Cz ($beta = -0.05, t = -2.05, p = .041$). Finally, there was a trend for a triple interaction between *Perspective Taking*, MPG conditions and error/correct trials ($beta = 0.05, t = 2.00, p = .045$) - see **Figure 7.7** for graphical representations, with solid lines representing regression lines and transparent grey areas representing 95% confidence interval.

The KinEmp scores also displayed an interaction with the MPG conditions for the beta band ($beta = 0.07, t = 3.79, p < .001$). This association remained significant after corrections ($p = .001$) and was driven by the central electrode Cz ($beta = 0.10, t = 2.73, p = .006$). KinEmp scores displayed also an interaction with error/correct trials ($beta = -0.09, t = -5.10, p < .001$). This association remained significant after corrections ($p < .001$) and was driven by the frontocentral electrode Fz, FCz and Cz ($beta = -0.09, t = -2.58, p = .010$, $beta = -0.11, t = -3.22, p = .001$ and $beta = -0.09, t = -2.38, p = .018$) - see **Figure 7.7** for graphical representations.

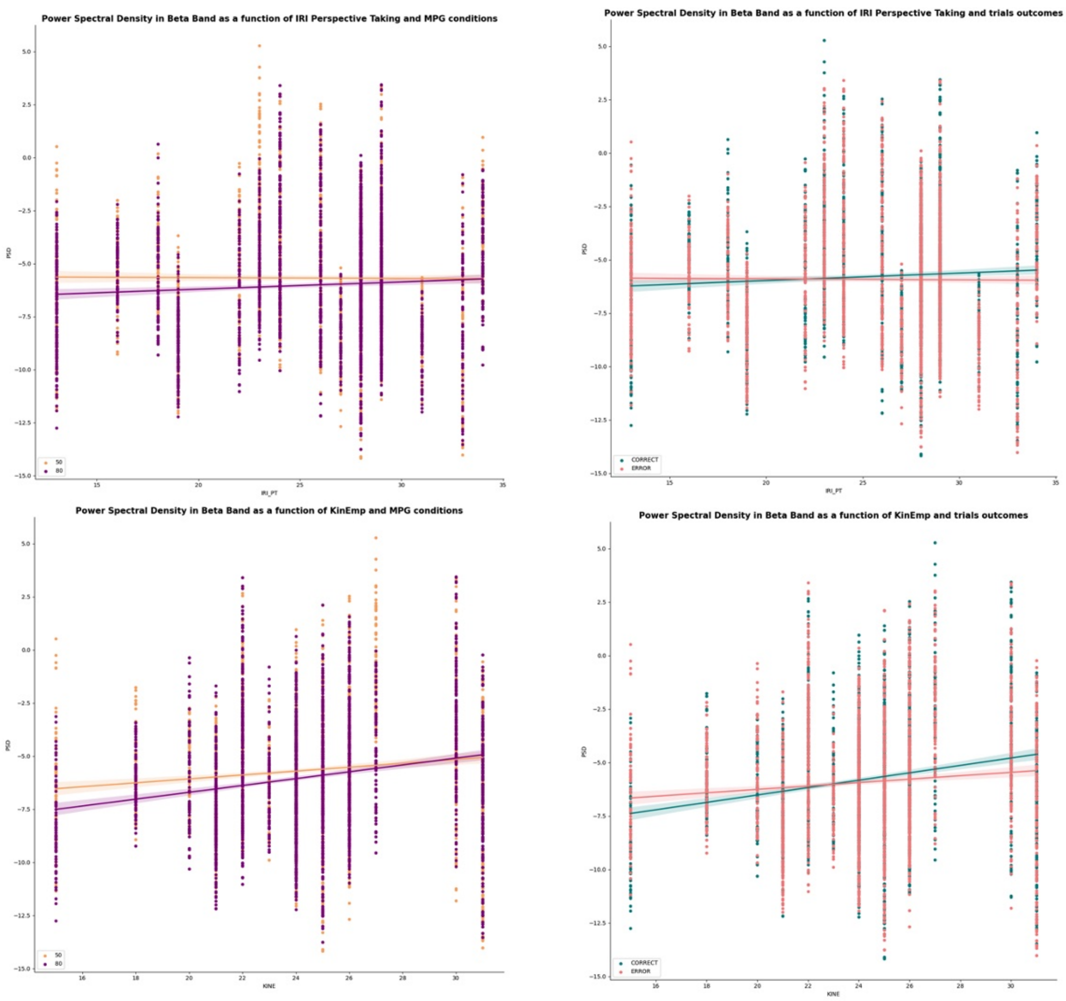

Fig. 7.7 Graphical plots of the power spectral density of the beta band for MPG conditions (left) and for trials outcomes (left) for IRI *Perspective Taking* (top) and KinEmp (bottom)

Empathy scores did not display associations nor interactions with the MPG conditions and error/correct trials for the FRN amplitude (all $p > .050$), but for the P300.

The IRI *Perspective Taking* scores displayed an interaction with correct/error trials for the P300 ($beta = -0.07, t = -2.98, p = .003$). This association remained significant after corrections ($p = .010$) and was driven by the Cz electrode ($beta = -0.13, t = -2.57, p = .012$). A similar pattern was observed for *Fantasy* scores ($beta = 0.06, t = 2.09, p = .037$). However, this association did not hold after correction for multiple comparisons ($p = .149$). See **Figure 7.8** for graphical representations, with solid lines representing regression lines and transparent grey areas representing 95% confidence interval.

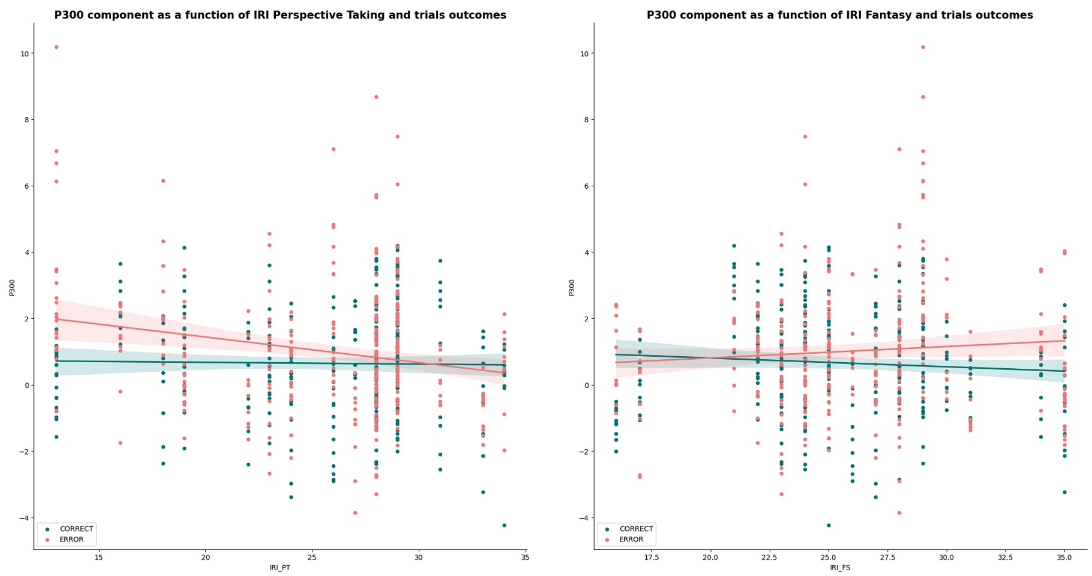

Fig. 7.8 Graphical plots of the beta band with IRI *Perspective Taking* and *Fantasy* for correct/error trials for FCz, Cz and CPz electrodes

7.4 Discussion

The present study investigated the association between inter-individual ToM abilities and an automated agent's predictability, aiming to disentangle their respective contribution to participants' behaviours and neural activity in predicting agent's state and anthropomorphism. The ability to accurately predict an automated agent's state is a crucial component of HCI that has attracted considerable attention for solving the OOTL problem (Gouraud et al., 2017). By reframing the OOTL problem as an interactive process, recent studies underlined the role of cognitive empathy (or ToM) as an important component in the ability to read others' minds (Leudar et al., 2004). However, to what extent understanding another mind can be translated in HCI context must be clarified. This study provides new insights into this question using an adapted version of the MPG as a second-order ToM assessment.

7.4.1 ToM as behavioural patterns

The results from this investigation do not support the first hypothesis postulating a positive association between cognitive empathy and abilities in predicting agents' choices (Koehne et al., 2016b; Novembre et al., 2019). The lack of association between self-reports of cognitive empathy and behavioural performances in the MPG task suggests a lack of convergence between self-report and behavioural assessments of cognitive empathy. As suggested by Melchers et al. (2015), this discrepancy could arise from the different conceptualisations underlying the methods employed. The empathy questionnaires are designed for measuring general tendencies for empathy (i.e., personality traits), whilst the MPG is designed for measuring specific cognitive abilities (i.e., pattern extraction). Furthermore, empathy questionnaires rely on self-perception while the MPG performances measure behaviours. **Chapter 4** highlighted the gap between subjective experience and effective task completion (Matthews et al., 2022), and the current findings reinforce this notion further. Finally, it is also possible that participants are not relying on ToM abilities for completing the MPG but follow simple game strategies that are less costly in cognitive resources (Devaine et al., 2014; de Weerd et al., 2018). Although the present findings prevent drawing any firm conclusions, future investigations must clarify these hypotheses by considering more sophisticated automated agents displaying recursive ToM abilities.

Nevertheless, the present study revealed some interactions between cognitive empathy and game strategies, suggesting that participants scoring higher on cognitive empathy (i.e., IRI subscale *Perspective Taking*) adjusted their strategies to the experimental conditions. Although this association did not hold after corrections for multiple comparisons, exploratory analyses revealed that participants scoring higher on this subscale spent more time making decisions - see **Appendix I**. This suggests that cognitive trait empathy is potentially associated with additional efforts (i.e., spending more time) to understand the agent's behaviour. Consistently with the conceptualisations (i.e., "trying to put oneself in others' shoes"), participants tried but failed, suggesting that accuracy is perhaps not the best measure for capturing cognitive empathy abilities in the context of the MPG task. Alternatively, behavioural patterns and cognitive effort may offer better assessments. This result points towards the misattunement hypothesis (Bolis and Schilbach, 2020; Milton, 2012), observing that empathy assessments are often normative and do not consider alternative views. The lack of direct association between conditions and accuracy scores and lack of significance after corrections suggest that participants might need longer interactions to extract meaningful patterns. Future investigations need to be conducted to identify the duration needed for building an internal model of virtual agents' behaviours (and potential inter-individual variability associated with empathy).

7.4.2 Anthropomorphism and predictability

The results from this study partially support the second hypothesis of a negative association between virtual agents' predictability and anthropomorphic tendencies (Dzindolet et al., 2003; Epley et al., 2007). Participants tended to perceive the most predictable agent as less human - although this association was not significant after post hoc comparisons[5]. Despite a trend for an association of perceived predictability with the most predictable MPG conditions, there was also a trend for a positive association between self-reports of humanness and predictability, contradicting the association between humanness and unpredictability (Dzindolet et al., 2003). The discrepancy between participants' behaviours (i.e., adjusting their strategies) and their perception of the agent is similar to the pattern observed in **Chapter 4**, revealing a mismatch between subjective experience and effective behaviour - see also Matthews et al. (2022). The positive correlation between MPG scores and perceived predictability suggests that participants may have used their performances to report their perception of the agent. The trend for a positive correlation between perceived humanness and predictability suggests that these measures may be conflated and future investigations must implement methods for segregating these measurements.

The role of empathy in modulating the association between anthropomorphism and predictability remains unclear. The correlations between empathy scores and perceived humanness displayed overall negative associations - apart from the IRI subscale *Perspective Taking* but these associations were not contrasted by MPG conditions. In contrast, some of the IRI subscales (*Fantasy* and *Personal Distress*) were associated with tendencies to perceive the agent's bias accurately. Consequently, controlling for inter-individual variability in empathy scores revealed the effect of the MPG conditions. However, these results must be taken with caution, considering their lack of significance after corrections and the possible confound between perceived predictability and participants' ratings of their performances. The lack of robust association between empathy and perceived humanness suggests that tendencies for anthropomorphism may be driven by latent variables closely related to empathy, such as tolerance to uncertainty that are not fully captured by empathy questionnaires (Dzindolet et al., 2003; Epley et al., 2007). This association between empathy and tolerance for uncertainty echoes empathy's history and its initial intertwining with aesthetic experiences (Bentwich and Gilbey, 2017; Haken, 2017; Lanzoni, 2018). Consequently, this finding paves the way for investigating the overlap between empathy and tolerance for uncertainty.

7.4.3 EEG components of MPG

The results from this study partially support the third hypothesis of a modulation of the EEG frequency bands and ERP associated with attentional and task-monitoring processes by the MPG conditions. Although there was no modulation of the alpha band by the MPG conditions and correct/error trials, participants displayed a decrease of the beta band in the most predictable condition. Additionally, the beta band was also mod-

[5] The discrepancy with the published manuscript suggests a possible weak association that was not detected considering the smaller sample size across studies - see Ayache et al. (2022)

ulated by anthropomorphism and perceived predictability. Whilst anthropomorphism was associated with an increase in the beta band, a reversed pattern was observed for predictability. Involved in maintaining internal models and predictions (Bressler and Richter, 2015), the beta band modulation suggested a disengagement from the task when the agent was easily predictable. In contrast, participants were more engaged in the task when they perceived the agent as human. This finding supports De Visser et al. (2018)'s suggestion encouraging human operators to see computers as collaborators. Interestingly, the cognitive subscale IRI *Perspective Taking* and the KinEmp were associated with an increase of the beta band in the 80% bias condition but with a decrease in the 50% bias condition, suggesting a modulation of the attention depending on agent predictability. The same subscales displayed also an interaction with trials' outcomes, suggesting that participants scoring higher in these subscales were more engaged in the task. However, artefacts associated with neuroanatomical differences can not be ruled out and future investigations need to include resting-state EEG recordings.

For the ERP components, the MPG conditions modulated the amplitude of the FRN whilst the errors were associated with an increase of the P300 component. These distinctive patterns suggest that the MPG conditions and error trials may be sustained by different areas of the frontoparietal network (Fan et al., 2005,0; Posner and Boies, 1971). Whilst the modulation of frontal areas by the conditions suggests the involvement of the alerting network and the central executive network in maintaining a vigilance state (Xuan et al., 2016), the modulation of the P300 by error trials suggests the involvement of the default mode network connected with the salience network, modulating executive function and cognitive control (Menon and Uddin, 2010; Uddin, 2015). Consequently, future studies could investigate the distinctive contribution of these neural networks in sustaining conflict-monitoring processes in HCI context.

The distinctive modulations of the P300 by the cognitive subscales IRI *Perspective Taking* and *Fantasy* cast an interesting light on the neurocognitive mechanisms supported by this ERP component. Whilst *Perspective Taking* was associated with a decrease of the P300 amplitude for error trials, *Fantasy* displayed a reversed pattern, with a decrease for correct responses. This reversed pattern questions the systematic association of the P300 with negative outcomes and suggests a link with the reward system and expectancy violations (Balconi and Canavesio, 2015). These results suggest that inter-individual differences in empathy could explain the mixed findings reported on the sensitivity of the P300 on valence or magnitude (Bernat et al., 2008; Wang et al., 2017; Zhou et al., 2010). Whilst the present data prevents any firm interpretations, these findings pave the way for future investigations exploring the role of inter-individual differences in modulating the ERP amplitude associated with task-monitoring processes.

7.4.4 Limitations and Future research

The present study showed several limitations that forthcoming studies must address. First, the use of biased agents challenges the interpretation of participants' behaviours, rendering it unclear if they relied on game strategies because of the task's simplicity or to avoid the cognitive cost associated with ToM abilities (Devaine et al., 2014; de Weerd et al., 2018). Second, the restricted number of trials per condition ($N = 30$) might have buffered the participant's abilities for extracting and building internal models of the automated agent behaviour. Furthermore, the restricted number of trials and small sample size influences the interpretation of ERP components and calls for cautious interpretations considering the lack of statistical significance after corrections (Larson et al., 2010; Olvet and Hajcak, 2009; Rietdijk et al., 2014). Finally, the discrepancy observed between measurements of perceived predictability and effective behavioural adjustments calls for refining self-report assessments and exploring the role of metacognition (Mazor and Fleming, 2021; Uddin and Menon, 2009). Notwithstanding these important limitations, the present study offers new insight into the OOTL problem. The identification of potential shared mechanisms of empathy in human-human and human-agent interactions paves the way for merging these research fields and encouraging theoretical and methodological cross-fertilization between scientific disciplines.

7.5 Conclusions

The present study provides novel insights into the interaction of inter-individual differences in cognitive empathy with an automated agent's predictability, disentangling their respective contributions in ToM abilities and anthropomorphism tendencies.

The discrepancy between subjective and objective ToM abilities underlines the mismatch between the measurements, where effort rather than accuracy appears to be a better proxy for capturing behavioural adjustments (Melchers et al., 2015). The association between anthropomorphism and predictability suggests tolerance to uncertainty as a shared mechanism with empathy (Epley et al., 2007; Lanzoni, 2018). Finally, EEG analyses revealed the respective contribution of distinctive neural networks, paving the way for further investigations investigating the role of the salience network in the OOTL problem (Singer et al., 2004; Uddin, 2015; Uddin and Menon, 2009). Altogether, these results have theoretical and methodological implications beyond the restricted context of HCI, underlying potential shared mechanisms for empathy and anthropomorphism.

CHAPTER 8

GENERAL DISCUSSION AND CONCLUSION

"The wheel is come full circle; I am here."
- William Shakespeare

The study of togetherness is an important research area at the crossroads between various scientific disciplines that require building a common ground. Starting from social sciences and psychology, this thesis project led to exploring these research fields, addressing the topic of togetherness from different standpoints.

This project highlighted that social connectedness is a core aspect of human psychology, as illustrated by the impact of early attachment on later adulthood trajectories (Bowlby and Ainsworth, 2013) and the fundamental human need for belongingness (Baumeister and Leary, 2017). Instead of considering the abilities for social interactions as an extension of human cognition, accumulative evidence stresses the role of the social environment in shaping the human neurocognitive architecture (Heyes and Frith, 2014; Parkinson and Wheatley, 2015; Rochat, 2005). This project reviewed theoretical accounts of moving (i.e., interpersonal motor coordination, IMC) and thinking or feeling together (i.e., empathy), two concepts associated with togetherness but coming from distinctive streams of research, ranging from physics to social neurosciences. Recent attempts have been made to merge their theories and methods to explore the "dark matter" of social interactions (Dumas, 2011; Konvalinka and Roepstorff, 2012; Schilbach et al., 2013). Finally, this project questions the possibility of designing automated agents capable of fulfilling belongingness by looking at the translation of mechanisms of social bonding, namely IMC and empathy in the Human-Computer Interaction (HCI) context. Consequently, this project addressed theoretical and methodological issues in studying the feeling of togetherness in virtual spaces.

In this last chapter, the two research questions addressed by this thesis project, namely (i) what is the association between IMC and empathy, and (ii) are virtual agents appropriate tools for studying togetherness, will be discussed, and the novel theoretical and methodological contributions of this thesis are summarised.

8.1 Disentangling interpersonal motor coordination and empathy facets

The first research question addressed by this thesis project investigated the association between IMC and empathy. Whilst the two concepts are often studied separately, theoretical models suggest a strong association between abilities for IMC and empathy (Decety and Jackson, 2006; Gallese et al., 1996; Preston and De Waal, 2002; Prinz, 1990; Sebanz and Knoblich, 2009; Shamay-Tsoory et al., 2019; Shamay-Tsoory, 2011). Nevertheless, empirical evidence is scarce with mixed findings. Whilst some studies observe an association between IMC and empathy (Novembre et al., 2019; Koehne et al., 2016b), others report null findings (Cracco et al., 2018; Preissmann et al., 2016). Furthermore, it was unclear if IMC needed to be understood as a component, a precursor or an outcome of empathy (Blair, 2005; Feldman, 2007; Novembre et al., 2019). To complicate matters further, various definitions of IMC and empathy co-exist in the literature, rendering it difficult to disentangle the two concepts (Athreya et al., 2014; Varlet et al., 2011; Heyes, 2011; Hall and Schwartz, 2019). Consequently, it was unclear if the discrepancy between theories and empirical evidence had to be attributed to theoretical inconsistencies or fuzzy taxonomies.

This section will briefly review the theoretical and methodological "jingle-jangle fallacy" encountered in IMC and empathy research and summarise the main findings and contributions of this thesis project, stressing the need for merging research fields studying these overlapping and distinctive concepts together.

Firstly, the main findings, strengths and limitations of **Chapter 3** investigating the associations between affective, cognitive, kinesthetic and somatic empathy facets using self-report questionnaires will be discussed. Second, the association between empathy and synchrony, as a specific subtype of IMC, conceptualised as temporal matching, using behavioural assessments of goal-oriented coordination with a virtual agent driven by the Haken-Kelso-Bunz (HKB) model of motor coordination. Finally, **Chapter 6** investigated the association between empathy and imitation, another facet of IMC, conceptualised as spatial matching, using the Automatic Imitation task (AIT) and electroencephalogram (EEG) recordings. Although most of the findings in this thesis are preliminary and exploratory, and must be taken with caution until experimental replications, they pave the way for future investigations merging research on IMC and empathy.

8.1.1 A theoretical and methodological jingle-jangle fallacy

Chapter I presented the "jingle-jangle fallacy" associated with IMC and empathy, highlighting the current conflation of terminologies in the literature. On the one hand, IMC is an umbrella term encompassing synchrony (i.e., temporal alignment) and imitation (i.e., spatial matching; Bernieri and Rosenthal (1991)). On the other hand, empathy is a multidimensional concept encompassing affective (i.e., affective sharing) and cognitive components (i.e., understanding others' mental state; Decety (2010)). However, the distinction between IMC components and empathy facets is not clear, and these dimensions are often entangled in experimental measures (Hall and Schwartz, 2019; Heym et al., 2019). To complicate matters further, IMC has been suggested as an additional facet of empathy, embedding motor components such as imitation and mimicry (Blair, 2005). Whilst historical and theoretical accounts suggest a common neurocognitive architecture supporting empathy and IMC (Gallese et al., 1996; Lanzoni, 2012), their association remains unclear, and the various definitions and assessments challenge the understanding of their intertwinement. Consequently, this thesis advocated for a systematic investigation of their association by taking into account their multiple facets.

Chapter 2 summarised the difficulties of psychology as a scientific discipline in measuring mental states that are inherently "private" (Boring, 1953). To overcome this limitation, psychometrics has been developed to improve the reliability of psychological measures, assuming the existence of latent variables that are not measured directly but inferred from factor analyses (Taherdoost et al., 2022). This method has been applied to developing questionnaires distinguishing affective and cognitive facets of empathy, such as the Questionaire of Cognitive and Affective Empathy (QCAE) developed by Reniers et al. (2011). Combining the QCAE with additional subscales, the Kinesthetic Empathy Scale (KinEmp) and the Somatic subscale from Cognitive, Affective and Somatic Empathy Scale (CASES) developed by Koehne et al. (2016b) and Raine and Chen (2018), measuring somatic and kinesthetic empathy, conceptualised as motor empathy, this thesis explored for the first time their respective association using Confirmatory Factor Analyses (CFA) in **Chapter 3**.

The results from this investigation showed that whilst affective, somatic, and kinesthetic empathy facets are positively correlated, they constitute distinct latent variables. Therefore, this thesis supports a "fine cut" approach of empathy (Blair, 2008). Nevertheless, the reliability of some empathy subscales was questioned, calling for a refinement of the QCAE and KinEmp questionnaires. Consequently, this thesis advocates for the systematic integration of motor-related components of social interactions as distinct facets of empathy, providing a unique contribution to the "empathy constellation".

8.1.2 Goal-oriented motor synchrony and empathy

Whilst self-report measures are useful for delineating latent variables and data structure, they can nevertheless be prone to problematic reliability, displaying variabilities and lack of convergence across studies (Myszkowski et al., 2017; Chrysikou and Thompson, 2016). Hence, by combining empathy questionnaires with behavioural assessments of synchrony, this thesis attempted to clarify the association between empathy facets and effective motor synchrony. Addressing this limitation, an online behavioural assessment of IMC, was introduced in **Chapter 2**, using a virtual agent driven by the HKB model of motor coordination (Haken et al., 1985).

Inspired by synergetics, the HKB is a modelisation of human motor coordination based on oscillator coupling theories, a branch of mathematics and physics modelling synchrony (Kuramoto, 1975; Pikovsky et al., 2002; Strogatz, 2004). Initially restricted to intrapersonal motor coordination (Kelso, 1984), the HKB has been expanded to interpersonal coordination (Schmidt and Richardson, 2008) and can replicate human-human motor coordination in controlled settings (Dumas et al., 2014a; Kelso et al., 2009). By combining self-reports and behavioural measures, this thesis attempted to disentangle the "feeling of" and the "being in" synchrony, rarely explored by previous studies.

Chapter 3 reported results from this experimental investigation conducted online amid the COVID-19 restrictions. This online investigation replicated previous findings associating cognitive empathy with capacities for interpersonal synchrony (Koehne et al., 2016b; Novembre et al., 2019). These results align with theoretical models postulating that the capacity for predicting others' behaviour is an important component for achieving goal-oriented IMC (Sebanz and Knoblich, 2009; Shamay-Tsoory et al., 2019). Interestingly, self-reports of kinesthetic empathy, conceptualised as spontaneous tendencies for behavioural synchrony, were negatively correlated with motor coordination scores. This discrepancy between self-reports and effective behavioural coordination calls for further investigations, looking at (i) the KinEmp structure, which displayed questionable consistency, (ii) the gap between "feeling" and "being" in synchrony, already identified in the experience of musical groove (Matthews et al., 2022).

Importantly, some of these associations did not hold after corrections and need to be interpreted with caution until further replications. Notwithstanding this important limitation, these results highlight the lack of convergence between self-reports and effective behavioural synchrony. Consequently, this thesis calls for exploring the role of meta-cognitive processes involved IMC and empathy by combining self-reports with behavioural measures of IMC (Garfinkel et al., 2015; Mazor and Fleming, 2021).

8.1.3 Automatic imitation and empathy

In **Chapter 2**, the behavioural indexes of motor synchronisation were briefly reviewed, and **Chapter 5** introduced theoretical and methodological debates for imitation assessments, stressing that various indexes of IMC co-exist, making it difficult to identify overlapping concepts and to delineate distinctive constructs. Whilst imitation is often broadly defined as spatial behavioural matching, the literature suggests a more fine-grained definition, distinguishing imitation from mimicry (Heyes, 2011). Empathy theories postulate shared mechanisms between imitation and empathy through the action/perception matching system, also known as the Mirror Neuron System (MNS) (Decety and Meltzoff, 2011; Gallese, 2001; Preston and De Waal, 2002). However, empirical evidence remains scarce (Cracco et al., 2018) and the multiplication of IMC conceptualisations led to a scattered vision of the role of spatial and temporal matching.

This thesis provided a systematic investigation of these distinctive components of IMC and their respective association with empathy facets. Whilst **Chapter 3** investigated the association between temporal matching (i.e., synchrony) and empathy, **Chapter 6** reported an in-laboratory study combining empathy self-reports (i.e., IRI, KinEmp and CASES) with a behavioural assessment of imitation, the Automatic Imitation Task (AIT) developed by Brass et al. (2001). EEG recordings were also performed, investigating neural correlates associated with attention and mirroring (i.e., the alpha-mu and beta bands, Fan et al. (2007); Hobson and Bishop (2016)), and with task monitoring processes (i.e., the ERP N2 and P3, Rauchbauer et al. (2021).

Although the sample size of this study was reduced resulting in a lack of statistical power, findings reported in **Chapter 6** revealed an association between somatic empathy and deficits in motor accuracy, suggesting possible general motor impairments that could be investigated in clinical populations displaying impairments in motor coordination and empathy (Cassidy et al., 2016; Hur et al., 2014). These results highlighted also the role of spatial rather than anatomical compatibility in inducing motor interference, stressing the conflation of social imitation with processing fluency mechanisms (Ramsey, 2018). Additionally, exploratory analyses revealed distinct patterns between affective and cognitive empathy for temporal sequences, stressing possible associations of empathy with rhythm processing (Cirelli et al., 2018; Malloch and Trevarthen, 2018). Finally, the EEG analyses stressed the role of processing fluency and self-other distinction in empathy and imitation (Polich, 2007; Verleger et al., 1994; Volpe et al., 2007). Altogether these results pave the way for investigating the mechanisms of integration/segregation (i.e., temporal and spatial binding) (Tognoli et al., 2011) underlying empathy mechanisms going beyond social interactions (i.e., multi-sensory integration).

8.2 Virtual agents, a paradigm for modelling human-human interactions?

The second research question addressed by this thesis project attempted to delineate the appropriate use of virtual agents for modelling social interactions. Scientific studies of social interactions are limited by confounding variables associated with social identity, rendering it difficult to isolate explanatory variables. Furthermore, human behaviour is difficult to control and is prone to inter-individual variability that can be associated with personality traits or triggered by specific contexts. Consequently, most studies on social interaction are conducted offline by presenting pictures or videos depicting predefined interactions, often contaminated by cultural bias and social norms. These limitations leave aside the dynamic or "dark matter" of social interactions, capturing reciprocal influences (Schilbach et al., 2013). Therefore, recent calls for a paradigm shift to a "second-person" or "two-body" approach in social neurosciences are made for exploring this uncharted territory by developing more naturalistic paradigms (Dumas, 2011; Konvalinka and Roepstorff, 2012). In this context, virtual agents are considered potential promising experimental tools for modelling and reducing the degree of freedom in reproducing human behaviours and, therefore, comply with the scientific requirement for replicability (Pan and Hamilton, 2018). Whilst some studies reported that humans tend to apply similar social norms in virtual worlds (Bailenson and Yee, 2005; Grynszpan et al., 2017; Hasler et al., 2014), other studies also reported backlash effects (Bailenson et al., 2008; Verberne et al., 2013). Consequently, there is a need to delineate in which contexts virtual agents are appropriate to study human-human interactions and which mechanisms can be translated into HCI context.

This section summarises the literature using virtual agents for studying IMC and empathy, stressing their methodological limitations and forecasting possible ethical issues. The main contributions from this thesis project will be underlined, highlighting the potential misuse of virtual agents in eliciting social bonding in virtual environments. First, the main findings from **Chapter 3** will be summarised, where an autonomous agent driven by the HKB model explored the association of synchrony and empathy, demonstrating the successful translation of socio-motor components in HCI context. Second, findings from **Chapter 4** will be discussed, showing the limitations of virtual agents in eliciting social connectedness, that question the systematic association between synchrony and prosocial outcomes. Finally, findings from **Chapter 7** will be summarised, exploring the role of predictability in anthropomorphism and its association with inter-individual differences in cognitive empathy (i.e., Theory of Mind, ToM), combining behavioural assessments and EEG recordings. This section provides several methodological and ethical implications for cultivating togetherness in virtual spaces.

8.2.1 A promising tool for exploring the dynamic of sensorimotor coupling

In **Chapter 1**, the literature on IMC was reviewed, highlighting the distinctive streams of research exploring the mechanisms underlying synchrony and imitation. On the one hand, ideomotor theories suggest that IMC relies on a shared neurocognitive architecture of action observation/execution matching, overlapping with the MNS (Gallese et al., 1996; Prinz, 1990; Shamay-Tsoory et al., 2019). Yet, this sole mechanism appears insufficient for sustaining IMC, which requires neurocognitive components associated with self-other distinction also involved in conflict monitoring processes (Sebanz and Knoblich, 2009; Shamay-Tsoory et al., 2019). In contrast, dynamical system theories postulate that synchrony is a coordination pattern emerging from the coupling between individuals and their (social) environment (Haken and Tschacher, 2011; Heggli et al., 2021; Kelso, 1995; Schmidt et al., 2012). According to this approach, IMC cannot be reduced to intra-individual components but needs to be understood as a self-organised pattern emerging from multiple interactions occurring within complex systems (Haken, 1987). Therefore, these approaches conceptualise IMC from different theoretical standpoints, challenging the emergence of a unified framework. This thesis attempted to merge these frameworks to improve our understanding of the inter and intra-individual mechanisms underlying IMC.

In **Chapter 2**, a brief overview of the HKB model was provided, illustrating the application of oscillator models to dynamical systems (Kelso, 2021; Strogatz, 2004). The Virtual Partner of Interaction (VPI), a virtual agent driven by the HKB model, was introduced, allowing the replication of synchrony in controlled experimental settings (Dumas et al., 2014a; Kelso et al., 2009). The VPI already demonstrated its efficiency for mapping neural networks involved in motor coordination (Dumas et al., 2020) and studying motor coordination impairments in autism (Baillin et al., 2020). In **Chapter 3**, the VPI was used for remotely investigating the association of synchrony with empathy.

This study replicated findings from previous in-laboratory studies reporting an association between cognitive empathy and synchrony (Koehne et al., 2016b; Novembre et al., 2019). Moreover, this study revealed an unexpected negative association between subjective experiences of kinesthetic empathy and effective motor coordination. Nevertheless, these results must be interpreted with caution considering the lack of significance after corrections and replications are required. Despite this important limitation, this study suggested that virtual agents are suitable experimental tools and offer promising industrial applications for replicating the socio-motor components occurring in social interactions in virtual environments.

8.2.2 The credibility problem of virtual agents

Chapter 3 validated virtual agents as appropriate tools for investigating socio-motor components of social interactions. However, the pre-existing literature offers mixed findings regarding the translation of human-human interactions in HCI. According to the Computer-As-Social Agent (CASA) model, humans tend to apply similar social norms in real and virtual worlds (Nass et al., 1994). Whilst some studies support this statement, showing that synchrony can elicit prosocial outcomes toward virtual agents (Grynszpan et al., 2017; Hasler et al., 2014), other studies do not replicate these patterns (Bailenson et al., 2008; Verberne et al., 2013). These mixed findings cast doubt on the systematic association of synchrony with social bonding and this thesis explored the distinct role of affective and cognitive pathways linking synchrony with prosocial outcomes in HCI context.

Chapter 1 summarised the main hypotheses formulated in the literature linking synchrony with prosocial outcomes, namely, (i) processing fluency, linking synchrony with environmental uncertainty reduction and the activation of the rewarding system (Hoehl et al., 2021; Hove and Risen, 2009; Lang, 2010; Machin and Dunbar, 2011), (ii) blurring self-other boundaries, linking synchrony with in-group categorisation, a phenomenon observed in body illusions induced through visuomotor or tactile synchronisation (Botvinick and Cohen, 1998; Cross et al., 2019; Reddish et al., 2013), and (iii) a sense of joint commitment, linking synchrony with social norms of mutual reciprocity, a mechanism where virtual agents may not be "credible enough" as social agents (Fernández Castro and Pacherie, 2021; Fernández-Castro and Pacherie, 2023; Tomasello et al., 2005; Tomasello, 2009).

Chapter 4 attempted to disentangle these pathways by reporting results from a study using the VPI driven by the HKB model. In two different populations, synchronising movements with a virtual agent increased self-other distinction, decreased anthropomorphism and did not elicit prosocial tendencies. Although unexpected, these results replicate previous observations casting doubt on the systematic association of synchrony with prosocial outcomes (Bailenson et al., 2008; Rennung and Göritz, 2016; Tarr and Dunbar, 2023; Verberne et al., 2013). Furthermore, this study revealed the discrepancy between self-reports of being in synchrony and effective motor synchronisation, a pattern already observed in previous studies (Matthews et al., 2022). Consequently, this thesis calls for a reassessment of the systematic association between synchrony and prosocial outcomes by considering effective behaviours and stresses the role of complexity rather than predictability in the experience of togetherness (Csíkszentmihályi and Larson, 2014; Dahan et al., 2016; Vuoskoski and Reynolds, 2019).

8.2.3 Predictability and Theory of Mind

Predictability is an important concept underlying the experience of togetherness. Whilst predictability is often depicted as beneficial for inferring our (social) environment (Friston, 2010; Hoehl et al., 2021; Schwartenbeck et al., 2013), excessive predictability can dampen our experience of interacting with another mind, capable of acting and thinking independently (Gray and Wegner, 2012; Wang et al., 2015). Illustrating this paradox, the 3-factor model of anthropomorphism suggests that the motivation for reducing uncertainty drives tendencies to perceive agents as human (Epley et al., 2007).

Chapter 5 highlighted this paradoxical situation for designing automated agents capable of sustaining human operators' attention. Labelled as the Out-Of-The-Loop (OOTL) problem, the inability to understand the state of an automated system is an active area of research for preventing dramatic outcomes (Gouraud et al., 2017). On the one hand, it has been suggested that the OOTL problem could be addressed by maintaining the human operators' attentional state at optimal levels (Di Flumeri et al., 2019). On the other hand, the OOTL is also suggested to arise from an excessive complacency toward machines, leading to a disengagement from the task (Dzindolet et al., 2003; Gouraud et al., 2017). To reconcile these approaches, human operators are encouraged to recognise automated agents as collaborators capable of agentivity (De Visser et al., 2018; Klien et al., 2004). Framing in those terms, the OOTL problem overlaps with empathy's conceptualisations and this thesis attempted to clarify the association between the OOTL problem and empathy.

Chapter 7 reported an investigation of this association using the Matching Pennies Game (MPG), a second-order ToM task (i.e., I think that you think that I think) combined with empathy questionnaires and EEG recordings. This study revealed a discrepancy between self-reports and effective capacity to infer others' behaviours, stressing the gap between subjective experience and effective behaviours (Matthews et al., 2022; Melchers et al., 2015). Furthermore, the association between unpredictability and anthropomorphism suggested a possible shared mechanism with empathy, the tolerance for uncertainty (Epley et al., 2007). Finally, the EEG analyses revealed distinctive patterns between MPG conditions and error trials, suggesting the modulation of attentional and conflict monitoring processes by empathy scores. Although these results are preliminary and require replications, they are in line with the literature suggesting a distinction between the frontoparietal network involved in attention (Posner and Boies, 1971) and the salience network involved in conflict monitoring processes (Uddin, 2015), paving the way for exploring their respective association with empathy processes and anthropomorphism for designing more efficient HCI.

8.3 General conclusion

"Whereof one cannot speak, thereof one must be silent."
- Ludwig Wittgenstein

To conclude, the feeling of togetherness is an important but problematic concept that has attracted considerable research interests from various scientific disciplines, challenging our current understanding of "what it is like" to be together in real and virtual worlds. Throughout this manuscript, togetherness was conceptualised through the lenses of the literature associated with IMC and empathy, both ill-defined, leading to a "jingle-jangle fallacy", participating in scattering this research field. Ironically, togetherness is a concept at the core of scientific collaborations. Researchers from different horizons must collaborate by acknowledging differences in their theoretical viewpoints, establishing a "common ground" necessary for building mutual understanding (Clark and Brennan, 1991). During this project, various theoretical approaches were discussed, stretching from physics, providing computational models of synchronisation (Haken et al., 1985), to philosophy, exploring the epistemology of empathy (Darwall, 1998; Lanzoni, 2012). How these disciplines can work together (or in "synergy") to improve our understanding of social interactions will depend on the capacities of researchers to build bridges across disciplines.

This last section will review the main contributions of this thesis and discuss its theoretical and practical implications for future investigations exploring togetherness. First, this thesis stresses the overlap between IMC and empathy, two different facets of togetherness that nurtured separated streams of research. This thesis advocates for establishing interdisciplinary collaborations aiming to constitute a common and unified theoretical framework. Second, this thesis highlights the current lack of appropriate methodological tools for exploring togetherness, leading to discrepancies across studies and measurements. This thesis calls for a refinement between coarse and fine-grain assessments of togetherness. Finally, going beyond the main goal of this thesis, the ethical implications of studying togetherness will be discussed, by questioning the current conceptualisations of togetherness as "sameness" and the role of new technologies in transforming social interactions. In a post-pandemic world that will soon face an ecological crisis, the role of science in sustaining our capacity to live together is critical and its societal impact must be carefully considered.

8.3.1 Mapping moving, feeling and thinking together

Interpersonal motor coordination and empathy share a common history that can be traced back to the cradle of psychology as a scientific discipline (Asthana, 2015). Nonetheless, these concepts slowly diverged, leading to the loss of their connection. These last decades showed a regained popularity around merging these research fields, fuelled by the ideo-motor theories and the discovery of the action/perception matching system (Decety, 2010; Gallese et al., 1996; Preston and De Waal, 2002; Prinz, 1990). Nevertheless, the multiplication of conceptualisations challenges the constitution of a common and appropriate taxonomy of IMC and empathy (Hall and Schwartz, 2019). This thesis advocates for reconciling the two concepts and for addressing the current "jingle-jangle fallacy" by clarifying their conceptualisations.

Theoretical models of IMC and empathy suggest a shared neurocognitive architecture (Decety and Jackson, 2006; Gallese et al., 1996; Sebanz and Knoblich, 2009; Shamay-Tsoory et al., 2019; Shamay-Tsoory, 2011). Empirical works conducted during this thesis highlighted their association using self-reports, behavioural measures and EEG recordings. In **Chapter 3**, a virtual agent driven by the HKB model provided new insights into the association between IMC and empathy. Replicating findings from previous studies (Koehne et al., 2016b; Novembre et al., 2019), this experimental work expanded the current understanding of their association by suggesting an important distinction between subfacets of IMC and empathy. Yet, combining behavioural measures of automatic imitation (i.e., the AIT) and EEG recordings, the experimental work presented in **Chapter 6** stressed the overlap between spatial and temporal matching, mirroring and conflict monitoring, calling for a simplification of the cardinal components associated with moving, feeling and thinking together.

Altogether, these experimental works have theoretical implications by delineating various facets of interpersonal coordination (i.e., spatial versus temporal matching) and empathy (i.e., integration versus segregation of the other) that could simplify merging these two research fields. Additionally, these experimental works have potential implications for improving our understanding of comorbidity impairments in social/motor coordination and meta-cognition, such as those encountered in autism or schizophrenia (Cassidy et al., 2016; Hur et al., 2014). Finally, this thesis initiated interdisciplinary collaborations, that are currently expanded beyond this project, combining social neurosciences with motion analyses in modelling socio-motor components of human-human interactions in virtual and mixed environments (Ayache et al., 2023a).

8.3.2 Complexity and rhythm in social interactions

By diving into the complexity of togetherness, this thesis attempted to provide a more subtle and nuanced account of "what it is like" to be together. Philosophical and neuroscientific accounts are plural and the definition of togetherness is far from being settled, encompassing both integration (i.e., mirroring) and segregation (i.e., monitoring) of the other, two facets that are not contradictory but complementary (Tognoli et al., 2011; Mayo and Gordon, 2020; Foster, 2010; Engstrøm and Kelso, 2008). Recalling the initial entanglement of empathy with aesthetic experiences (Lanzoni, 2012), this thesis supports the hypothesis of a subtle balance (or "sweet spot") between predictability and surprise in generating and nurturing social connectedness and aesthetic experiences (Berlyne, 1970; Madison and Schiölde, 2017; Stupacher et al., 2022; Vincent, 2012; Vuoskoski and Reynolds, 2019). Consequently, this project calls for a clarification of "what it is like" to be together and the delineation of the feeling of togetherness as a specific consciousness state.

The feeling of "being with" and its behavioural components nurtured different research, focusing either on a subjective, first-person experience or behavioural assessments of togetherness (Pacherie, 2014; Varlet et al., 2011). **Chapters 4** and **7** explored this gap by combining self-reports with behavioural assessments, revealing discrepancies across measurements. In line with recent studies, these investigations suggested that togetherness assessments must be refined (Dahan et al., 2016; Ravreby et al., 2022). The feeling of togetherness can indeed be considered as phenomenologically "thin", ranging from subtle alteration (e.g., "fringe" states) to radical experience of self-dissolution (e.g., "oceanic" states) (Haggard, 2005; Norman et al., 2010; Saarinen, 2014). Thus, despite historical dissensions about introspection, the subjective and first-hand experience of togetherness could provide valuable insights for delineating its behavioural and neural signatures (Boring, 1953; Cleeremans and Tallon-Baudry, 2022; Varela, 1996).

These considerations have important implications for modelling social interactions. The discrepancy between subjective and effective measurements calls for a reassessment of togetherness measurements going beyond the experience of self-other overlap. Behavioural and neural indices of togetherness must also be expanded beyond spatial and temporal matching to unravel the complexity of social coordination patterns. The study of complex coordination patterns could also allow future works to explore a wider range of rhythmic patterns in social interactions (Malloch and Trevarthen, 2018). Consequently, new approaches and methodological tools must be employed to explore and improve our understanding of togetherness.

8.3.3 Togetherness, an important but problematic concept

Togetherness is an important but ill-defined concept, often conceptualised as a synonym of "sameness"' where the experience of the otherness is disregarded (Han, 2018). Tracing back from its apparition in the English vocabulary in the 1960s, depicting the American dream, togetherness has often been jeopardised for silencing minorities (Friedan, 2010). Nowadays, metrics associated with togetherness are often flawed by social norms and biased toward maintaining social injustice and an unfair status quo (Gough, 2021; Mills, 2014). Consequently, the research on togetherness is not neutral and has important societal impacts that need to be anticipated, considering their ethical implications. Echoing the initial references to Alan Turing's works, it is therefore important to bear in mind the following open questions:

(i) Where do patterns come from?

As discussed in this manuscript, the problem of defining and creating boundaries between concepts lies at the core of scientific knowledge. Acknowledging that these boundaries can sometimes be shifted for the better and the worse is important. Scientific categories are indeed the byproduct of human knowledge acquisition. Therefore, they can be reframed and reconstructed according to the ebb and flow of scientific advances[1]. Consequently, it is important to remain aware of the harmful consequences of categorisation, especially when they are performed by automated algorithms mimicking human behaviours[2].

(ii) What is it like to be human?

The reliance on automated agents questions the role of humans in modern societies. The replacement of humans by artificial intelligence, robots and avatars transforms how humans interact, and the spatial and temporal scaffolding of social interactions. The COVID-19 pandemic, the recent wars and the forthcoming ecological crisis have already underlined our difficulties in maintaining an open dialogue between communities, stressing the brittleness of global peace and our fragile capacity for cultivating togetherness. Adding these advanced technologies to the equation is a gamble that could either advance and unlock solutions for a sustainable future or unleash the darkest side of humanity.

[1]For a discussion on psychological categories and the role of phenomenology, see Drummond (2008)

[2]For an in-depth discussion on the problematic classification by "black box" and "parroting" machine learning, see Barlas et al. (2021); Birhane (2021)

The research field of togetherness is fairly new and while some of these research questions were partially addressed during this thesis, further investigations are required. Most of the experimental works conducted during this thesis were exploratory, with restricted sample sizes, and p-values near significance threshold. Hence, their interpretations need to be taken with caution and the patterns observed must be replicated before drawing any firm conclusions.

Despite these important limitations, similar findings were observed across studies:

(i) Behavioral matching is more than mirroring

In **Chapter 3**, an association was observed between cognitive empathy and synchrony (i.e., temporal matching). This result is consistent with in-laboratory studies showing that capacities for temporal predictions, acquired through musical experience for example, are associated with better capacity for temporal synchronisation and empathic perspective-taking (Koehne et al., 2016b; Novembre et al., 2019). In contrast, motor-related empathy components were associated with lower behavioural synchrony scores, revealing a discrepancy between self-report measures and effective behavioural matching. This pattern was replicated in **Chapter 6**, where participants scoring higher on motor-related empathy facets displayed overall lower accuracy in the automatic imitation task. Altogether, these results support an overlap of empathy mechanisms with spatial and temporal behavioural matching and stress the role of meta-cognitive processes.

Expanding these results further, an experimental investigation was conducted in collaboration with EuroMov DHM, combining hyperscanning EEG recordings with a motion-capture system during a "Rock Paper Scissor" Game. Hyperscanning methods allow the simultaneous recording of neural activity across two or more participants, a technique that is becoming popular for studying live social interactions (Babiloni and Astolfi, 2014; Czeszumski et al., 2020; Dumas et al., 2011; Liu et al., 2018; Mu et al., 2018). Yet, hyperscanning studies remain challenging and the different indices challenge their comparisons (Hakim et al., 2023; Burgess, 2013)[3]. Furthermore, it remains to clarify the causal mechanisms underlying inter-brain synchrony (Moreau and Dumas, 2021; Novembre and Iannetti, 2021; Gvirts Provolovski and Perlmutter, 2021)). Consequently, this investigation will participate in the growing literature exploring the role of neural and behavioural synchrony in social interactions.

[3]Inter-brain synchronisation can be computed using phase-locking-index, calculated from temporal domain (Lachaux et al., 1999; Stam et al., 2007; Varela et al., 2001) or inter-brain coherence, calculated from frequency domain (Dikker et al., 2017; Lindenberger et al., 2009; Sänger et al., 2012)

(ii) The role of uncertainty in human-human and human-avatar interactions

In **Chapter 4**, an unexpected negative association was observed between behavioural synchrony and affiliative experiences. This pattern contrasts the systematic positive associations between synchrony and social bonding typically seen in human-human interactions. Although less expected, similar negative associations have been observed in some HCI contexts, raising possible issues in translating socio-motor components of interactions to virtual environments (Bailenson et al., 2008; Verberne et al., 2013). **Chapter 7** explored the hypothesis suggesting that the excessive predictability displayed by a virtual agent could impede its capacity for eliciting social bonding. This hypothesis was partially confirmed by observing reduced tendencies for anthropomorphism when interacting with an excessively predictable agent. Altogether these results suggest that there is a "sweet spot" between predictability and uncertainty for designing efficient human-human and HCI interactions, leading to optimal attentional state (Csíkszentmihályi and Larson, 2014; Dahan et al., 2016; Stupacher et al., 2022).

This idea is currently taken further by the ShareSpace project, exploring the impact of synchronization in virtual and mixed environments (Milgram and Kishino, 1994). This European project expands the scope of the present thesis by exploring the role of synchronization between human-human and human-artificial agents for fostering social connectedness and mitigating pain sensation (Cohen et al., 2010; Tarr et al., 2015). Importantly, this project aims to promote user-centric and humanistic principles in designing automated agents driven by artificial intelligence. Thus, this project will scrutinize and consider the ethical issues and potential misuses of transforming the socio-motor components of human-human interactions by autonomous and semi-autonomous agents (De Vries and Peter, 2013; Farmer, 2023; Fuchs, 2021; Norman, 2014; Turkle, 1996). Consequently, this project will investigate the rendering of human motion in virtual environments and its consequences on the experience of social connectedness.

As a final note it is worth mentioning that the research questions investigated in this thesis have already nurtured fruitful collaborations, expanding these research questions beyond the scope of the present thesis. Most importantly, these interdisciplinary collaborations participate in nurturing a sense of "learned ignorance" whereby acknowledging our current lack of understanding of certain concepts, we cultivate a sense of humility and are further driven to expand our knowledge (Bellitto, 2023). This state of mind will, hopefully, facilitate in moving forward our understanding of the feeling of togetherness, a core aspect of human experience.

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LIST OF PUBLICATIONS

1. Ayache, J., Connor, A., Marks, S., Kuss, D. J., Rhodes, D., Sumich, A., Heym, N. (2021). Exploring the "dark matter" of social interaction: Systematic review of a decade of research in spontaneous interpersonal coordination. *Frontiers in Psychology, 12,* 718237.

2. Ayache, J., Heym, N., Sumich, A., Rhodes, D., Connor, A. M., Marks, S. (2021). Feeling closer despite the distance: How to cultivate togetherness within digital spaces. *Handbook of Research on Remote Work and Worker Well-Being in the Post-COVID-19 Era,* 243-263.

3. Ayache, J., Connor, A. M., Marks, S., Sumich, A., Heym, N. (2022, December). Humanness lies in unpredictability: Role of Theory of Mind on anthropomorphism in human-computer interactions. In *Proceedings of the 10th International Conference on Human-Agent Interaction* (pp. 306-308).

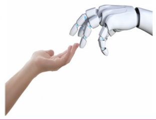
4. Ayache, J., Dumas, G., Sumich, A., Kuss, D. J., Rhodes, D., Heym, N. Disentangling the Multiple Dimensions of Empathy Through Interactive Psychometrics. *Available at SSRN 4560985*.

Appendices

Appendix A

POSTER PRESENTATION - BSPID 2022

The mediating role of alexithymia in the association of autistic and psychopathic traits with kinesthetic empathy and experiences of self-other overlap ~ distinction



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BACKGROUND

Autism is associated with deficits in cognitive empathy, whereas psychopathy with deficits in affective empathy [1]

Associations with kinesthetic/motor empathy and self-other overlap ~ distinction are less clear:

→Autism is linked to **imitation-facilitation** associated with **self-other overlap**, whereas psychopathy to **imitation-inhibition** associated with **self-other distinction** [2]

→ Yet mixed findings are reported [3] and **alexithymia**, a common comorbidity of autism and psychopathy, **might be driven their associations with kinesthetic empathy by modulating self-other boundaries**

METHODS

1. Participants (***N*=214**) completed self-reports of kinesthetic empathy, alexithymia, autistic and psychopathic traits [4-7]

2. Subsample (***N*=139**) executed a motor coordination task with a virtual agent [8]

3. Participants reported their experiences of self-other overlap ~ distinction.

DISCUSSION

There are different pathways for autistic, primary and secondary psychopathy traits in their association with kinesthetic empathy and motor coordination.

→**Alexithymia mediates associations for autism** and appears as **core mechanisms of empathy impairment in autism**

→**Primary and secondary psychopathy displayed distinctive associations with kinesthetic empathy**

Altogether these results pave the way for future investigations using virtual agent to study empathy in clinical populations.

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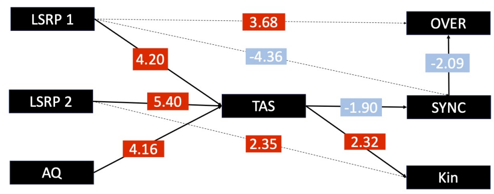
University Alliance
Doctoral Training Alliance

RESULTS

1. **Autism and psychopathy** positively associated with **kinesthetic empathy → TAS** mediated the association, but not for **secondary psychopathy**
2. **Autism and psychopathy** negatively associated with **motor coordination** (SYNC) **→ TAS** mediated the association, but not **primary psychopathy**
3. **Primary psychopathy** associated with increased experiences of **self-other overlap** (OVER)

	SYNC	OVER	Cogn	Aff	Kin	TAS	AQ	LSRP 1
QCAE Cognitive (Cogn)	.11	-.01						
QCAE Affective (Aff)	-.03	-.15	.39***					
KINEmp Kinesthetic (Kin)	-.27**	.08	-.08	.34***				
Toronto Alexithymia Scale (TAS)	-.38***	.10	-.40***	-.05	.39***			
Autism Quotient (AQ)	-.19*	-.01	-.49***	-.12	.27***	.51***		
Levenson Self-Report Psychopathy (LSRP 1)	-.48***	.40***	-.31***	-.21**	.21**	.55***	.26***	
Levenson Self-Report Psychopathy (LSRP 2)	-.35***	.15	-.37***	-.03	.37***	.66***	.40***	.57***



Values represented are standardized beta coefficient of path analysis testing a model with direct association for **LSRP2** with **Kin** and for **LSRP1** for **SYNC** and **OVER** compared to full mediation by **TAS** [$\chi 2$ (8, N = 139) =35.749, $p < 0.01$, AIC = 2082.1 and BIC = 2123.2]

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Appendix B

POSTER PRESENTATION - ESSEX 2022

Interpersonal synchrony as a disruption of individual homeostasis: Exploring the role of emotion dysregulation and self-awareness in the behavioural and phenomenological experience of synchrony

NTU School of Social Sciences

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BACKGROUND

Interpersonal synchrony (SYNC) is characterized by the tendency to synchronize behavioural rhythms between individuals and is a core component of **social attachment** [1]

Yet the modulation of **self-other boundaries** by SYNC could disrupt **self-regulation processes** [2]

This study aimed to clarify this relationship by investigating the association of SYNC with self-regulation processes.

METHODS

Participants (***N*=100**) completed self-reports of empathy, emotion dysregulation and interoceptive awareness [3-6]

Subsample (***N*=70**) executed a motor coordination task with a virtual agent inducing experiences of self-other overlap or distinction [7]

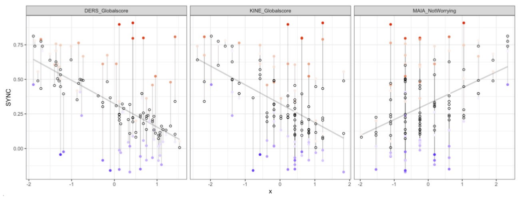
RESULTS

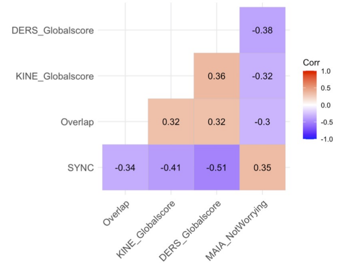
Kinesthetic empathy (i.e., spontaneous tendency to SYNC) is positively associated with **difficulties in emotion regulation**

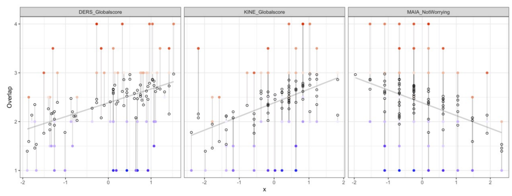
⇒ Both scales are negatively with the interoceptive subscale **MAIA NotWorrying** (i.e., tendencies to experience emotional distress during sensations of body discomfort)

Emotion dysregulation and **kinesthetic empathy** are both associated with **lower SYNC scores** and **higher self-other overlap**

⇒ The subscale **MAIA NotWorrying** displayed the opposite (e.g., **higher SYNC scores** + **lower self-other overlap**)







DISCUSSION

⇒ **Shared mechanisms** between kinesthetic empathy and difficulties in emotion regulation and motor control ?

⇒ **Role of self-awareness and metacognitive processes** in the discrepancy between SYNC and experiences of self-other overlap ?

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Appendix C

POSTER PRESENTATION - CCPM 2022

Empathy as "being moved" by the Other

Association between emotion dysregulation, kinesthetic empathy and experiences of self-other overlap ~ distinction using a virtual agent

Cognitive Control and Performance Monitoring
in memory of Laurence Questienne
May 29-31, 2022
~~June 3-5, 2021~~, Carry-le-Rouet (France)

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BACKGROUND

Empathy, praised for its pro-socially adaptive outcomes, is a multidimensional concept encompassing [1]:

- **Cognitive:** Perspective-taking abilities associated with experiences of self-other distinction
- **Affective and kinesthetic empathy:** Sharing of affective and motor states, with experiences of self-other overlap

However, empathy can also lead to emotion dysregulation due to its modulation of self-other boundaries [2]

⇒ The association between emotion dysregulation, empathy and experience of self-other overlap remains underexplored.

METHOD

1. Psychometrics assessments:
Participants (*N*=281) completed self-report of empathy (QCAE + KinEmp) [3,4] and emotion dysregulation (DERS)[5]

2. Motor coordination with a virtual agent:
A subsample (*N*=181) executed a motor task (SYNC) with a virtual agent eliciting experience of self-other overlap [6]

3. Self-other overlap ~ distinction experiences:
Reported their feelings of similarity/closeness with the virtual agent (OVER)

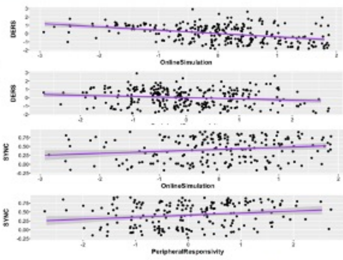
RESULTS AND DISCUSSION

⇒ **DERS** was positively correlated with **kinesthetic,** but negatively with **cognitive empathy**

⇒ **SYNC** was negatively correlated with **DERS** and **kinesthetic empathy**

⇒ **Affective empathy** was negatively correlated with **self-other overlap**

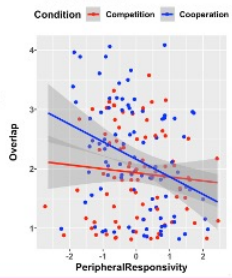
	SYNC	OVER	Cogn	Aff	Kin
QCAE Cognitive Empathy (Cogn)	0.08	-0.07	-		
QCAE Affective Empathy (Aff)	0.05	-0.15*	0.41***	-	
KINEmp Kinesthetic Empathy (Kin)	-0.23**	0.08	-0.06	0.38***	-
Difficulties in Emotion Regulation (DERS)	-0.33***	0.08	-0.36***	0.01	0.35***



Multiple linear regressions revealed that the QCAE facets

⇒ **Online Simulation** and **Peripheral responsivity** predicted **lower DERS scores** but **higher scores of SYNC**

⇒ **Peripheral responsivity** modulated the effect of the virtual agent on **experiences of self-other overlap.**



These results replicated findings suggesting **shared mechanisms between emotion dysregulation and motor skills impairments,** calling for futures investigations on integrating measures of **kinesthetic empathy.**

The role of **Peripheral Responsivity**, associated with empathy for fictional characters, needs to be clarified in the context of human-computer interactions.

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[4] Koehne, et al. (2016). The role of interpersonal movement synchronisation in empathic functions: Insights from Tango Argentino and Capoeira. International Journal of Psychology, 51(4), 318-322.
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Appendix D

Self-reports affiliation and anthropomorphism

1. **How similar do you feel to your virtual partner?**
   - Very similar
   - Similar
   - Neutral
   - Very dissimilar
2. **How close do you feel to your virtual partner?**
   - Very close
   - Close
   - Neutral
   - Not close at all
3. **How likely do you feel you achieved the goal of synchronizing with your virtual partner?**
   - Extremely unlikely
   - Unlikely
   - Neutral
   - Likely
   - Extremely likely
4. **How often have you felt in synchronization with your virtual partner?**
   - Never (0-20% of the time)
   - Almost never (20-40%)
   - Occasionally/Sometimes (40-60%)
   - Almost all time (60-80%)

- All-time (80 - 90%)

5. **How difficult it was to synchronize with your partner?**
    - Very difficult
    - Difficult
    - Neutral
    - Easy
    - Very easy

6. **How human-like was the partner?**
    - Robot-like
    - Slightly robot-like
    - I don’t know...
    - Slightly human-like
    - Human-like

7. **How cooperative was the partner?**
    - Very competitive
    - Competitive
    - Neutral
    - Cooperative
    - Very cooperative

Appendix E

Supplementary Material Chapter 3

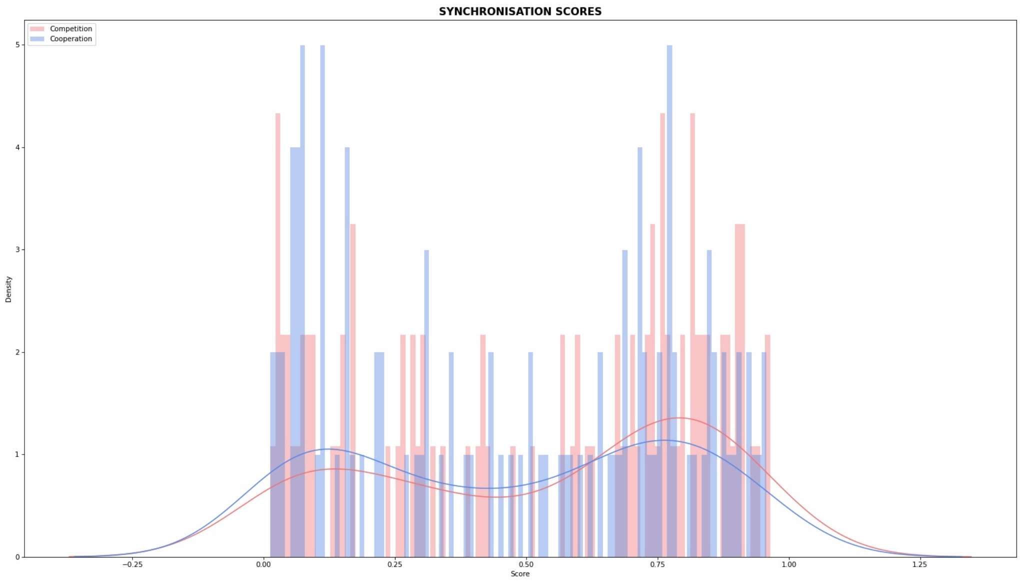

Fig. E.1 Graphical plot of the synchronisation scores distribution across VPI conditions

Appendix F

Supplementary Material Chapter 3

	1.	2.	3.	4.	5.	6.	7.	8.
2.	.16*							
3.	.31***	.15*						
4.	.57***	.09	.39***					
5.	.41***	.11	.52***	.49***				
6.	.44***	.07	.38***	.43***	.48***			
7.	.05	.28***	.05	.11	-.09	.03		
8.	.03	.39***	.13*	-.01	-.01	.03	.31***	
9.	.32***	-.18**	.29***	.36***	.37***	.40***	.01	-.11

Table F.1 Inter-items correlations between KinEmp items

1. When listening to somebody giving a speech who is tense, I often feel myself tensing up
2. Even when someone sitting across from me repeatedly runs his/her hand through his/her hair, I don't feel an increased tendency to touch my own head
3. When I see someone who tends to wink often, I tend to wink more myself
4. I often feel my own body tensing up when talking to somebody who is tense
5. When I hear someone around me clearing his throat, my throat feels rough, too
6. When I see someone stumbling, I often feel myself holding my own breath
7. It doesn't make me feel restless, when somebody next to me is fidgety
8. I hardly ever tend to mimic facial expressions of people that I am having a conversation with
9. I can feel a sensation in my own body, when I see somebody who is about to fall over

Appendix G

Supplementary Material Chapter 4

	Study 1 ($N = 143$)	Study 2 ($N = 118$)	Studies comparisons
Age	36.70 ± 10.58	32.75 ± 10.50	$t = 3.01, p = .003$
Gender	86 men, 54 women 3 non-binary	59 men, 59 women	$p = .065$
Motor coordination	0.44 ± 0.34	0.58 ± 0.29	$W = 6340, p = .001$
Positive Affect (*T0*)	33.98 ± 8.94	32.36 ± 9.61	$t = 1.39, p = .165$
Positive Affect (*T1*)	34.06 ± 9.20	32.83 ± 10.29	$t = 1.00, p = .316$
Negative Affect (*T0*)	20.37 ± 11.24	15.34 ± 6.82	$t = 4.45, p < .001$
Negative Affect (*T1*)	20.69 ± 11.09	14.89 ± 6.42	$t = 5.27, p < .001$

Table G.1 Descriptive statistics and population comparison across studies 1 and 2

Appendix H

Supplementary Material Chapter 6

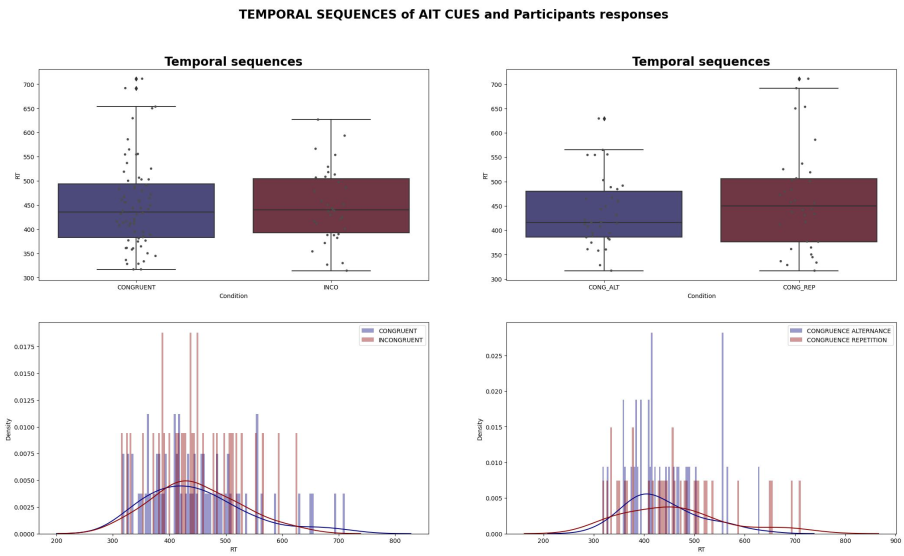

Fig. H.1 Graphical plots of reaction time between congruent and incongruent repetition/alternation of participants' and AIT sequences (left) and between congruence of repetition and congruence of alternation of participants' and AIT sequences (right)

Bold lines represent the median; upper and lower bound of the box represent the first and third quartiles.

Appendix I

Supplementary Material Chapter 7

	Correlations with reaction times
IRI Perspective Taking	.37***
IRI Fantasy	.28**
IRI Personal Distress	.04
IRI Empathic Concern	-.10
Somatic Empathy (CASES)	-.14
Kinesthetic Empathy (KinEmp)	.09

Table I.1 Correlations between empathy scores and times to decisions during the MPG

There was a significant association between the cognitive IRI subscales *Perspective Taking* and *Fantasy* with decision times ($\rho = .37, p < .001$ and $\rho = .28, p = .001$). However, this was not the case for the other empathy subscales (all $p > 0.50$) - see I.1 for full summary with significant correlations reported $*p < .05$, $**\,p < .01$, $***p < .001$.